INTERGOVERNMENTAL PANEL ON climate change

Climate Change 2022

Mitigation of Climate Change

Summary for Policymakers

WGIII

Working Group III contribution to the
Sixth Assessment Report of the
Intergovernmental Panel on Climate Change

WMO UNEP

WORKING GROUP III CONTRIBUTION
TO THE IPCC SIXTH ASSESSMENT REPORT (AR6)

Summary for Policymakers

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A. Introduction and framing

The Working Group III (WG III) contribution to the IPCC's Sixth Assessment Report (AR6) assesses literature on the scientific, technological, environmental, economic and social aspects of mitigation of climate change. [FOOTNOTE 1] Levels of confidence [FOOTNOTE 2] are given in () brackets. Numerical ranges are presented in square [] brackets. References to Chapters, Sections, Figures and Boxes in the underlying report and Technical Summary (TS) are given in {} brackets.

FOOTNOTE 1: The Report covers literature accepted for publication by 11 October 2021.

FOOTNOTE 2: Each finding is grounded in an evaluation of underlying evidence and agreement. A level of confidence is expressed using five qualifiers, typeset in italics: *very low*, *low*, *medium*, *high* and *very high*. The assessed likelihood of an outcome or a result is described as: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, more likely than not 50–100%, about as likely as not 33–66%, unlikely 0–33%, very unlikely 0–10%, exceptionally unlikely 0–1%. Additional terms may also be used when appropriate, consistent with the IPCC uncertainty guidance: https://www.ipcc.ch/site/assets/uploads/2018/05/uncertainty-guidance-note.pdf.

The report reflects new findings in the relevant literature and builds on previous IPCC reports, including the WG III contribution to the IPCC's Fifth Assessment Report (AR5), the WG I and WG II contributions to AR6 and the three Special Reports in the Sixth Assessment cycle, [FOOTNOTE 3] as well as other UN assessments. Some of the main developments relevant for this report include {TS.1, TS.2}:

FOOTNOTE 3: The three Special Reports are: Global Warming of 1.5°C: an IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (2018); Climate Change and Land: an IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (2019); IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (2019).

- **An evolving international landscape.** The literature reflects, among other factors: developments in the UN Framework Convention on Climate Change (UNFCCC) process, including the outcomes of the Kyoto Protocol and the adoption of the Paris Agreement {13, 14, 15, 16}; the UN 2030 Agenda for Sustainable Development including the Sustainable Development Goals (SDGs) {1, 3, 4, 17}; and the evolving roles of international cooperation {14}, finance {15} and innovation {16}.

- **Increasing diversity of actors and approaches to mitigation.** Recent literature highlights the growing role of non-state and sub-national actors including cities, businesses, Indigenous Peoples, citizens including local communities and youth, transnational initiatives, and public-private entities in the global effort to address climate change {5, 13, 14, 15, 16, 17}. Literature documents the global spread of climate policies and cost declines of existing and emerging low emission technologies, along with varied types and levels of mitigation efforts, and sustained reductions in greenhouse gas (GHG) emissions in some countries {2, 5, 6, 8, 12, 13, 16}, and the impacts of, and some lessons from, the COVID-19 pandemic. {1, 2, 3, 5, 13, 15, Box TS.1, Cross-Chapter Box 1 in Chapter 1}

- **Close linkages between climate change mitigation, adaptation and development pathways**. The development pathways taken by countries at all stages of economic development impact GHG emissions and hence shape mitigation challenges and opportunities, which vary across countries and regions. Literature explores how development choices and the establishment of enabling conditions for action and support influence the feasibility and the cost of limiting emissions {1, 3, 4, 5, 13, 15, 16}. Literature highlights that climate change mitigation action designed and conducted in the context of sustainable development, equity, and poverty eradication, and rooted in the development aspirations of the societies within which they take place, will be more acceptable, durable and effective {1, 3, 4, 5}. This report covers mitigation from both targeted measures, and from policies and governance with other primary objectives.

- **New approaches in the assessment**. In addition to the sectoral and systems chapters {3, 6, 7, 8, 9, 10, 11, 12}, the report includes, for the first time in a WG III report, chapters dedicated to demand for services, and social aspects of mitigation {5, Box TS.11}, and to innovation, technology development and transfer {16}. The assessment of future pathways in this report covers near term (to 2030), medium term (up to 2050), and long term (to 2100) timescales, combining assessment of existing pledges and actions {4, 5}, with an assessment of emissions reductions, and their implications, associated with long-term temperature outcomes up to the year 2100 {3}.[FOOTNOTE 4] The assessment of modelled global pathways addresses ways of shifting development pathways towards sustainability. Strengthened collaboration between IPCC Working Groups is reflected in Cross-Working Group boxes that integrate physical science, climate risks and adaptation, and the mitigation of climate change. [FOOTNOTE 5]

  FOOTNOTE 4: The term 'temperature' is used in reference to "global surface temperatures" throughout this SPM as defined in footnote 8 of WG I SPM. See FOOTNOTE 14 of Table SPM.1. Emission pathways and associated temperature changes are calculated using various forms of models, as summarised in Box SPM.1 and Chapter 3 and discussed in Annex III.

  FOOTNOTE 5: Namely: Economic Benefits from Avoided Climate Impacts along Long-Term Mitigation Pathways {Cross-Working Group Box 1 in Chapter 3}; Urban: Cities and Climate Change {Cross-Working Group Box 2 in Chapter 8}; and Mitigation and Adaptation via the Bioeconomy {Cross-Working Group Box 3 in Chapter 12}.

- **Increasing diversity of analytic frameworks from multiple disciplines including social sciences.** This report identifies multiple analytic frameworks to assess the drivers of, barriers to and options for, mitigation action. These include: economic efficiency including the benefits of avoided impacts; ethics and equity; interlinked technological and social transition processes; and socio-political frameworks, including institutions and governance {1, 3, 13, Cross-Chapter Box 12 in Chapter 16}. These help to identify risks and opportunities for action including co-benefits and just and equitable transitions at local, national and global scales. {1, 3, 4, 5, 13, 14, 16, 17}

Section B of this Summary for Policymakers (SPM) assesses *Recent developments and current trends*, including data uncertainties and gaps. Section C, *System transformations to limit global warming*, identifies emission pathways and alternative mitigation portfolios consistent with limiting global warming to different levels, and assesses specific mitigation options at the sectoral and system level. Section D addresses *Linkages between mitigation, adaptation, and sustainable development*. Section E, *Strengthening the response,* assesses knowledge of how enabling conditions of institutional design, policy, finance, innovation and governance arrangements can contribute to climate change mitigation in the context of sustainable development.

B. Recent developments and current trends

B.1 Total net anthropogenic GHG emissions [FOOTNOTE 6] have continued to rise during the period 2010–2019, as have cumulative net CO_2 emissions since 1850. Average annual GHG emissions during 2010-2019 were higher than in any previous decade, but the rate of growth between 2010 and 2019 was lower than that between 2000 and 2009. *(high confidence)* (Figure SPM.1) {Figure 2.2, Figure 2.5, Table 2.1, 2.2, Figure TS.2}

FOOTNOTE 6: Net GHG emissions in this report refer to releases of greenhouse gases from anthropogenic sources minus removals by anthropogenic sinks, for those species of gases that are reported under the common reporting format of the United Nations Framework Convention on Climate Change (UNFCCC): CO_2 from fossil fuel combustion and industrial processes (CO_2-FFI); net CO_2 emissions from land use, land use change and forestry (CO_2-LULUCF); methane (CH_4); nitrous oxide (N_2O); and fluorinated gases (F-gases) comprising hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF6) as well as nitrogen trifluoride (NF3). Different datasets for GHG emissions exist, with varying time horizons and coverage of sectors and gases, including some that go back to 1850. In this report, GHG emissions are assessed from 1990, and CO_2 sometimes also from 1850. Reasons for this include data availability and robustness, scope of the assessed literature, and the differing warming impacts of non-CO_2 gases over time.

B.1.1 Global net anthropogenic GHG emissions were 59±6.6 $GtCO_2$-eq [FOOTNOTE 7, 8] in 2019, about 12% (6.5 $GtCO_2$-eq) higher than in 2010 and 54% (21 $GtCO_2$-eq) higher than in 1990. The annual average during the decade 2010–2019 was 56±6.0 $GtCO_2$-eq, 9.1 $GtCO_2$-eq yr^{-1} higher than in 2000-2009. This is the highest increase in average decadal emissions on record. The average annual rate of growth slowed from 2.1% yr^{-1} between 2000 and 2009 to 1.3% yr^{-1} between 2010 and 2019. (*high confidence*) (Figure SPM.1) {Figure 2.2, Figure 2.5, Table 2.1, 2.2, Figure TS.2}

FOOTNOTE 7: GHG emission metrics are used to express emissions of different greenhouse gases in a common unit. Aggregated GHG emissions in this report are stated in CO_2-equivalent (CO_2-eq) using the Global Warming Potential with a time horizon of 100 years (GWP100) with values based on the contribution of Working Group I to the AR6. The choice of metric depends on the purpose of the analysis and all GHG emission metrics have limitations and uncertainties, given that they simplify the complexity of the physical climate system and its response to past and future GHG emissions. {Chapter 2 SM 2.3, Cross-Chapter Box 2 in Chapter 2, Box TS.2, WG I Chapter 7 Supplementary Material}

FOOTNOTE 8: In this SPM, uncertainty in historic GHG emissions is reported using 90 % uncertainty intervals unless stated otherwise. GHG emission levels are rounded to two significant digits; as a consequence, small differences in sums due to rounding may occur.

B.1.2 Growth in anthropogenic emissions has persisted across all major groups of GHGs since 1990, albeit at different rates. By 2019, the largest growth in absolute emissions occurred in CO_2 from fossil fuels and industry followed by CH_4, whereas the highest relative growth occurred in fluorinated gases, starting from low levels in 1990 (*high confidence*). Net anthropogenic CO_2 emissions from land use, land-use change and forestry (CO_2-LULUCF) are subject to large uncertainties and high annual variability, with *low confidence* even in the direction of the long-term trend [FOOTNOTE 9]. (Figure SPM.1) {Figure 2.2, Figure 2.5, 2.2, Figure TS.2}

FOOTNOTE 9: Global databases make different choices about which emissions and removals occurring on land are considered anthropogenic. Currently, net CO_2 fluxes from land reported by global book-keeping models used here are estimated to be about ~5.5 $GtCO_2$ yr^{-1} higher than the aggregate global net emissions based on national GHG inventories. This difference, which has been considered in the literature, mainly reflects differences in how anthropogenic forest sinks and areas of managed land are defined. Other reasons for this difference, which are more difficult to quantify, can arise from the limited representation of land management in global models and varying levels of accuracy and completeness of estimated LULUCF fluxes in national GHG inventories. Neither method is inherently preferable. Even when the same methodological approach is applied, the large uncertainty of CO_2-LULUCF emissions can lead to substantial revisions to estimated emissions. {Cross-Chapter Box 3 in Chapter 3, 7.2, SRCCL SPM A.3.3}

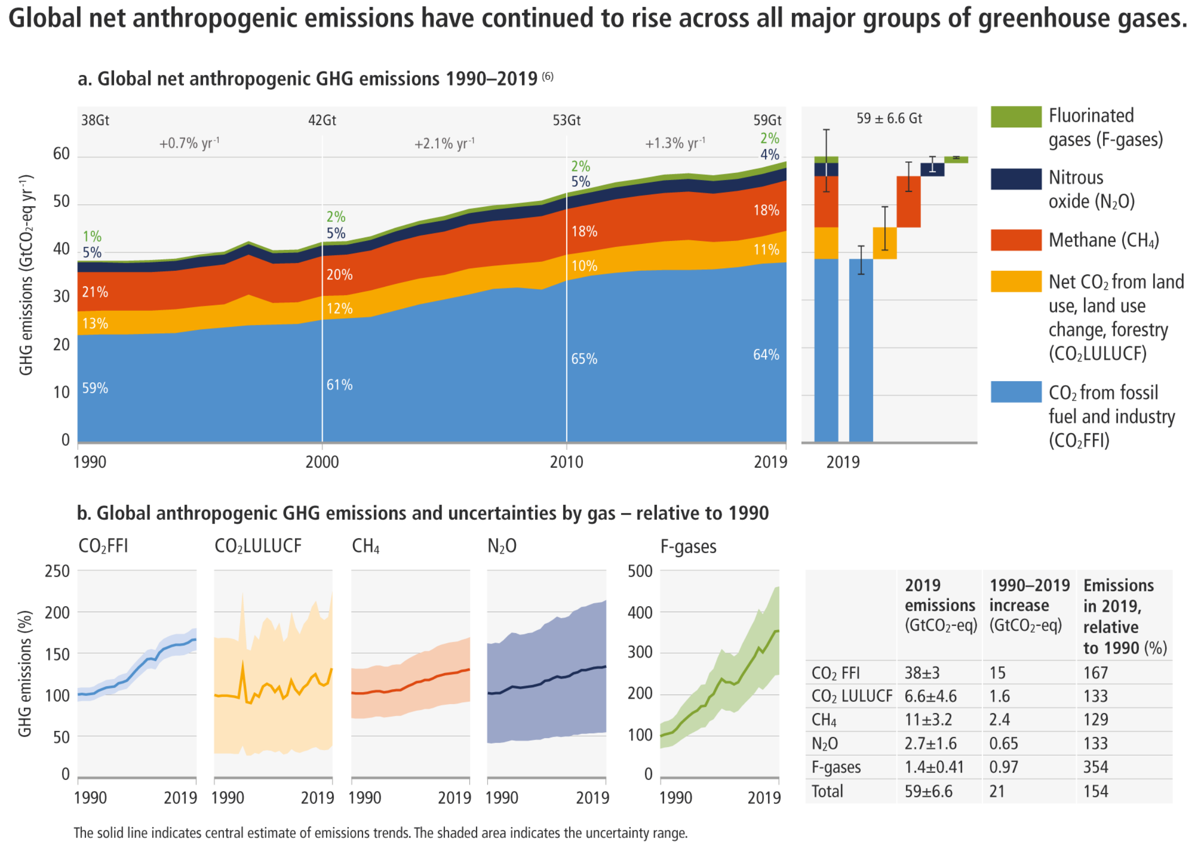
B.1.3 Historical cumulative net CO_2 emissions from 1850 to 2019 were 2400±240 $GtCO_2$ (*high confidence*). Of these, more than half (58%) occurred between 1850 and 1989 [1400±195 $GtCO_2$], and about 42% between 1990 and 2019 [1000±90 $GtCO_2$]. About 17% of historical cumulative net CO_2 emissions since 1850 occurred between 2010 and 2019 [410±30 $GtCO_2$]. [FOOTNOTE 10] By comparison, the current central estimate of the remaining carbon budget from 2020 onwards for limiting warming to 1.5°C with a probability of 50% has been assessed as 500 Gt CO_2, and as 1150 Gt CO_2 for a probability of 67% for limiting warming to 2°C. Remaining carbon budgets depend on the amount of non-CO_2 mitigation (±220 Gt CO_2) and are further subject to geophysical uncertainties. Based on central estimates only, cumulative net CO_2 emissions between 2010-2019 compare to about four fifths of the size of the remaining carbon budget from 2020 onwards for a 50% probability of limiting global warming to 1.5°C, and about one third of the remaining carbon budget for a 67% probability to limit global warming to 2°C. Even when taking uncertainties into account, historical emissions between 1850 and 2019 constitute a large share of total carbon budgets for these global warming levels [FOOTNOTE 11, 12]. Based on central estimates only, historical cumulative net CO_2 emissions between 1850-2019 amount to about four fifths [FOOTNOTE 12] of the total carbon budget for a 50% probability of limiting global warming to 1.5°C (central estimate about 2900 $GtCO_2$), and to about two thirds [FOOTNOTE 12] of the total carbon budget for a 67% probability to limit global warming to 2°C (central estimate about 3550 $GtCO_2$). {Figure 2.7, 2.2, Figure TS.3, WG I Table SPM.2}

FOOTNOTE 10: For consistency with WGI, historical cumulative CO_2 emissions from 1850-2019 are reported using 68% confidence intervals.

FOOTNOTE 11: The carbon budget is the maximum amount of cumulative net global anthropogenic CO_2 emissions that would result in limiting global warming to a given level with a given likelihood, taking into account the effect of other anthropogenic climate forcers. This is referred to as the total carbon budget when expressed starting from the pre-industrial period, and as the remaining carbon budget when expressed from a recent specified date. The total carbon budgets reported here are the sum of historical emissions from 1850 to 2019 and the remaining carbon budgets from 2020 onwards, which extend until global net zero CO_2 emissions are reached. {Annex I: Glossary; WG I SPM}

FOOTNOTE 12: Uncertainties for total carbon budgets have not been assessed and could affect the specific calculated fractions.

B.1.4 Emissions of CO_2–FFI dropped temporarily in the first half of 2020 due to responses to the COVID-19 pandemic (*high confidence*), but rebounded by the end of the year (*medium confidence*). The annual average CO_2-FFI emissions reduction in 2020 relative to 2019 was about 5.8% [5.1-6.3%], or 2.2 [1.9-2.4] $GtCO_2$ (*high confidence*). The full GHG emissions impact of the COVID-19 pandemic could not be assessed due to a lack of data regarding non-CO_2 GHG emissions in 2020. {Cross-Chapter Box 1 in Chapter 1, Figure 2.6, 2.2, Box TS.1, Box TS.1 Figure 1}



	2019 emissions ($GtCO_2$-eq)	1990–2019 increase ($GtCO_2$-eq)	Emissions in 2019, relative to 1990 (%)
CO_2 FFI	38±3	15	167
CO_2 LULUCF	6.6±4.6	1.6	133
CH_4	11±3.2	2.4	129
N_2O	2.7±1.6	0.65	133
F-gases	1.4±0.41	0.97	354
Total	59±6.6	21	154

Figure SPM.1: Global net anthropogenic GHG emissions ($GtCO_2$-eq yr^{-1}) 1990–2019

Global net anthropogenic GHG emissions include CO_2 from fossil fuel combustion and industrial processes (CO_2-FFI); net CO_2 from land use, land use change and forestry (CO_2-LULUCF) [FOOTNOTE 9]; methane (CH_4); nitrous oxide (N_2O); fluorinated gases (HFCs; PFCs, SF_6, NF_3). [FOOTNOTE 6]

Panel a shows aggregate annual global net anthropogenic GHG emissions by groups of gases from 1990 to 2019 reported in $GtCO_2$-eq converted based on global warming potentials with a 100-year time horizon (GWP100-AR6) from the IPCC Sixth Assessment Report Working Group I (Chapter 7). The fraction of global emissions for each gas is shown 1990, 2000, 2010, 2019; as well as the aggregate average annual growth rate between these decades. At the right side of Panel a, GHG emissions in 2019 are broken down into individual components with the associated uncertainties [90% confidence interval] indicated by the error bars: CO_2 FFI ±8%, CO_2-LULUCF ±70%, CH_4 ±30%, N_2O ±60%, F-gases ±30%, GHG ±11%. Uncertainties in GHG emissions are assessed in the Supplementary Material to Chapter 2. The single year peak of emissions in 1997 was due to higher CO_2-LULUCF emissions from a forest and peat fire event in South East Asia.

Panel b shows global anthropogenic CO_2-FFI, net CO_2-LULUCF, CH_4, N_2O and fluorinated gas emissions individually for the period 1990–2019, normalised relative to 100 in 1990. Note the different scale for the included fluorinated gas emissions compared to other gases, highlighting its rapid growth from a low base. Shaded areas indicate the uncertainty range. Uncertainty ranges as shown here are specific for individual groups of greenhouse gases and cannot be compared. The table shows the central estimate for: absolute emissions in 2019, the absolute change in emissions between 1990 and 2019, and emissions in 2019 expressed as a percentage of 1990 emissions. {2.2, Figure 2.5, Figure TS.2, Chapter 2 SM}

FOOTNOTE 9: Global databases make different choices about which emissions and removals occurring on land are considered anthropogenic. Currently, net CO_2 fluxes from land reported by global book-keeping models used here are estimated to be about ~5.5 $GtCO_2$ yr^{-1} higher than the aggregate global net emissions based on national GHG inventories. This difference, which has been considered in the literature, mainly reflects differences in how anthropogenic forest sinks and areas of managed land are defined. Other reasons for this difference, which are more difficult to quantify, can arise from the limited representation of land management in global models and varying levels of accuracy and completeness of estimated LULUCF fluxes in national GHG inventories. Neither method is inherently preferable. Even when the same methodological approach is applied, the large uncertainty of CO_2-LULUCF emissions can lead to substantial revisions to estimated emissions. {Cross-Chapter Box 3 in Chapter 3, 7.2, SRCCL SPM A.3.3}

FOOTNOTE 6: Net GHG emissions in this report refer to releases of greenhouse gases from anthropogenic sources minus removals by anthropogenic sinks, for those species of gases that are reported under the common reporting format of the United Nations Framework Convention on Climate Change (UNFCCC): CO_2 from fossil fuel combustion and industrial processes (CO_2-FFI); net CO_2 emissions from land use, land use change and forestry (CO_2-LULUCF); methane (CH_4); nitrous oxide (N_2O); and fluorinated gases (F-gases) comprising hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF6) as well as nitrogen trifluoride (NF3). Different datasets for GHG emissions exist, with varying time horizons and coverage of sectors and gases, including some that go back to 1850. In this report, GHG emissions are assessed from 1990, and CO_2 sometimes also from 1850. Reasons for this include data availability and robustness, scope of the assessed literature, and the differing warming impacts of non-CO_2 gases over time.

B.2 Net anthropogenic GHG emissions have increased since 2010 across all major sectors globally. An increasing share of emissions can be attributed to urban areas. Emissions reductions in CO_2 from fossil fuels and industrial processes, due to improvements in energy intensity of GDP and carbon intensity of energy, have been less than emissions increases from rising global activity levels in industry, energy supply, transport, agriculture and buildings. *(high confidence)* {2.2, 2.4, 6.3, 7.2, 8.3, 9.3, 10.1, 11.2}

B.2.1 In 2019, approximately 34% [20 $GtCO_2$-eq] of total net anthropogenic GHG emissions came from the energy supply sector, 24% [14 $GtCO_2$-eq] from industry, 22% [13 $GtCO_2$-eq]from agriculture, forestry and other land use (AFOLU), 15% [8.7 $GtCO_2$-eq] from transport and 6% [3.3 $GtCO_2$-eq] from buildings.[13] If emissions from electricity and heat production are attributed to the sectors that use the final energy, 90% of these indirect emissions are allocated to the industry and buildings sectors, increasing their relative GHG emissions shares from 24% to 34%, and from 6% to 16%, respectively. After reallocating emissions from electricity and heat production, the energy supply sector accounts for 12% of global net anthropogenic GHG emissions. (*high confidence*) {Figure 2.12, 2.2, 6.3, 7.2, 9.3, 10.1, 11.2, Figure TS.6}

FOOTNOTE 13: Sector definitions can be found in Annex II 9.1.

B.2.2 Average annual GHG emissions growth between 2010 and 2019 slowed compared to the previous decade in energy supply [from 2.3% to 1.0%] and industry [from 3.4% to 1.4%], but remained roughly constant at about 2% per year in the transport sector *(high confidence)*. Emissions growth in AFOLU, comprising emissions from agriculture (mainly CH_4 and N_2O) and forestry and other land use (mainly CO_2) is more uncertain than in other sectors due to the high share and uncertainty of CO_2-LULUCF emissions (*medium confidence*). About half of total net AFOLU emissions are from CO_2 LULUCF, predominantly from deforestation. [FOOTNOTE 14] (*medium confidence*). {Figure 2.13, 2.2, 6.3, 7.2, Figure 7.3, 9.3, 10.1, 11.2, TS.3}

FOOTNOTE 14: Land overall constituted a net sink of -6.6 (±4.6) $GtCO_2$ yr^{-1} for the period 2010-2019, comprising a gross sink of -12.5 (±3.2) $GtCO_2$ yr^{-1} resulting from responses of all land to both anthropogenic environmental change and natural climate variability, and net anthropogenic CO_2-LULUCF emissions +5.9 (±4.1) $GtCO_2$ yr^{-1} based on book-keeping models. {2.2, 7.2, Table 7.1}

B.2.3 The global share of emissions that can be attributed to urban areas is increasing. In 2015, urban emissions were estimated to be 25 $GtCO_2$-eq (about 62% of the global share) and in 2020, 29 $GtCO_2$-eq (67-72% of the global share).[15] The drivers of urban GHG emission are complex and include population size, income, state of urbanisation and urban form. (*high confidence*) {8.1, 8.3}

FOOTNOTE 15: This estimate is based on consumption-based accounting, including both direct emissions from within urban areas, and indirect emissions from outside urban areas related to the production of electricity, goods and services consumed in cities. These estimates include all CO_2 and CH_4 emission categories except for aviation and marine bunker fuels, land-use change, forestry and agriculture. {8.1, Annex I: Glossary}

B.2.4 Global energy intensity (total primary energy per unit GDP) decreased by 2% yr^{-1} between 2010 and 2019. Carbon intensity (CO_2 from fossil fuel combustion and industrial processes (CO_2 FFI) per unit primary energy) decreased by 0.3% yr^{-1}, with large regional variations, over the same period mainly due to fuel switching from coal to gas, reduced expansion of coal capacity, and increased use of renewables. This reversed the trend observed for 2000–2009. For comparison, the carbon intensity of primary energy is projected to decrease globally by about 3.5% yr^{-1} between 2020 and 2050 in modelled scenarios that limit warming to 2°C (>67%), and by about 7.7% yr^{-1} globally in scenarios that limit warming to 1.5°C (>50%) with no or limited overshoot.[16] (*high confidence*) {Figure 2.16, 2.2, 2.4, Table 3.4, 3.4, 6.3}

FOOTNOTE 16: See Box SPM.1 for the categorisation of modelled long-term emission scenarios based on projected temperature outcomes and associated probabilities adopted in this report.

B.3 Regional contributions [FOOTNOTE 17] to global GHG emissions continue to differ widely. Variations in regional, and national per capita emissions partly reflect different development stages, but they also vary widely at similar income levels. The 10% of households with the highest per capita emissions contribute a disproportionately large share of global household GHG emissions. At least 18 countries have sustained GHG emission reductions for longer than 10 years. (*high confidence*) (Figure SPM.2) {Figure 1.1, Figure 2.9, Figure 2.10, Figure 2.25, 2.2, 2.3, 2.4, 2.5, 2.6, Figure TS.4, Figure TS.5}

FOOTNOTE 17: See Working Group III Annex II, Part 1 for regional groupings adopted in this report.

B.3.1 GHG emissions trends over 1990-2019 vary widely across regions and over time, and across different stages of development as shown in Figure SPM.2. Average global per capita net anthropogenic GHG emissions increased from 7.7 to 7.8 tCO_2-eq, ranging from 2.6 tCO_2-eq to 19 tCO_2-eq across regions. Least Developed Countries (LDCs) and Small Island Developing States (SIDS) have much lower per capita emissions (1.7 tCO_2-eq, 4.6 tCO_2-eq, respectively) than the global average (6.9 tCO_2-eq), excluding CO_2-LULUCF [FOOTNOTE 18]. (*high confidence*) (Figure SPM.2) {Figure1.2, Figure 2.9, Figure 2.10, 2.2, Figure TS.4}

FOOTNOTE 18: In 2019, LDCs are estimated to have emitted 3.3% of global GHG emissions, and SIDS are estimated to have emitted 0.60% of global GHG emissions, excluding CO_2-LULUCF. These country groupings cut across geographic regions and are not depicted separately in Fig SPM2. {Figure 2.10}

B.3.2 Historical contributions to cumulative net anthropogenic CO_2 emissions between 1850 and 2019 vary substantially across regions in terms of total magnitude, but also in terms of contributions to CO_2-FFI (1650 +/- 73 $GtCO_2$-eq) and net CO_2-LULUCF (760 +/- 220 $GtCO_2$-eq) emissions.[FOOTNOTE 19] Globally, the major share of cumulative CO_2-FFI emissions is concentrated in a few regions, while cumulative CO_2-LULUCF [FOOTNOTE 9] emissions are concentrated in other regions. LDCs contributed less than 0.4% of historical cumulative CO_2-FFI emissions between 1850 and 2019, while SIDS contributed 0.5%. (*high confidence*) (Figure SPM.2) {Figure 2.10, 2.2, TS.3, Figure 2.7}

FOOTNOTE 9: Global databases make different choices about which emissions and removals occurring on land are considered anthropogenic. Currently, net CO_2 fluxes from land reported by global book-keeping models used here are estimated to be about ~5.5 $GtCO_2$ yr^{-1} higher than the aggregate global net emissions based on national GHG inventories. This difference, which has been considered in the literature, mainly reflects differences in how anthropogenic forest sinks and areas of managed land are defined. Other reasons for this difference, which are more difficult to quantify, can arise from the limited representation of land management in global models and varying levels of accuracy and completeness of estimated LULUCF fluxes in national GHG inventories. Neither method is inherently preferable. Even when the same methodological approach is applied, the large uncertainty of CO_2-LULUCF emissions can lead to substantial revisions to estimated emissions. {Cross-Chapter Box 3 in Chapter 3, 7.2, SRCCL SPM A.3.3}

FOOTNOTE 19: For consistency with WGI, historical cumulative CO_2 emissions from 1850-2019 are reported using 68% confidence intervals.

B.3.3 In 2019, around 48% of the global population lives in countries emitting on average more than 6t CO_2-eq per capita, excluding CO_2-LULUCF. 35% live in countries emitting more than 9 tCO_2-eq per capita. Another 41% live in countries emitting less than 3 tCO_2-eq per capita. A substantial share of the population in these low emitting countries lack access to modern energy services (FOOTNOTE 20). Eradicating extreme poverty, energy poverty, and providing decent living standards (FOOTNOTE 21) to all in these regions in the context of achieving sustainable development objectives, in the near-term, can be achieved without significant global emissions growth. (*high confidence*) (Figure SPM.2) {Figure 1.2, 2.2, 2.4, 2.6, 3.7, 4.2, 6.7, Figure TS.4, Figure TS.5}

FOOTNOTE 20: In this report, access to modern energy services is defined as access to clean, reliable and affordable energy services for cooking and heating, lighting, communications, and productive uses (See Annex I: Glossary)

FOOTNOTE 21: In this report, decent living standards are defined as a set of minimum material requirements essential for achieving basic human well-being, including nutrition, shelter, basic living conditions, clothing, health care, education, and mobility. (See 5.1)

B.3.4 Globally, the 10% of households with the highest per capita emissions contribute 34-45% of global consumption-based household GHG emissions [**FOOTNOTE 22**], while the middle 40% contribute 40-53%, and the bottom 50% contribute 13-15%. (*high confidence*) {2.6, Figure 2.25}

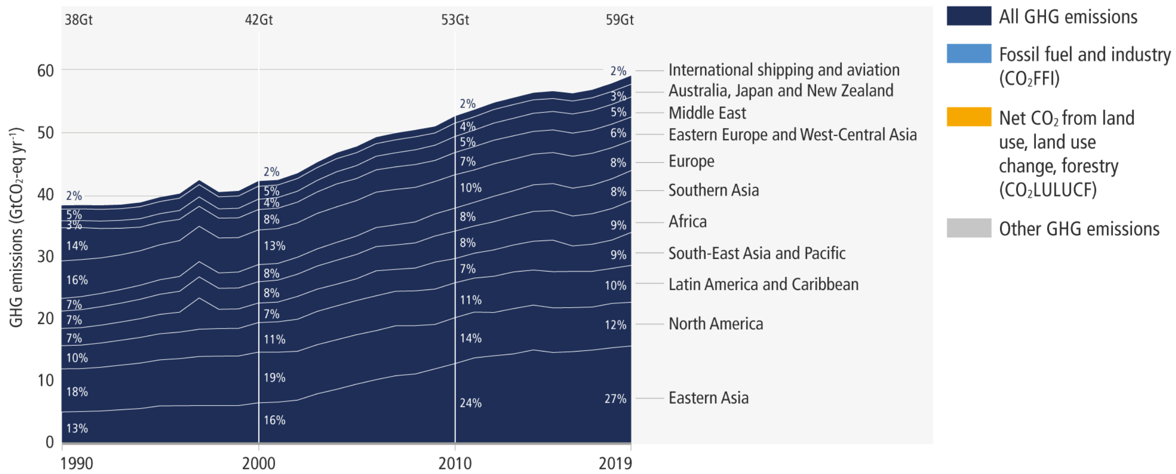
FOOTNOTE 22: Consumption-based emissions refer to emissions released to the atmosphere to generate the goods and services consumed by a certain entity (e.g., a person, firm, country, or region).

The bottom 50% of emitters spend less than USD3PPP per capita per day. The top 10% of emitters (an open-ended category) spend more than USD23PPP per capita per day. The wide range of estimates for the contribution of the top 10% result from the wide range of spending in this category and differing methods in the assessed literature. {Annex I: Glossary; 2.6}

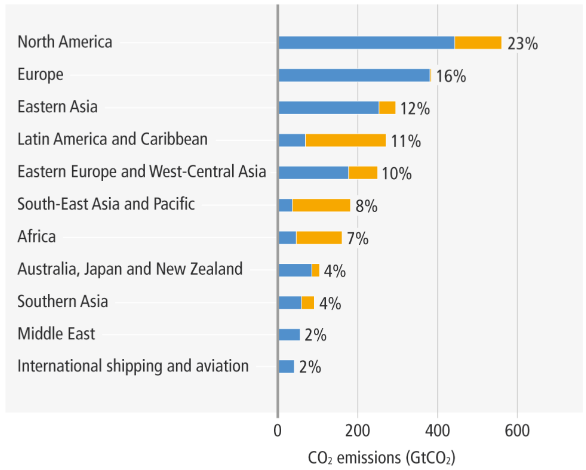
B.3.5 At least 18 countries have sustained production-based GHG and consumption-based CO_2 emission reductions for longer than 10 years. Reductions were linked to energy supply decarbonisation, energy efficiency gains, and energy demand reduction, which resulted from both policies and changes in economic structure. Some countries have reduced production-based GHG emissions by a third or more since peaking, and some have achieved several years of consecutive reduction rates of around 4 %/yr, comparable to global reductions in scenarios limiting warming to 2°C (>67%) or lower. These reductions have only partly offset global emissions growth. (*high confidence*) (Figure SPM.2) {Figure TS.4, 2.2, 1.3.2}

Emissions have grown in most regions but are distributed unevenly, both in the present day and cumulatively since 1850.

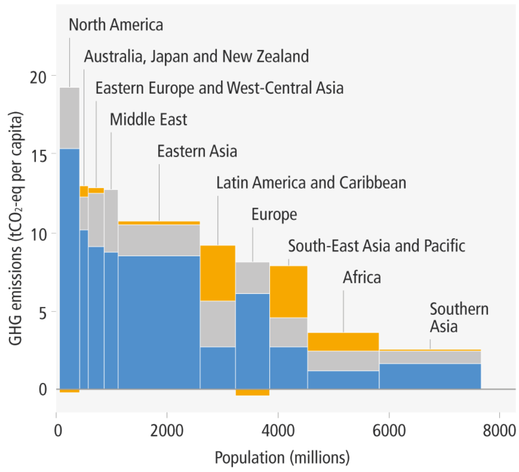
a. Global net anthropogenic GHG emissions by region (1990–2019)



b. Historical cumulative net anthropogenic CO_2 emissions per region (1850–2019)



c. Net anthropogenic GHG emissions per capita and for total population, per region (2019)



d. Regional indicators (2019) and regional production vs consumption accounting (2018)

	Africa	Australia, Japan, New Zealand	Eastern Asia	Eastern Europe, West-Central Asia	Europe	Latin America and Caribbean	Middle East	North America	South-East Asia and Pacific	Southern Asia
Population (million persons, 2019)	1292	157	1471	291	620	646	252	366	674	1836
GDP per capita (USD1000$_{ppp}$2017 per person)[1]	5.0	43	17	20	43	15	20	61	12	6.2
Net GHG 2019[2] (production basis)										
% GHG contributions	9%	3%	27%	6%	8%	10%	5%	12%	9%	8%
GHG emissions intensity (tCO_2-eq / USD1000$_{ppp}$ 2017)	0.78	0.30	0.62	0.64	0.18	0.61	0.64	0.31	0.65	0.42
GHG per capita (tCO_2-eq per person)	3.9	13	11	13	7.8	9.2	13	19	7.9	2.6
CO_2FFI, 2018, per person										
Production-based emissions (tCO_2FFI per person, based on 2018 data)	1.2	10	8.4	9.2	6.5	2.8	8.7	16	2.6	1.6
Consumption-based emissions (tCO_2FFI per person, based on 2018 data)	0.84	11	6.7	6.2	7.8	2.8	7.6	17	2.5	1.5

[1] GDP per capita in 2019 in USD2017 currency purchasing power basis.
[2] Includes CO_2FFI, CO_2LULUCF and Other GHGs, excluding international aviation and shipping.

The regional groupings used in this figure are for statistical purposes only and are described in Annex II, Part I.

Figure SPM.2: Regional GHG emissions, and the regional proportion of total cumulative production-based CO_2 emissions from 1850–2019

Panel a shows global net anthropogenic GHG emissions by region (in $GtCO_2$-eq yr-1 (GWP100 AR6)) for the time period 1990–2019 [FOOTNOTE 6]. Percentage values refer to the contribution of each region to total GHG emissions in each respective time period. The single year peak of emissions in 1997 was due to higher CO_2-LULUCF emissions from a forest and peat fire event in South East Asia. Regions are as grouped in Annex II.

Panel b shows the share of historical cumulative net anthropogenic CO_2 emissions per region from 1850 to 2019 in $GtCO_2$. This includes CO_2 from fossil fuel combustion and industrial processes (CO_2-FFI) and net CO_2 Land use, land use change, forestry (CO_2-LULUCF). Other GHG emissions are not included [FOOTNOTE 6]. CO_2-LULUCF emissions are subject to high uncertainties, reflected by a global uncertainty estimate of ± 70% (90% confidence interval).

Panel c shows the distribution of regional GHG emissions in tonnes CO_2-eq per capita by region in 2019. GHG emissions are categorised into: CO_2-FFI, net CO_2-LULUCF and other GHG emissions (methane, nitrous oxide, fluorinated gases, expressed in CO_2-eq using GWP100-AR6). The height of each rectangle shows per-capita emissions, the width shows the population of the region, so that the area of the rectangles refers to the total emissions for each region. Emissions from international aviation and shipping are not included. In the case of two regions, the area for CO_2-LULUCF is below the axis, indicating net CO_2 removals rather than emissions. CO_2-LULUCF emissions are subject to high uncertainties, reflected by a global uncertainty estimate of ± 70% (90% confidence interval).

Panel d shows population, GDP per person, emission indicators by region in 2019 for percentage GHG contributions, total GHG per person, and total GHG emissions intensity, together with production-based and consumption-based CO_2-FFI data, which is assessed in this report up to 2018. Consumption-based emissions are emissions released to the atmosphere in order to generate the goods and services consumed by a certain entity (e.g., region). Emissions from international aviation and shipping are not included.
{1.3, Figure 1.2, 2.2, Figure 2.9, Figure 2.10, Figure 2.11, Annex II}

B.4 The unit costs of several low-emission technologies have fallen continuously since 2010. Innovation policy packages have enabled these cost reductions and supported global adoption. Both tailored policies and comprehensive policies addressing innovation systems have helped overcome the distributional, environmental and social impacts potentially associated with global diffusion of low-emission technologies. Innovation has lagged in developing countries due to weaker enabling conditions. Digitalisation can enable emission reductions, but can have adverse side-effects unless appropriately governed. *(high confidence)* (Figure SPM.3) {2.2, 6.3, 6.4, 7.2, 12.2, 16.2, 16.4, 16.5, Cross-Chapter Box 11 in Chapter 16}

B.4.1 From 2010–2019, there have been sustained decreases in the unit costs of solar energy (85%), wind energy (55%), and lithium-ion batteries (85%), and large increases in their deployment, e.g., >10x for solar and >100x for electric vehicles (EVs), varying widely across regions (Figure SPM.3). The mix of policy instruments which reduced costs and stimulated adoption includes public R&D, funding for demonstration and pilot projects, and demand pull instruments such as deployment subsidies to attain scale. In comparison to modular small-unit size technologies, the empirical record shows that multiple large-scale mitigation technologies, with fewer opportunities for learning, have seen minimal cost reductions and their adoption has grown slowly. (*high confidence*) {1.3, 1.5, Figure 2.5, 2.5, 6.3, 6.4, 7.2, 11.3, 12.2, 12.3, 12.6, 13.6, 16.3, 16.4, 16.6}

B.4.2 Policy packages tailored to national contexts and technological characteristics have been effective in supporting low-emission innovation and technology diffusion. Appropriately designed policies and governance have helped address distributional impacts and rebound effects. Innovation has provided opportunities to lower emissions and reduce emission growth and created social and environmental co-benefits. (*high confidence*) Adoption of low-emission technologies lags in most developing countries, particularly least developed ones, due in part to weaker enabling conditions, including limited finance, technology development and transfer, and capacity. In many countries, especially those with limited institutional capacities, several adverse side-effects have been observed as a result of diffusion of low-emission technology, e.g., low-value employment, and dependency on foreign knowledge and suppliers. Low-emission innovation along with strengthened enabling conditions can reinforce development benefits, which can, in turn, create feedbacks towards greater public support for policy. *(medium confidence)* {9.9, 13.6, 13.7, 16.3, 16.4, 16.5, 16.6, Cross-Chapter Box 12 in Chapter 16, TS.3}

B.4.3 Digital technologies can contribute to mitigation of climate change and the achievement of several SDGs (*high confidence*). For example, sensors, Internet of Things, robotics, and artificial intelligence can improve energy management in all sectors, increase energy efficiency, and promote the adoption of many low-emission technologies, including decentralised renewable energy, while creating economic opportunities (*high confidence*). However, some of these climate change mitigation gains can be reduced or counterbalanced by growth in demand for goods and services due to the use of digital devices (*high confidence*). Digitalisation can involve trade-offs across several SDGs, e.g., increasing electronic waste, negative impacts on labour markets, and exacerbating the existing digital divide. Digital technology supports decarbonisation only if appropriately governed (*high confidence*). {5.3, 10, 12.6, 16.2, Cross-Chapter Box 11 in Chapter 16, TS.5, Box TS.14}

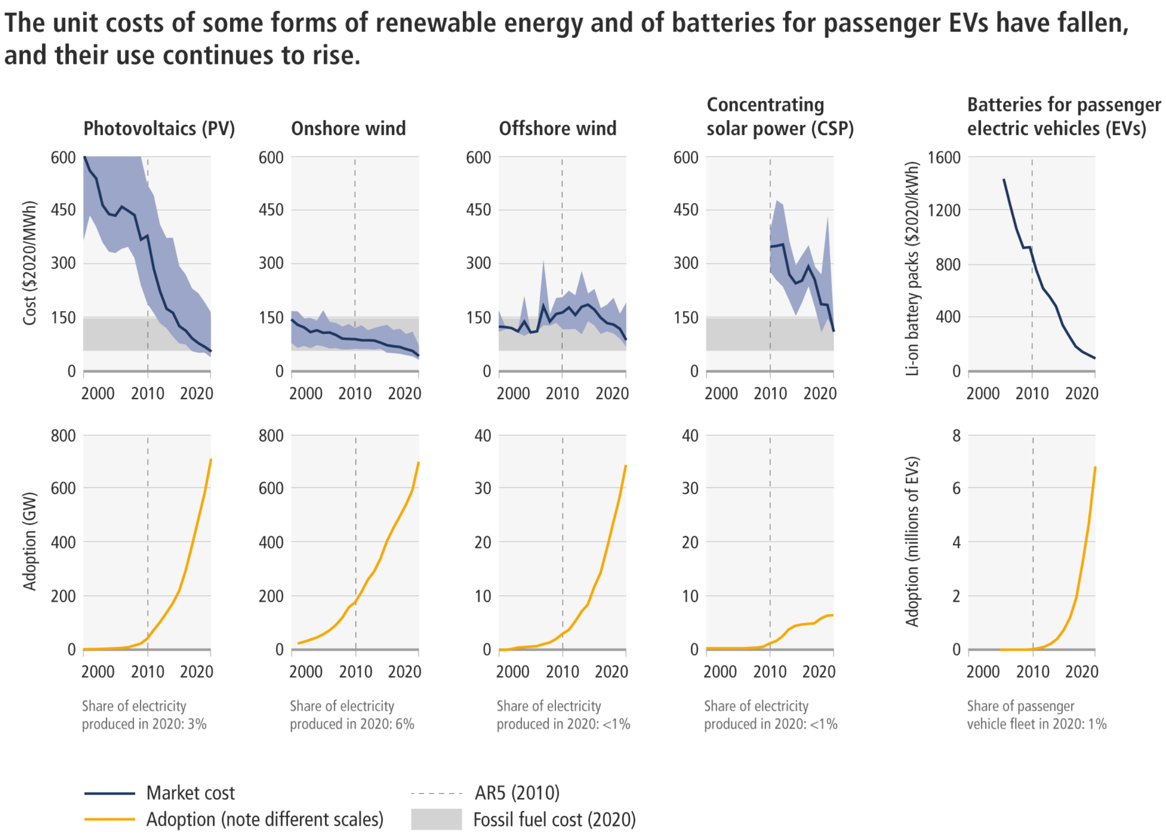


Figure SPM.3: Unit cost reductions and use in some rapidly changing mitigation technologies

The top panel shows global costs per unit of energy (USD/MWh) for some rapidly changing mitigation technologies. Solid blue lines indicate average unit cost in each year. Light blue shaded areas show the range between the 5th and 95th percentiles in each year. Grey shading indicates the range of unit costs for new fossil fuel (coal and gas) power in 2020 (corresponding to USD55–148 per MWh). In 2020, the levelised costs of energy (LCOE) of the four renewable energy technologies could compete with fossil fuels in many places. For batteries, costs shown are for 1 kWh of battery storage capacity; for the others, costs are LCOE, which includes installation, capital, operations, and maintenance costs per MWh of electricity produced. The literature uses LCOE because it allows consistent comparisons of cost trends across a diverse set of energy technologies to be made. However, it does not include the costs of grid integration or climate impacts. Further, LCOE does not take into account other environmental and social externalities that may modify the overall (monetary and non-monetary) costs of technologies and alter their deployment.

The bottom panel shows cumulative global adoption for each technology, in GW of installed capacity for renewable energy and in millions of vehicles for battery-electric vehicles. A vertical dashed line is placed in 2010 to indicate the change since AR5. Shares of electricity produced and share of passenger vehicle fleet are indicated in text for 2020 based on provisional data, i.e., percentage of total electricity production (for PV, onshore wind, offshore wind, CSP) and of total stock of passenger vehicles (for electric vehicles). The electricity production share reflects different capacity factors; e.g., for the same amount of installed capacity, wind produces about twice as much electricity as solar PV. {2.5, 6.4}

Renewable energy and battery technologies were selected as illustrative examples because they have recently shown rapid changes in costs and adoption, and because consistent data are available. Other mitigation options assessed in the report are not included as they do not meet these criteria.

B.5 There has been a consistent expansion of policies and laws addressing mitigation since AR5. This has led to the avoidance of emissions that would otherwise have occurred and increased investment in low-GHG technologies and infrastructure. Policy coverage of emissions is uneven across sectors. Progress on the alignment of financial flows towards the goals of the Paris Agreement remains slow and tracked climate finance flows are distributed unevenly across regions and sectors. (*high confidence*) {5.6, 13.2, 13.4, 13.5, 13.6, 13.9, 14.3, 14.4, 14.5, Cross-Chapter Box 10 in Chapter 14, 15.3, 15.5}

B.5.1 The Kyoto Protocol led to reduced emissions in some countries and was instrumental in building national and international capacity for GHG reporting, accounting and emissions markets (*high confidence*). At least 18 countries that had Kyoto targets for the first commitment period have had sustained absolute emission reductions for at least a decade from 2005, of which two were countries with economies in transition (*very high confidence*). The Paris Agreement, with near universal participation, has led to policy development and target-setting at national and sub-national levels, in particular in relation to mitigation, as well as enhanced transparency of climate action and support (*medium confidence*). {14.3, 14.6}

B.5.2 The application of diverse policy instruments for mitigation at the national and sub-national levels has grown consistently across a range of sectors (*high confidence*). By 2020, over 20% of global GHG emissions were covered by carbon taxes or emissions trading systems, although coverage and prices have been insufficient to achieve deep reductions (*medium confidence*). By 2020, there were 'direct' climate laws focused primarily on GHG reductions in 56 countries covering 53% of global emissions (*medium confidence*). Policy coverage remains limited for emissions from agriculture and the production of industrial materials and feedstocks *(high confidence)*. {5.6, 7.6, 11.5, 11.6, 13.2, 13.6}

B.5.3 In many countries, policies have enhanced energy efficiency, reduced rates of deforestation and accelerated technology deployment, leading to avoided and in some cases reduced or removed emissions (*high confidence*). Multiple lines of evidence suggest that mitigation policies have led to avoided global emissions of several Gt CO_2-eq yr^{-1} (*medium confidence*). At least 1.8 Gt CO_2-eq yr^{-1} can be accounted for by aggregating separate estimates for the effects of economic and regulatory instruments. Growing numbers of laws and executive orders have impacted global emissions and were estimated to result in 5.9 Gt CO_2-eq yr^{-1} less in 2016 than they otherwise would have been. (*medium confidence*) (Figure SPM.3) {2.2, 2.8, 6.7, 7.6, 9.9, 10.8, 13.6, Cross-chapter Box 10 in Chapter 14}

B.5.4 Annual tracked total financial flows for climate mitigation and adaptation increased by up to 60% between 2013/14 and 2019/20 (in USD2015), but average growth has slowed since 2018[23] (*medium confidence*). These financial flows remained heavily focused on mitigation, are uneven, and have developed heterogeneously across regions and sectors (*high confidence*). In 2018, public and publicly mobilised private climate finance flows from developed to developing countries were below the collective goal under the UNFCCC and Paris Agreement to mobilize USD 100 billion per year by 2020 in the context of meaningful mitigation action and transparency on implementation (*medium confidence*). Public and private finance flows for fossil fuels are still greater than those for climate adaptation and mitigation (*high confidence*). Markets for green bonds, ESG (environmental, social and governance) and sustainable finance products have expanded significantly since AR5. Challenges remain, in particular around integrity and additionality, as well as the limited applicability of these markets to many developing countries. (*high confidence*) {Box 15.4, 15.3, 15.5, 15.6, Box 15.7}

FOOTNOTE 23: Estimates of financial flows (comprising both private and public, domestic and international flows) are based on a single report which assembles data from multiple sources and which has applied various changes to their methodology over the past years. Such data can suggest broad trends but is subject to uncertainties.

B.6 Global GHG emissions in 2030 associated with the implementation of nationally determined contributions (NDCs) announced prior to COP26 [FOOTNOTE 24] would make it *likely* that warming will exceed 1.5°C during the 21st century.[FOOTNOTE 25] *Likely* limiting warming to below 2°C would then rely on a rapid acceleration of mitigation efforts after 2030. Policies implemented by the end of 2020 [FOOTNOTE 26] are projected to result in higher global GHG emissions than those implied by NDCs. (*high confidence*) (Figure SPM.4) {3.3, 3.5, 4.2, Cross-Chapter Box 4 in Chapter 4}

FOOTNOTE 24: NDCs announced prior to COP26 refer to the most recent nationally determined contributions submitted to the UNFCCC up to the literature cut-off date of this report, 11 October 2021, and revised NDCs announced by China, Japan and the Republic of Korea prior to October 2021 but only submitted thereafter. 25 NDC updates were submitted between 12 October 2021 and prior to the start of COP26.

FOOTNOTE 25: This implies that mitigation after 2030 can no longer establish a pathway with less than 67% probability to exceed 1.5°C during the 21st century, a defining feature of the class of pathways that limit warming to 1.5°C (>50%) with no or limited overshoot assessed in this report (Category C1 in Table SPM.1). These pathways limit warming to 1.6°C or lower throughout the 21st century with a 50% likelihood.

FOOTNOTE 26: The policy cut-off date in studies used to project GHG emissions of "policies implemented by the end of 2020" varies between July 2019 and November 2020. {Table 4.2}

B.6.1 Policies implemented by the end of 2020 are projected to result in higher global GHG emissions than those implied by NDCs, indicating an implementation gap. A gap remains between global GHG emissions in 2030 associated with the implementation of NDCs announced prior to COP26 and those associated with modelled mitigation pathways assuming immediate action (for quantification see Table SPM.X). [FOOTNOTE 27] The magnitude of the emission gap depends on the global warming level considered and whether only unconditional or also conditional elements of NDCs [FOOTNOTE 28] are considered.[FOOTNOTE 29] (*high confidence*) {3.5, 4.2, Cross-Chapter Box 4 in Chapter 4}

Table SPM.X: Projected global emissions in 2030 associated with policies implemented by the end of 2020 and NDCs announced prior to COP26, and associated emission gaps. *Emissions projections for 2030 and absolute differences in emissions are based on emissions of 52-56 $GtCO_2$-eq yr^{-1} in 2019 as assumed in underlying model studies. (*medium confidence*){4.2, Table 4.3, Cross-Chapter Box 4 in Chapter 4}

$GtCO_2$-eq yr^{-1}	Implied by policies implemented by the end of 2020	Implied by NDCs announced prior to COP26	
		Unconditional elements	Inc. conditional elements
Median (Min–Max)*	57 (52–60)	53 (50–57)	50 (47–55)
Implementation gap between implemented policies and NDCs (Median)		4	7
Emission gap between NDCs and pathways that limit warming to 2°C (>67%) with immediate action		10–16	6–14
Emissions gap between NDCs and pathways that limit warming to 1.5°C (>50%) with no or limited overshoot with immediate action		19–26	16–23

FOOTNOTE 27: Immediate action in modelled global pathways refers to the adoption between 2020 and at latest before 2025 of climate policies intended to limit global warming to a given level. Modelled

pathways that limit warming to 2°C (>67%) based on immediate action are summarised in Category C3a in Table SPM.1. All assessed modelled global pathways that limit warming to 1.5°C (>50%) with no or limited overshoot assume immediate action as defined here (Category C1 in Table SPM.1).

FOOTNOTE 28: In this report, “unconditional” elements of NDCs refer to mitigation efforts put forward without any conditions. “Conditional” elements refer to mitigation efforts that are contingent on international cooperation, for example bilateral and multilateral agreements, financing or monetary and/or technological transfers. This terminology is used in the literature and the UNFCCC’s NDC Synthesis Reports, not by the Paris Agreement. {4.2.1, 14.3.2}

FOOTNOTE 29: Two types of gaps are assessed: The implementation gap is calculated as the difference between the median of global emissions in 2030 implied by policies implemented by the end of 2020 and those implied by NDCs announced prior to COP26. The emissions gap is calculated as the difference between GHG emissions implied by the NDCs (minimum/maximum emissions in 2030) and the median of global GHG emissions in modelled pathways limiting warming to specific levels based on immediate action and with stated likelihoods as indicated (Table SPM.1).

B.6.2 Global emissions in 2030 associated with the implementation of NDCs announced prior to COP26 are lower than the emissions implied by the original NDCs [FOOTNOTE 30] (*high confidence*). The original emission gap has fallen by about 20% to one third relative to pathways that limit warming to 2°C (>67%) with immediate action (Category C3a in Table SPM.1), and by about 15-20% relative to pathways limiting warming to 1.5°C (>50%) with no or limited overshoot (Category C1 in Table SPM.1) (*medium confidence*). (Figure SPM.4) {3.5, 4.2, Cross-Chapter Box 4 in Chapter 4}

FOOTNOTE 30: Original NDCs refer to those submitted to the UNFCCC in 2015 and 2016. Unconditional elements of NDCs announced prior to COP26 imply global GHG emissions in 2030 that are 3.8 [3.0–5.3] $GtCO_2$-eq yr^{-1} lower than those from the original NDCs, and 4.5 [2.7–6.3] $GtCO_2$-eq yr^{-1} lower when conditional elements of NDCs are included. NDC updates at or after COP26 could further change the implied emissions.

B.6.3 Modelled global emission pathways consistent with NDCs announced prior to COP26 that limit warming to 2°C (>67%) (Category C3b in Table SPM.1) imply annual average global GHG emissions reduction rates of 0–0.7 $GtCO_2$-eq per year during the decade 2020-2030, with an unprecedented acceleration to 1.4–2.0 $GtCO_2$-eq per year during 2030-2050 (*medium confidence*). Continued investments in unabated high emitting infrastructure and limited development and deployment of low emitting alternatives prior to 2030 would act as barriers to this acceleration and increase feasibility risks (*high confidence*). {3.3, 3.5, 3.8, Cross-Chapter Box 5 in Chapter 4}

B.6.4 Modelled global emission pathways consistent with NDCs announced prior to COP26 will *likely* exceed 1.5°C during the 21st century. Those pathways that then return warming to 1.5°C by 2100 with a likelihood of 50% or greater imply a temperature overshoot of 0.15-0.3°C (42 pathways in category C2 in Table SPM.1). In such pathways, global cumulative net-negative CO_2 emissions are -380 [-860 to -200] $GtCO_2$ [FOOTNOTE 31] in the second half of the century, and there is a rapid acceleration of other mitigation efforts across all sectors after 2030. Such overshoot pathways imply increased climate-related risk, and are subject to increased feasibility concerns[FOOTNOTE 32], and greater social and environmental risks, compared to pathways that limit warming to 1.5°C (>50%) with no or limited overshoot. (*high confidence*) (Figure SPM.4, Table SPM.1) {3.3, 3.5, 3.8, 12.3; WG II SPM.B.6}

FOOTNOTE 31: Median and very likely range [5th to 95th percentile].

FOOTNOTE 32: Returning to below 1.5°C in 2100 from GHG emissions levels in 2030 associated with the implementation of NDCs is infeasible for some models due to model-specific constraints on the deployment of mitigation technologies and the availability of net negative CO_2 emissions.

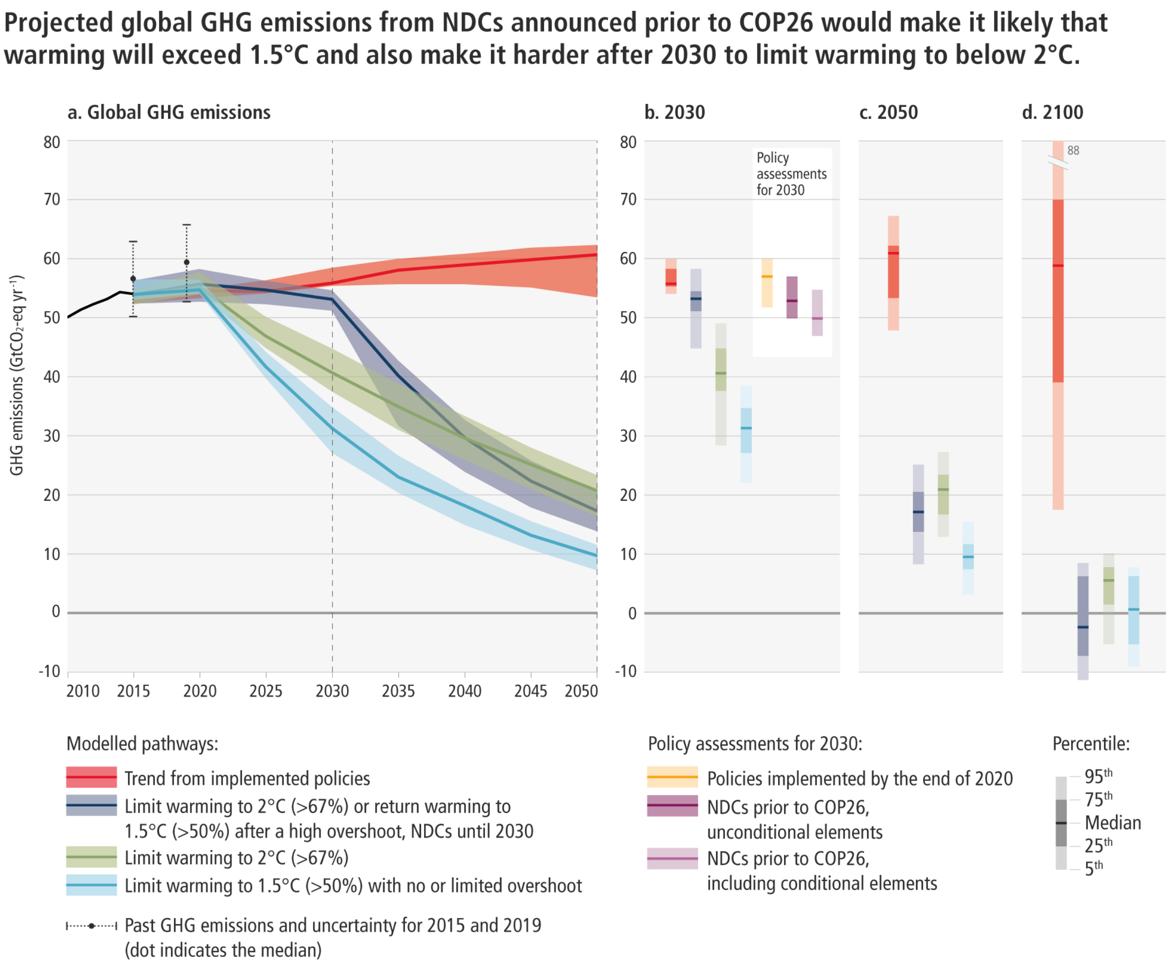


Figure SPM.4: Global GHG emissions of modelled pathways (funnels in Panel a. and associated bars in Panels b, c, d) and projected emission outcomes from near-term policy assessments for 2030 (Panel b).

Panel a shows global GHG emissions over 2015-2050 for four types of assessed modelled global pathways:

- Trend from implemented policies: Pathways with projected near-term GHG emissions in line with policies implemented until the end of 2020 and extended with comparable ambition levels beyond 2030 (29 scenarios across categories C5-C7, Table SPM.1)
- Limit to 2°C (>67%) or return warming to 1.5°C (>50%) after a high overshoot, NDCs until 2030: Pathways with GHG emissions until 2030 associated with the implementation of NDCs announced prior to COP26, followed by accelerated emissions reductions *likely* to limit warming to 2°C (C3b, Table SPM.1) or to return warming to 1.5°C with a probability of 50% or greater after high overshoot (subset of 42 scenarios from C2, Table SPM.1).

- Limit to 2°C (>67%) with immediate action: Pathways that limit warming to 2°C (>67%) with immediate action after 2020[27] (C3a, Table SPM.1).
- Limit to 1.5°C (>50%) with no or limited overshoot: Pathways limiting warming to 1.5°C with no or limited overshoot (C1, Table SPM.1 C1). All these pathways assume immediate action after 2020.

Past GHG emissions for 2010-2015 used to project global warming outcomes of the modelled pathways are shown by a black line [FOOTNOTE 33] and past global GHG emissions in 2015 and 2019 as assessed in Chapter 2 are shown by whiskers.

FOOTNOTE 33: See the Box SPM.1 for a description of the approach to project global warming outcomes of modelled pathways and its consistency between the climate assessment in AR6 WG I.

Panels b, c and d show snapshots of the GHG emission ranges of the modelled pathways in 2030, 2050, and 2100, respectively. Panel b also shows projected emissions outcomes from near-term policy assessments in 2030 from Chapter 4.2 (Tables 4.2 and 4.3; median and full range). GHG emissions are in CO_2-equivalent using GWP100 from AR6 WG I. {3.5, 4.2, Tables 4.2 and 4.3, Cross-Chapter Box 4 in Chapter 4}

B.7 Projected cumulative future CO_2 emissions over the lifetime of existing and currently planned fossil fuel infrastructure without additional abatement exceed the total cumulative net CO_2 emissions in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot. They are approximately equal to total cumulative net CO_2 emissions in pathways that limit warming to 2°C (>67%). (*high confidence*) {2.7, 3.3}

B.7.1 If historical operating patterns are maintained, [FOOTNOTE 34] and without additional abatement [FOOTNOTE 35], estimated cumulative future CO_2 emissions from existing fossil fuel infrastructure, the majority of which is in the power sector, would, from 2018 until the end of its lifetime, amount to 660 [460–890] $GtCO_2$. They would amount to 850 [600–1100] $GtCO_2$ when unabated emissions from currently planned infrastructure in the power sector is included. These estimates compare with cumulative global net CO_2 emissions from all sectors of 510 [330–710] $GtCO_2$ until the time of reaching net zero CO_2 emissions [FOOTNOTE 36] in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, and 890 [640–1160] $GtCO_2$ in pathways that limit warming to 2°C (>67%). (Table SPM.1) (*high confidence*) {2.7, Figure 2.26, Figure TS.8}

FOOTNOTE 34: Historical operating patterns are described by load factors and lifetimes of fossil fuel installations as observed in the past (average and range).

FOOTNOTE 35: Abatement here refers to human interventions that reduce the amount of greenhouse gases that are released from fossil fuel infrastructure to the atmosphere.

FOOTNOTE 36: Total cumulative CO_2 emissions up to the time of global net zero CO_2 emissions are similar but not identical to the remaining carbon budget for a given temperature limit assessed by Working Group I. This is because the modelled emission scenarios assessed by Working Group III cover a range of temperature levels up to a specific limit, and exhibit a variety of reductions in non-CO_2 emissions that also contribute to overall warming. {Box 3.4}

B.7.2 In modelled global pathways that limit warming to 2°C (>67%) or lower, most remaining fossil fuel CO_2 emissions until the time of global net zero CO_2 emissions are projected to occur outside the power sector, mainly in industry and transport. Decommissioning and reduced utilisation of existing fossil fuel based power sector infrastructure, retrofitting existing installations with CCS [FOOTNOTE 37] switches to low carbon fuels, and cancellation of new coal installations without CCS are major options that can contribute to aligning future CO_2 emissions from the power sector with emissions in the assessed global modelled least-cost pathways. The most appropriate strategies will depend on national and regional circumstances, including enabling conditions and technology availability. (*high confidence*) {Table 2.7, 2.7, 3.4, 6.3, 6.5, 6.7, Box SPM.1}

FOOTNOTE 37: In this context, capture rates of new installations with CCS are assumed to be 90-95% + {11.3.5}. Capture rates for retrofit installations can be comparable, if plants are specifically designed for CCS retrofits {11.3.6}.

C. System transformations to limit global warming

C.1 Global GHG emissions are projected to peak between 2020 and at the latest before 2025 in global modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot and in those that limit warming to 2°C (>67%) and assume immediate action. [Table SPM footnote [#9], FOOTNOTE 38] **In both types of modelled pathways, rapid and deep GHG emissions reductions follow throughout 2030, 2040 and 2050 (*high confidence*). Without a strengthening of policies beyond those that are implemented by the end of 2020, GHG emissions are projected to rise beyond 2025, leading to a median global warming of 3.2 [2.2 to 3.5] °C by 2100 [FOOTNOTE 39, 40] (*medium confidence*). (Table SPM.1, Figure SPM.4, Figure SPM.5) {3.3, 3.4}**

FOOTNOTE 38: All reported warming levels are relative to the period 1850–1900. If not otherwise specified, 'pathways' always refer to pathways computed with a model. Immediate action in the pathways refers to the adoption of climate policies between 2020 and at latest 2025 intended to limit global warming at a given level.

FOOTNOTE 39: Long-term warming is calculated from all modelled pathways assuming mitigation efforts consistent with national policies that were implemented by the end of 2020 (scenarios that fall into policy category P1b of Chapter 3) and that pass through the 2030 GHG emissions ranges of such pathways assessed in Chapter 4 (See FOOTNOTE 25) {3.2, Table 4.2}

FOOTNOTE 40: Warming estimates refer to the 50th and [5th–95th] percentile across the modelled pathways and the median temperature change estimate of the probabilistic WG I climate model emulators[Footnote 1] (Table SPM1).

C.1.1 Net global GHG emissions are projected to fall from 2019 levels by 27% [13–45%] by 2030 and 63% [52-76%] [FOOTNOTE 41] by 2050 in global modelled pathways that limit warming to 2°C (>67%) and assuming immediate action (category C3a, Table SPM.1). This compares with reductions of 43% [34–60%] by 2030 and 84% [73–98%] by 2050 in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot (C1, Table SPM.1) (*high confidence*).[[FOOTNOTE 42] In modelled pathways that return warming to 1.5°C (>50%) after a high overshoot [FOOTNOTE 43], GHG emissions are reduced by 23 [0-44%] in 2030 and by 75 [62-91%] in 2050 (C2, Table SPM.1) (*high confidence*). Modelled pathways that are consistent with NDCs announced prior to COP26 until 2030 and assume no increase in ambition thereafter have higher emissions, leading to a median global warming of 2.8°C [2.1-3.4°C] by 2100 (*medium confidence*). [FOOTNOTE 24] (Figure SPM .4). {3.3}

FOOTNOTE 41: In this report, emissions reductions are reported relative to 2019 modelled emission levels, while in SR1.5 emissions reductions were calculated relative to 2010. Between 2010 and 2019 global GHG and global CO_2 emissions have grown by 12% (6.5 $GtCO_2eq$) and 13% (5.0 Gt CO_2) respectively. In global modelled pathways assessed in this report that limit warming to 1.5°C (>50%) with no or limited overshoot, GHG emissions are projected to be reduced by 37% [28-57%] in 2030 relative to 2010. In the same type of pathways assessed in SR1.5, GHG emissions are reduced by 45% (40-60% interquartile range) relative to 2010. In absolute terms, the 2030 GHG emissions levels of pathways that limit warming to 1.5°C (>50%) with no or limited overshoot are higher in AR6 (31 [21-36] $GtCO_2eq$) than in SR1.5 (28 (26-31 interquartile range) $GtCO_2eq$). (Figure SPM. 1, Table SPM.1) {3.3, SR1.5}

FOOTNOTE 42: Scenarios in this category limit peak warming to 2°C throughout the 21st century with close to, or more than, 90% likelihood.

FOOTNOTE 43: This category contains 91 scenarios with immediate action and 42 scenarios that are consistent with the NDCs until 2030.

C.1.2 In modelled pathways that limit warming to 2°C (>67%) assuming immediate action, global net CO_2 emissions are reduced compared to modelled 2019 emissions by 27% [11–46%] in 2030 and by 52% [36-70%] in 2040; and global CH_4 emissions are reduced by 24% [9–53%] in 2030 and by 37% [20–60%] in 2040. In pathways that limit warming to 1.5°C (>50%) with no or limited overshoot global net CO_2 emissions are reduced compared to modelled 2019 emissions by 48% [36–69%] in 2030 and by 80% [61-109%] in 2040; and global CH_4 emissions are reduced by 34% [21–57%] in 2030 and 44% [31-63%] in 2040. There are similar reductions of non-CO_2 emissions by 2050 in both types of pathways: CH_4 is reduced by 45% [25–70%]; N_2O is reduced by 20% [-5 – 55%]; and F-Gases are reduced by 85% [20–90%]. [FOOTNOTE 44] Across most modelled pathways, this is the maximum technical potential for anthropogenic CH_4 reductions in the underlying models *(high confidence)*. Further emissions reductions, as illustrated by the IMP-SP pathway, may be achieved through changes in activity levels and/or technological innovations beyond those represented in the majority of the pathways *(medium confidence)*. Higher emissions reductions of CH_4 could further reduce peak warming. (*high confidence*) (Figure SPM.5) {3.3}

FOOTNOTE 44: These numbers for CH_4, N_2O, and F-gases are rounded to the nearest 5% except numbers below 5%.

C.1.3 In modelled pathways consistent with the continuation of policies implemented by the end of 2020, GHG emissions continue to rise, leading to global warming of 3.2 [2.2–3.5]°C by 2100 (within C5-C7, Table SPM 1) (*medium confidence*). Pathways that exceed warming of >4°C (≥50%) (C8, SSP5-8.5, Table SPM.1) would imply a reversal of current technology and/or mitigation policy trends (*medium confidence*). Such warming could occur in emission pathways consistent with policies implemented by the end of 2020 if climate sensitivity is higher than central estimates (*high confidence*). (Table SPM.1, Figure SPM.4) {3.3, Box 3.3}

C.1.4 Global modelled pathways falling into the lowest temperature category of the assessed literature (C1, Table SPM.1) are on average associated with a higher median peak warming in AR6 compared to pathways in the same category in SR1.5. In the modelled pathways in AR6, the likelihood of limiting warming to 1.5°C has on average declined compared to SR1.5. This is because GHG emissions have risen since 2017, and many recent pathways have higher projected emissions by 2030, higher cumulative net CO_2 emissions and slightly later dates for reaching net zero CO_2 or net zero GHG emissions. High mitigation challenges, for example, due to assumptions of slow technological change, high levels of global population growth, and high fragmentation as in the Shared Socioeconomic Pathway SSP3, may render modelled pathways that limit warming to 2°C (> 67%) or lower infeasible. (*medium confidence*) (Table SPM.1, Box SPM.1) {3.3, 3.8, Annex III Figure II.1, Annex III Figure II.3}

Table SPM.1 | Key characteristics of the modelled global emissions pathways: Summary of projected CO_2 and GHG emissions, projected net zero timings and the resulting global warming outcomes. Pathways are categorised (rows), according to their likelihood of limiting warming to different peak warming levels (if peak temperature occurs before 2100) and 2100 warming levels.

Values shown are for the median [p50] and 5th-95th percentiles [p5-p95], noting that not all pathways achieve net zero CO_2 or GHGs.

p50 [p5-p95] [1]			GHG emissions Gt CO_2-eq/yr [7]			GHG emissions reductions from 2019 % [8]			Emissions milestones [9,10]				Cumulative CO_2 emissions Gt CO_2 [13]		Cumulative net-negative CO_2 emissions Gt CO_2	Global mean temperature change 50% probability [14] °C		Likelihood of peak global warming staying below (%) [15]		
Category [2, 3, 4] [# pathways]	Category / subset label	WG I SSP & WG III IPs/IMPs alignment [5, 6]	2030	2040	2050	2030	2040	2050	Peak CO_2 emissions (% peak before 2100)	Peak GHG emissions (% peak before 2100)	Net-zero CO_2 (% net-zero pathways)	Net-zero GHGs [11, 12] (% net-zero pathways)	2020 to net-zero CO_2	2020-2100	Year of net-zero CO_2 to 2100	at peak warming	2100	<1.5°C	<2.0°C	<3.0°C
Modelled global emissions pathways categorised by projected global warming levels (GWL). Detailed likelihood definitions are provided in SPM Box1. The five illustrative scenarios (SSPx-y) considered by AR6 WGI and the Illustrative (Mitigation) Pathways assessed in WGIII are aligned with the temperature categories and are indicated in a separate column. Global emission pathways contain regionally differentiated information. This assessment focuses on their global characteristics.			*Projected median annual GHG emissions in the year across the scenarios, with the 5th-95th percentile in brackets. Modelled GHG emissions in 2019: 55 [53-58] Gt CO_2-eq*			*Projected median GHG emissions reductions of pathways in the year across the scenarios compared to modelled 2019, with the 5th-95th percentile in brackets. Negative numbers indicate increase in emissions compared to 2019*			*Median 5-year intervals at which projected CO_2 & GHG emissions peak, with the 5th-95th percentile interval in square brackets. Percentage of peaking pathways is denoted in round brackets. Three dots (…) denotes emissions peak in 2100 or beyond for that percentile.*		*Median 5-year intervals at which projected CO_2 & GHG emissions of pathways in this category reach net-zero, with the 5th-95th percentile interval in square brackets. Percentage of net zero pathways is denoted in round brackets. Three dots (…) denotes net zero not reached for that percentile.*		*Median cumulative net CO_2 emissions across the projected scenarios in this category until reaching net-zero or until 2100, with the 5th-95th percentile interval in square brackets.*		*Median cumulative net-negative CO_2 emissions between the year of net-zero CO_2 and 2100. More net-negative results in greater temperature declines after peak.*	*Projected temperature change of pathways in this category (50% probability across the range of climate uncertainties), relative to 1850-1900, at peak warming and in 2100, for the median value across the scenarios and the 5th-95th percentile interval in square brackets.*		*Median likelihood that the projected pathways in this category stay below a given global warming level, with the 5th-95th percentile interval in square brackets.*		
C1 [97]	**limit warming to 1.5°C (>50%) with no or limited overshoot**		31 [21-36]	17 [6-23]	9 [1-15]	43 [34-60]	69 [58-90]	84 [73-98]				2095-2100 (52%) [2050-...]	510 [330-710]	320 [-210-570]	-220 [-660–20]	1.6 [1.4-1.6]	1.3 [1.1-1.5]	38 [33-58]	90 [86-97]	100 [99-100]
C1a [50]	**... with net-zero GHGs**	SSP1-1.9, SP LD	33 [22-37]	18 [6-24]	8 [0-15]	41 [31-59]	66 [58-89]	85 [72-100]	2020-2025 (100%) [2020-2025]		2050-2055 (100%) [2035-2070]	2070-2075 (100%) [2050-2090]	550 [340-760]	160 [-220-620]	-360 [-680–140]	1.6 [1.4-1.6]	1.2 [1.1-1.4]	38 [34-60]	90 [85-98]	100 [99-100]
C1b [47]	**... without net-zero GHGs**	Ren	29 [21-36]	16 [7-21]	9 [4-13]	48 [35-61]	70 [62-87]	84 [76-93]				...-... [0%] [...-...]	460 [320-590]	360 [10-540]	-60 [-440-0]	1.6 [1.5-1.6]	1.4 [1.3-1.5]	37 [33-56]	89 [87-96]	100 [99-100]
C2 [133]	**return warming to 1.5°C (>50%) after a high overshoot**	Neg	42 [31-55]	25 [17-34]	14 [5-21]	23 [0-44]	55 [40-71]	75 [62-91]	2020-2025 (100%) [2020-2030]	[2020-2025]	2055-2060 (100%) [2045-2070]	2070-2075 (87%) [2055-...]	720 [530-930]	400 [-90-620]	-360 [-680–60]	1.7 [1.5-1.8]	1.4 [1.2-1.5]	24 [15-42]	82 [71-93]	100 [99-100]
C3 [311]	***limit warming to 2°C (>67%)***		44 [32-55]	29 [20-36]	20 [13-26]	21 [1-42]	46 [34-63]	64 [53-77]	2020-2025 (100%) [2020-2030]	[2020-2025]	2070-2075 (93%) [2055-...]	...-... (30%) [2075-...]	890 [640-1160]	800 [510-1140]	-40 [-290-0]	1.7 [1.6-1.8]	1.6 [1.5-1.8]	20 [13-41]	76 [68-91]	99 [98-100]
C3a [204]	**... with action starting in 2020**	SSP1-2.6	40 [30-49]	29 [21-36]	20 [14-27]	27 [13-45]	47 [35-63]	63 [52-76]	2020-2025 (100%) [2020-2025]		2070-2075 (91%) [2055-...]	...-... (24%) [2080-...]	860 [640-1180]	790 [480-1150]	-30 [-280-0]	1.7 [1.6-1.8]	1.6 [1.5-1.8]	21 [14-42]	78 [69-91]	100 [98-100]
C3b [97]	**... NDCs until 2030**	GS	52 [47-56]	29 [20-36]	18 [10-25]	5 [0-14]	46 [34-63]	68 [56-82]			2065-2070 (97%) [2055-2090]	...-... (41%) [2075-...]	910 [720-1150]	800 [560-1050]	-60 [-300-0]	1.8 [1.6-1.8]	1.6 [1.5-1.7]	17 [12-35]	73 [67-87]	99 [98-99]
C4 [159]	**limit warming to 2°C (>50%)**		50 [41-56]	38 [28-44]	28 [19-35]	10 [0-27]	31 [20-50]	49 [35-65]	2020-2025 (100%) [2020-2030]		2080-2085 (86%) [2065-...]	...-... (31%) [2075-...]	1210 [970-1490]	1160 [700-1490]	-30 [-390-0]	1.9 [1.7-2.0]	1.8 [1.5-2.0]	11 [7-22]	59 [50-77]	98 [95-99]
C5 [212]	**limit warming to 2.5°C (>50%)**		52 [46-56]	45 [37-53]	39 [30-49]	6 [-1-18]	18 [4-33]	29 [11-48]			...-... (41%) [2080-...]	...-... (12%) [2090-...]	1780 [1400-2360]	1780 [1260-2360]	0 [-160-0]	2.2 [1.9-2.5]	2.1 [1.9-2.5]	4 [0-10]	37 [18-59]	91 [83-98]
C6 [97]	**limit warming to 3°C (>50%)**	SSP2-4.5 Mod-Act	54 [50-62]	53 [48-61]	52 [45-57]	2 [-10-11]	3 [-14-14]	5 [-2-18]	2030-2035 (96%) [2020-2090]	2020-2025 (97%)				2790 [2440-3520]			2.7 [2.4-2.9]	0 [0-0]	8 [2-18]	71 [53-88]
C7 [164]	**limit warming to 4°C (>50%)**	SSP3-7.0 Cur-Pol	62 [53-69]	67 [56-76]	70 [58-83]	-11 [-18-3]	-19 [-31-1]	-24 [-41–2]	2085-2090 (57%) [2040-...]	2090-2095 (56%)	no net-zero		no net-zero	4220 [3160-5000]	no net-zero	temperature does not peak by 2100	3.5 [2.8-3.9]	0 [0-0]	0 [0-2]	22 [7-60]
C8 [29]	**exceed warming of 4°C (>=50%)**	SSP5-8.5	71 [69-81]	80 [78-96]	88 [82-112]	-20 [-34–17]	-35 [-65–29]	-46 [-92–36]	2080-2085 (90%) [2070-...]					5600 [4910-7450]			4.2 [3.7-5.0]	0 [0-0]	0 [0-0]	4 [0-11]

1 Values in the table refer to the 50th and [5th–95th] percentile values across the pathways falling within a given category as defined in Box SPM.1. For emissions-related columns these values relate to the distribution of all the pathways in that category. Harmonized emissions values are given for consistency with projected global warming outcomes using climate emulators. Based on the assessment of climate emulators in AR6 WG I (Chapter 7, Box 7.1), two climate emulators are used for the probabilistic assessment of the resulting warming of the pathways. For the 'Temperature Change' and 'Likelihood' columns, the single upper row values represent the 50th percentile across the pathways in that category and the median [50th percentile] across the warming estimates of the probabilistic MAGICC climate model emulator. For the bracketed ranges, the median warming for every pathway in that category is calculated for each of the two climate model emulators (MAGICC and FaIR). Subsequently, the 5th and 95th percentile values across all pathways for each emulator are calculated. The coolest and warmest outcomes (i.e. the lowest p5 of two emulators, and the highest p95, respectively) are shown in square brackets. These ranges therefore cover both the uncertainty of the emissions pathways as well as the climate emulators' uncertainty.
2 For a description of pathways categories see Box SPM.1.
3 All global warming levels are relative to 1850–1900. See Table SPM 1 Footnote 13 below and SPM Scenarios Box FOOTNOTE 46 for more details.
4 C3 pathways are sub-categorised according to the timing of policy action to match the emissions pathways in Figure SPM.4. Two pathways derived from a cost-benefit analysis have been added to C3a, whilst 10 pathways with specifically designed near-term action until 2030, whose emissions fall below those implied by NDCs announced prior to COP26, are not included in either of the two subsets.
5 Alignment with the categories of the illustrative SSP scenarios considered in AR6 WG I, and the Illustrative (Mitigation) Pathways (IPs/IMPs) of WG III. The IMPs have common features such as deep and rapid emissions reductions, but also different combinations of sectoral mitigation strategies. See SPM Box 1 for an introduction of the IPs and IMPs and Chapter 3 for full descriptions. {3.2, 3.3, Annex III.II.4}
6 The Illustrative Mitigation Pathway 'Neg' has extensive use of carbon dioxide removal (CDR) in the AFOLU, energy and the industry sectors to achieve net negative emissions. Warming peaks around 2060 and declines to below 1.5°C (50% likelihood) shortly after 2100. Whilst technically classified as C3, it strongly exhibits the characteristics of C2 high overshoot pathways, hence it has been placed in the C2 category. See SPM C3.1 for an introduction of the IPs and IMPs.
7 The 2019 range of harmonized GHG emissions across the pathways [53-58 $GtCO_2eq$] is within the uncertainty ranges of 2019 emissions assessed in Chapter 2 [53-66 $GtCO_2$-eq]. {Fig SPM 1, Fig SPM 2, Box SPM1 FOOTNOTE 50}
8 Rates of global emission reduction in mitigation pathways are reported on a pathway-by-pathway basis relative to harmonized modelled global emissions in 2019 rather than the global emissions reported in SPM Section B and Chapter 2; this ensures internal consistency in assumptions about emission sources and activities, as well as consistency with temperature projections based on the physical climate science assessment by WG I. {Annex III.II.2.5, FOOTNOTE 50} Negative values (e.g., in C7, C8) represent an increase in emissions.
9 Emissions milestones are provided for 5-year intervals in order to be consistent with the underlying 5-year time-step data of the modelled pathways. Peak emissions (CO_2 and GHGs) are assessed for 5 year reporting intervals starting in 2020. The interval 2020-2025 signifies that projected emissions peak as soon as possible between 2020 and at latest before 2025. The upper 5-year interval refers to the median interval within which the emissions peak or reach net zero. Ranges in square brackets underneath refer to the range across the pathways, comprising the lower bound of the 5th percentile 5-year interval and the upper bound of the 95th percentile 5-year interval. Numbers in round brackets signify the fraction of pathways that reach specific milestones.
10 Percentiles reported across all pathways in that category include those that do not reach net zero before 2100 (fraction of pathways reaching net zero is given in round brackets). If the fraction of pathways that reach net zero before 2100 is lower than the fraction of pathways covered by a percentile (e.g., 0.95 for the 95th percentile), the percentile is not defined and denoted with "…". The fraction of pathways reaching net zero includes all with reported non-harmonised, and / or harmonised emissions profiles that reach net zero. Pathways were counted when at least one of the two profiles fell below 100 $MtCO_2\ yr^{-1}$ until 2100.
11 The timing of net zero is further discussed in SPM C2.4 and the Cross-Chapter Box 3 in Chapter 3 on net zero CO_2 and net zero GHG emissions.
12 For cases where models do not report all GHGs, missing GHG species are infilled and aggregated into a Kyoto basket of GHG emissions in CO_2-eq defined by the 100 year global warming potential. For each pathway, reporting of CO_2, CH_4, and N_2O emissions was the minimum required for the assessment of the climate

response and the assignment to a climate category. Emissions pathways without climate assessment are not included in the ranges presented here. See Annex III.II.5.
13 Cumulative emissions are calculated from the start of 2020 to the time of net zero and 2100, respectively. They are based on harmonized net CO_2 emissions, ensuring consistency with the WG I assessment of the remaining carbon budget. {Box 3.4, FOOTNOTE 51 in SPM C.2}.
14 Global mean temperature change for category (at peak, if peak temperature occurs before 2100, and in 2100) relative to 1850–1900, based on the median global warming for each pathway assessed using the probabilistic climate model emulators calibrated to the AR6 WG I assessment, see also SPM Scenarios Box. {SPM FOOTNOTE 12, WG I Cross Chapter Box 7.1, Annex III.II.2.5}.
15 Probability of staying below the temperature thresholds for the pathways in each category, taking into consideration the range of uncertainty from the climate model emulators consistent with the AR6 WG I assessment. The probabilities refer to the probability at peak temperature. Note that in the case of temperature overshoot (e.g., category C2 and some pathways in C1), the probabilities of staying below at the end of the century are higher than the probabilities at peak temperature.

<START BOX SPM.1 HERE>

Box SPM.1: Assessment of modelled global emission scenarios

A wide range of modelled global emission pathways and scenarios from the literature is assessed in this report, including pathways and scenarios with and without mitigation.[FOOTNOTE 45] Emissions pathways and scenarios project the evolution of GHG emissions based on a set of internally consistent assumptions about future socio-economic conditions and related mitigation measures.[FOOTNOTE 46] These are quantitative projections and are neither predictions nor forecasts. Around half of all modelled global emission scenarios assume cost-effective approaches that rely on least-cost emission abatement options globally. The other half looks at existing policies and regionally and sectorally differentiated actions. Most do not make explicit assumptions about global equity, environmental justice or intra-regional income distribution. Global emission pathways, including those based on cost effective approaches contain regionally differentiated assumptions and outcomes, and have to be assessed with the careful recognition of these assumptions. This assessment focuses on their global characteristics. The majority of the assessed scenarios (about 80%) have become available since the SR1.5, but some were assessed in that report. Scenarios with and without mitigation were categorised based on their projected global warming over the 21st century, following the same scheme as in the SR1.5 for warming up to and including 2°C. {1.5, 3.2, 3.3, Annex III.II.2, Annex III.II.3}

FOOTNOTE 45: In the literature, the terms pathways and scenarios are used interchangeably, with the former more frequently used in relation to climate goals. For this reason, this SPM uses mostly the term (emissions and mitigation) pathways. {Annex III.II.1.1}

FOOTNOTE 46: Key assumptions relate to technology development in agriculture and energy systems and socio-economic development, including demographic and economic projections. IPCC is neutral with regard to the assumptions underlying the scenarios in the literature assessed in this report, which do not cover all possible futures. Additional scenarios may be developed. The underlying population assumptions range from 8.5 to 9.7 billion in 2050 and 7.4 to 10.9 billion in 2100 (5-95th percentile) starting from 7.6 billion in 2019. The underlying assumptions on global GDP growth (ppp) range from 2.5 to 3.5% per year in the 2019-2050 period and 1.3 to 2.1% per year in the 2050-2100 (5-95th percentile). Many underlying assumptions are regionally differentiated. {1.5; 3.2; 3.3; Figure 3.9; Annex III.II.1.4; Annex III.II.3}

Scenario categories are defined by their likelihood of exceeding global warming levels (at peak and in 2100) and referred to in this report as follows [FOOTNOTE 47, 48]:

- Category C1 comprises modelled scenarios that limit warming to 1.5°C in 2100 with a likelihood of greater than 50%, and reach or exceed warming of 1.5°C during the 21st century with a likelihood of 67% or less. In this report, these scenarios are referred to as scenarios that limit warming to 1.5°C (>50%) with no or limited overshoot. Limited overshoot refers to exceeding 1.5°C global warming by up to about 0.1°C and for up to several decades. [FOOTNOTE 49]

- Category C2 comprises modelled scenarios that limit warming to 1.5°C in 2100 with a likelihood of greater than 50%, and exceed warming of 1.5°C during the 21st century with a likelihood of greater than 67%. In this report, these scenarios are also referred to as scenarios that return warming to 1.5°C (>50%) after a high overshoot. High overshoot refers to temporarily exceeding 1.5°C global warming by 0.1-0.3°C for up to several decades.

- Category C3 comprises modelled scenarios that limit peak warming to 2°C throughout the 21st century with a likelihood of greater than 67%. In this report, these scenarios are also referred to as scenarios that limit warming to 2°C (>67%).

- Categories C4-C7 comprise modelled scenarios that limit warming to 2°C, 2.5°C, 3°C, 4°C, respectively, throughout the 21st century with a likelihood of greater than 50%. In some scenarios in C4 and many scenarios in C5-C7, warming continues beyond the 21st century.

- Category C8 comprises modelled scenarios that exceed warming of 4°C during the 21st century with a likelihood of 50% or greater. In these scenarios warming continues to rise beyond the 21st century.

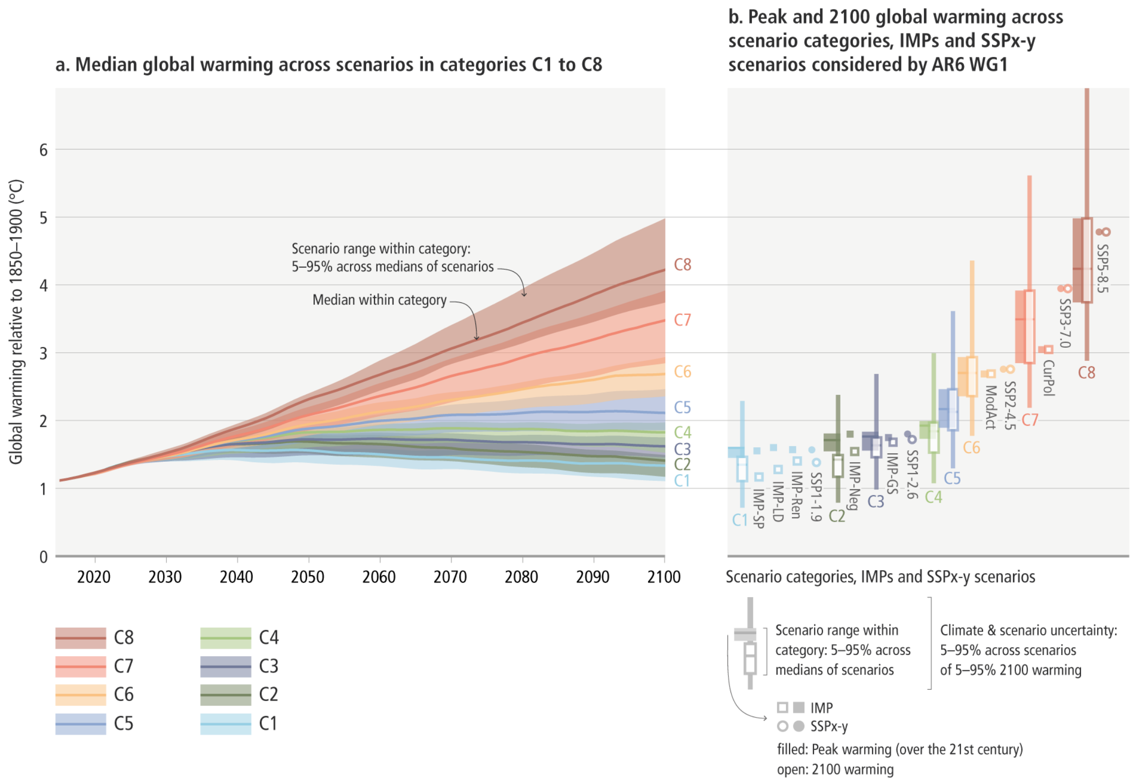
Categories of modelled scenarios are distinct and do not overlap; they do not contain categories consistent with lower levels of global warming, e.g., the category of C3 scenarios that limit warming to 2°C (>67%) does not include the C1 and C2 scenarios that limit or return warming to 1.5°C (>50%). Where relevant, scenarios belonging to the group of categories C1-C3 are referred to in this report as scenarios that limit warming to 2°C (>67%) or lower.

FOOTNOTE 47: The future scenario projections presented here are consistent with the total observed increase in global surface temperature between 1850-1900 and 1995-2014 as well as to 2011-2020 (with best estimates of 0.85 and 1.09°C, respectively) assessed in WGI. The largest contributor to historical human-induced warming is CO_2, with historical cumulative CO_2 emissions from 1850 to 2019 being 2400 ± 240 ($GtCO_2$). {WGI SPM A.1.2,WGI Table SPM.2, WGI Table 5.1, Section B}

FOOTNOTE 48: In case no explicit likelihood is provided, the reported warming levels are associated with a likelihood of >50%.

FOOTNOTE 49: Scenarios in this category are found to have simultaneous likelihood to limit peak global warming to 2°C throughout the 21st century of close to and more than 90%.

The range of assessed scenarios results in a range of 21st century projected global warming.



Box SPM.1, Figure 1

Projected global mean warming of the ensemble of modelled scenarios included in the climate categories C1-C8 and IMPs (based on emulators calibrated to the WGI assessment), as well as five illustrative scenarios (SSPx-y) as considered by AR6 WG I. The left panel shows the p5-p95 range of projected median warming across global modelled pathways within a category, with the category medians (line). The right panel shows the peak and 2100 emulated temperature outcomes for the categories C1 to C8 and for IMPs, and the five illustrative scenarios (SSPx-y) as considered by AR6 WG I. The boxes show the p5-p95 range within each scenario category as in panel-a. The combined p5-p95 range across scenarios and the climate uncertainty for each category C1- C8 is also shown for 2100 warming (thin vertical lines). {Table SPM.1, Figure 3.11, WGI Figure SPM.8}

Methods to project global warming associated with the scenarios were updated to ensure consistency with the AR6 WG1 assessment of physical climate science [FOOTNOTE 50]· {3.2, Annex III.II.2.5, WG I Cross-chapter box 7.1}

FOOTNOTE 50: This involved improved methodologies to use climate emulators (MAGICC7 and FAIR v1.6), which were evaluated and calibrated to closely match the global warming response to emissions as assessed in AR6 WGI. It included harmonisation of global GHG emissions in 2015 in modelled scenarios (51-56 $GtCO_2$-eq; 5th to 95th percentiles) with the corresponding emission value underlying the CMIP6 projected climate response assessed by WG I (54 $GtCO_2$-eq), based on similar data sources of historical emissions that are updated over time. The assessment of past GHG emissions in Chapter 2 of the report is based on a more recent dataset providing emissions of 57 [±6.3] $GtCO_2$-eq in 2015 (B.1). Differences are well within the assessed uncertainty range, and arise mainly from differences in estimated CO_2-LULUCF emissions, which are subject to large uncertainties, high annual variability and revisions over time. Projected rates of global emission reduction in mitigation scenarios are reported relative to modelled global emissions in 2019 rather than the global emissions reported in Chapter 2; this ensures internal consistency in assumptions about emission sources and activities, as well as consistency with temperature projections based on the physical climate science assessment by WG I. {Annex III.II.2.5}

These updated methods affect the categorisation of some scenarios. On average across scenarios, peak global warming is projected to be lower by up to about 0.05[±0.1]°C than if the same scenarios were evaluated using the SR1.5 methodology, and global warming in 2100 is projected to be lower by about 0.1[±0.1]°C. {Annex III.II.2.5.1, Annex III, Figure II.3}

Resulting changes to the emission characteristics of scenario categories described in Table SPM.1 interact with changes in the characteristics of the wider range of emission scenarios published since the SR1.5. Proportionally more scenarios assessed in AR6 are designed to limit temperature overshoot and more scenarios limit large-scale net negative CO_2 emissions than in SR1.5. As a result, AR6 scenarios in the lowest temperature category (C1) generally reach net zero GHG emissions later in the 21st century than scenarios in the same category assessed in SR1.5, and about half do not reach net zero GHG by 2100. The rate of decline of GHG emissions in the near term by 2030 in category C1 scenarios is very similar to the assessed rate in SR1.5, but absolute GHG emissions of category C1 scenarios in AR6 are slightly higher in 2030 than in SR1.5, since the reductions start from a higher emissions level in 2020. (Table SPM.1) {Annex III 2.5, 3.2, 3.3}

The large number of global emissions scenarios assessed, including 1202 scenarios with projected global warming outcomes using climate emulators, come from a wide range of modelling approaches. They include the five illustrative scenarios (Shared Socioeconomic Pathways; SSPs) assessed by WG I for their climate outcomes but cover a wider and more varied set in terms of assumptions and modelled outcomes. For this assessment, Illustrative Mitigation Pathways (IMPs) were selected from this larger set to illustrate a range of different mitigation strategies that would be consistent with different warming levels. The IMPs illustrate pathways that achieve deep and rapid emissions reductions through different combinations of mitigation strategies. The IMPs are not intended to be comprehensive and do not address all possible themes in the underlying report. They differ in terms of their focus, for example, placing greater emphasis on renewables (IMP-Ren), deployment of carbon dioxide removal that result in net negative global GHG emissions (IMP-Neg) and efficient resource use as well as shifts in consumption patterns globally, leading to low demand for resources, while ensuring a high level of services and satisfying basic needs (IMP-LD) (Figure SPM.5). Other IMPs illustrate the implications of a less rapid introduction of mitigation measures followed by a subsequent gradual strengthening (IMP-GS), and how shifting global pathways towards sustainable development, including by reducing inequality, can lead to mitigation (IMP-SP). The IMPs reach different climate goals as indicated in Table SPM.1 and Figure Box SPM.1.{1.5, 3.1, 3.2, 3.3, 3.6, Figure 3.7, Figure 3.8, Box 3.4, Annex III.II.2.4}

<END BOX SPM.1 HERE>

C.2 Global net zero CO_2 emissions are reached in the early 2050s in modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, and around the early 2070s in modelled pathways that limit warming to 2°C (>67%). Many of these pathways continue to net negative CO_2 emissions after the point of net zero. These pathways also include deep reductions in other GHG emissions. The level of peak warming depends on cumulative CO_2 emissions until the time of net zero CO_2 and the change in non-CO_2 climate forcers by the time of peaking. Deep

GHG emissions reductions by 2030 and 2040, particularly reductions of methane emissions, lower peak warming, reduce the likelihood of overshooting warming limits and lead to less reliance on net negative CO_2 emissions that reverse warming in the latter half of the century. Reaching and sustaining global net zero GHG emissions results in a gradual decline in warming. (*high confidence)* (Table SPM.1) {3.3, 3.5, Box 3.4, Cross-Chapter Box 3 in Chapter 3, AR6 WG I SPM D1.8}

C.2.1 Modelled global pathways limiting warming to 1.5°C (>50%) with no or limited overshoot are associated with projected cumulative net CO_2 emissions [FOOTNOTE 51] until the time of net zero CO_2 of 510 [330–710] $GtCO_2$. Pathways limiting warming to 2°C (>67%) are associated with 890 [640–1160] $GtCO_2$ (Table SPM.1) . (*high confidence*). {3.3, Box 3.4}

FOOTNOTE 51: Cumulative net CO_2 emissions from the beginning of the year 2020 until the time of net zero CO_2 in assessed pathways are consistent with the remaining carbon budgets assessed by WG I, taking account of the ranges in the WG III temperature categories and warming from non-CO_2 gases. {Box 3.4}

C.2.2 Modelled global pathways that limit warming to 1.5°C (>50%) with no or limited overshoot involve more rapid and deeper near-term GHG emissions reductions through to 2030, and are projected to have less net negative CO_2 emissions and less carbon dioxide removal (CDR) in the longer term, than pathways that return warming to 1.5°C (>50%) after a high overshoot (C2 category). Modelled pathways that limit warming to 2°C (>67%) have on average lower net negative CO_2 emissions compared to pathways that limit warming to 1.5°C (>50%) with no or limited overshoot and pathways that return warming to 1.5°C (>50%) after a high overshoot (C1 and C2 categories respectively). Modelled pathways that return warming to 1.5°C (>50%) after a high overshoot (C2 category) show near-term GHG emissions reductions similar to pathways that limit warming to 2°C (>67%) (C3 category). For a given peak global warming level, greater and more rapid near-term GHG emissions reductions are associated with later net zero CO_2 dates. (*high confidence*) (Table SPM.1) {3.3, Table 3.5, Cross-Chapter Box 3 in Chapter 3, Annex I: Glossary}

C.2.3 Future non-CO_2 warming depends on reductions in non-CO_2 GHG, aerosol and their precursor, and ozone precursor emissions. In modelled global low emission pathways, the projected reduction of cooling and warming aerosol emissions over time leads to net warming in the near- to mid-term. In these mitigation pathways, the projected reductions of cooling aerosols are mostly due to reduced fossil fuel combustion that was not equipped with effective air pollution controls. Non-CO_2 GHG emissions at the time of net zero CO_2 are projected to be of similar magnitude in modelled pathways that limit warming to 2°C (>67%) or lower. These non-CO_2 GHG emissions are about 8 [5–11] $GtCO_2$-eq per year, with the largest fraction from CH_4 (60% [55–80%]), followed by N_2O (30% [20–35%]) and F-gases (3% [2–20%]). [FOOTNOTE 52] Due to the short lifetime of CH_4 in the atmosphere, projected deep reduction of CH_4 emissions up until the time of net zero CO_2 in modelled mitigation pathways effectively reduces peak global warming. (*high confidence*) {3.3, AR6 WG I SPM D1.7}

FOOTNOTE 52: All numbers here rounded to the closest 5%, except values below 5% (for F-gases).

C.2.4 At the time of global net zero GHG emissions, net negative CO_2 emissions counterbalance metric-weighted non-CO_2 GHG emissions. Typical emissions pathways that reach and sustain global net zero GHG emissions based on the 100 year global warming potential (GWP100) [FOOTNOTE 7] are projected to result in a gradual decline of global warming. About half of the assessed pathways that limit warming to 1.5°C (>50%) with no or limited overshoot (C1 category) reach net zero GHG emissions during the second half of the 21st century. These pathways show greater reduction in global warming after the peak to 1.2 [1.1-1.4]°C by 2100 than modelled pathways in the same category that do not reach net zero GHG emissions before 2100 and that result in warming of 1.4 [1.3–1.5]°C by 2100. In modelled pathways that limit warming to 2°C (>67%) (C3 category), there is no significant difference in warming by 2100 between those pathways that reach net zero GHGs (around 30%) and those that do not (*high confidence*). In pathways that limit warming to 2°C (>67%) or lower and that do reach net zero GHG, net zero GHG occurs around 10–40 years later than net zero CO_2 emissions (*medium confidence*). {3.3, Cross-Chapter Box 3 in Chapter 3, Cross-Chapter Box 2 in Chapter 2; AR6 WG I SPM D1.8}

C.3 All global modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, and those that limit warming to 2°C (>67%) involve rapid and deep and in most cases immediate GHG emission reductions in all sectors. Modelled mitigation strategies to achieve these reductions include transitioning from fossil fuels without CCS to very low- or zero-carbon energy sources, such as renewables or fossil fuels with CCS, demand side measures and improving efficiency, reducing non-CO_2 emissions, and deploying carbon dioxide removal (CDR) methods to counterbalance residual GHG emissions. Illustrative Mitigation Pathways (IMPs) show different combinations of sectoral mitigation strategies consistent with a given warming level. (*high confidence*) (Figure SPM.5) {3.2, 3.3, 3.4, 6.4, 6.6}

C.3.1 There is a variation in the contributions of different sectors in modelled mitigation pathways, as illustrated by the Illustrative Mitigation Pathways. However, modelled pathways that limit warming to 2°C (>67%) or lower share common characteristics, including rapid and deep GHG emission reductions. Doing less in one sector needs to be compensated by further reductions in other sectors if warming is to be limited. (*high confidence*) (Figure SPM.5) {3.2, 3.3, 3.4}

C.3.2 In modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, the global use of coal, oil and gas in 2050 is projected to decline with median values of about 95%, 60% and 45% compared to 2019. The interquartile ranges are (80 to 100%), (40 to 75%) and (20 to 60%) and the p5-p95 ranges are [60 to 100%], [25 to 90%] and [-30 to 85%], respectively. In modelled pathways that limit warming to 2°C (>67%), these projected declines have a median value and interquartile range of 85% (65 to 95%), 30% (15 to 50%) and 15% (-10 to 40%) respectively by 2050. The use of coal, oil and gas without CCS in modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot is projected to be reduced to a greater degree, with median values of about 100%, 60% and 70% in 2050 compared to 2019. The interquartile ranges are (95 to 100%), (45 to 75%) and (60 to 80%) and the p5-p95 range of about [85 to 100%], [25 to 90%], and [35 to 90%] for coal, oil and gas respectively. In these global modelled pathways, in 2050 almost all electricity is supplied from zero or low-carbon sources, such as renewables or fossil fuels with CCS, combined with increased electrification of energy demand. As indicated by the ranges, choices in one sector can be compensated for by choices in another while being consistent with assessed warming levels. [FOOTNOTE 53] (*high confidence*) {3.4, 3.5, Table 3.6, Figure 3.22, Figure 6.35}

FOOTNOTE 53: Most but not all models include the use of fossil fuels for feedstock with varying underlying standards.

C.3.3 In modelled pathways that reach global net zero CO_2 emissions, at the point they reach net zero, 5-16 $GtCO_2$ of emissions from some sectors are compensated for by net negative CO_2 emissions in other sectors. In most global modelled pathways that limit warming to 2°C (>67%) or lower, the AFOLU sector, via reforestation and reduced deforestation, and the energy supply sector reach net zero CO_2 emissions earlier than the buildings, industry and transport sectors. (*high confidence*) (Figure SPM.5, panel e and f) {3.4}

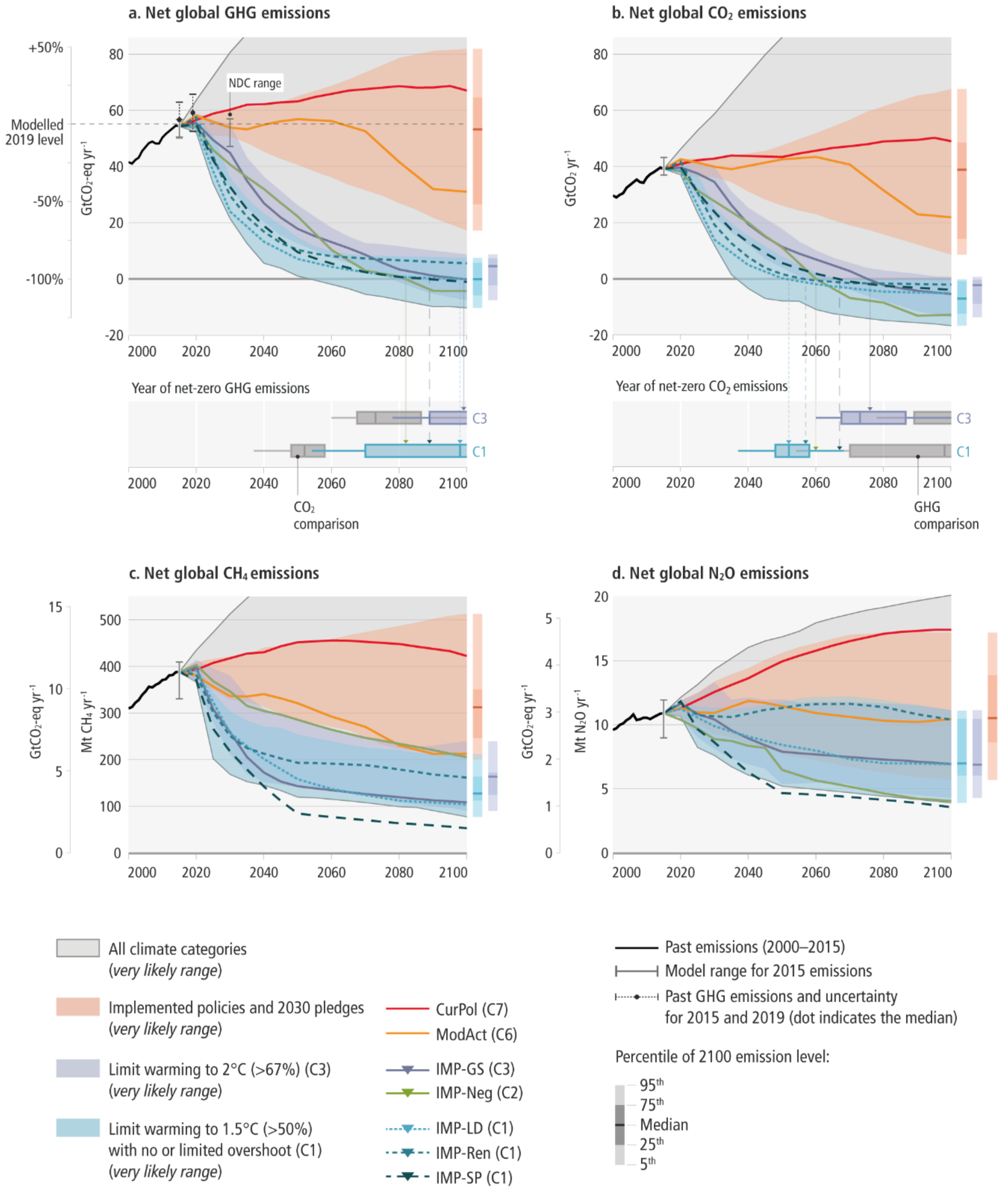
C.3.4 In modelled pathways that reach global net zero GHG emissions, at the point they reach net zero GHG, around 74% [54 to 90%] of global emissions reductions are achieved by CO_2 reductions in energy supply and demand, 13% [4 to20%] by CO_2 mitigation options in the AFOLU sector, and 13% [10 to18%] through the reduction of non-CO_2 emissions from land-use, energy and industry (*medium confidence*). (Figure SPM.5f) {3.3, 3.4}

C.3.5 Methods and levels of CDR deployment in global modelled mitigation pathways vary depending on assumptions about costs, availability and constraints. [FOOTNOTE 54] In modelled pathways that report CDR and that limit warming to 1.5°C (>50%) with no or limited overshoot, global cumulative CDR during 2020-2100 from Bioenergy with Carbon Dioxide Capture and Storage (BECCS) and Direct Air Carbon Dioxide Capture and Storage (DACCS) is 30-780 $GtCO_2$ and 0-310 $GtCO_2$, respectively. In these modelled pathways, the AFOLU sector contributes 20-400 $GtCO_2$ net negative emissions. Total cumulative net negative CO_2 emissions including CDR deployment across all options represented in these modelled pathways are 20–660 $GtCO_2$. In modelled pathways that limit warming to 2°C (>67%), global cumulative CDR during 2020–2100 from BECCS and DACCS is 170–650 and 0–250 $GtCO_2$ respectively, the AFOLU sector contributes 10–250 $GtCO_2$ net negative emissions, and total cumulative net negative CO_2 emissions are around 40 [0–290] $GtCO_2$. (Table SPM.1) (*high confidence*) {Table 3.2, 3.3, 3.4}

FOOTNOTE 54: Aggregate levels of CDR deployment are higher than total net negative CO_2 emissions given that some of the deployed CDR is used to counterbalance remaining gross emissions. Total net negative CO_2 emissions in modelled pathways might not match the aggregated net negative CO_2 emissions attributed to individual CDR methods. Ranges refer to the 5-95th percentile across modelled pathways that include the specific CDR method. Cumulative levels of CDR from AFOLU cannot be quantified precisely given that: a) some pathways assess CDR deployment relative to a baseline; and b) different models use different reporting methodologies that in some cases combine gross emissions and removals in AFOLU. Total CDR from AFOLU equals or exceeds the net negative emissions mentioned.

C.3.6 All mitigation strategies face implementation challenges, including technology risks, scaling, and costs. Many challenges, such as dependence on CDR, pressure on land and biodiversity (e.g., bioenergy) and reliance on technologies with high upfront investments (e.g., nuclear), are significantly reduced in modelled pathways that assume using resources more efficiently (e.g., IMP-LD) or shift global development towards sustainability (e.g., IMP-SP). (*high confidence*) (Figure SPM 5) {3.2, 3.4, 3.7, 3.8, 4.3, 5.1}

Modelled mitigation pathways that limit warming to 1.5°C, and 2°C, involve deep, rapid and sustained emissions reductions.



Net zero CO_2 and net zero GHG emissionsare possible through different modelled mitigation pathways.

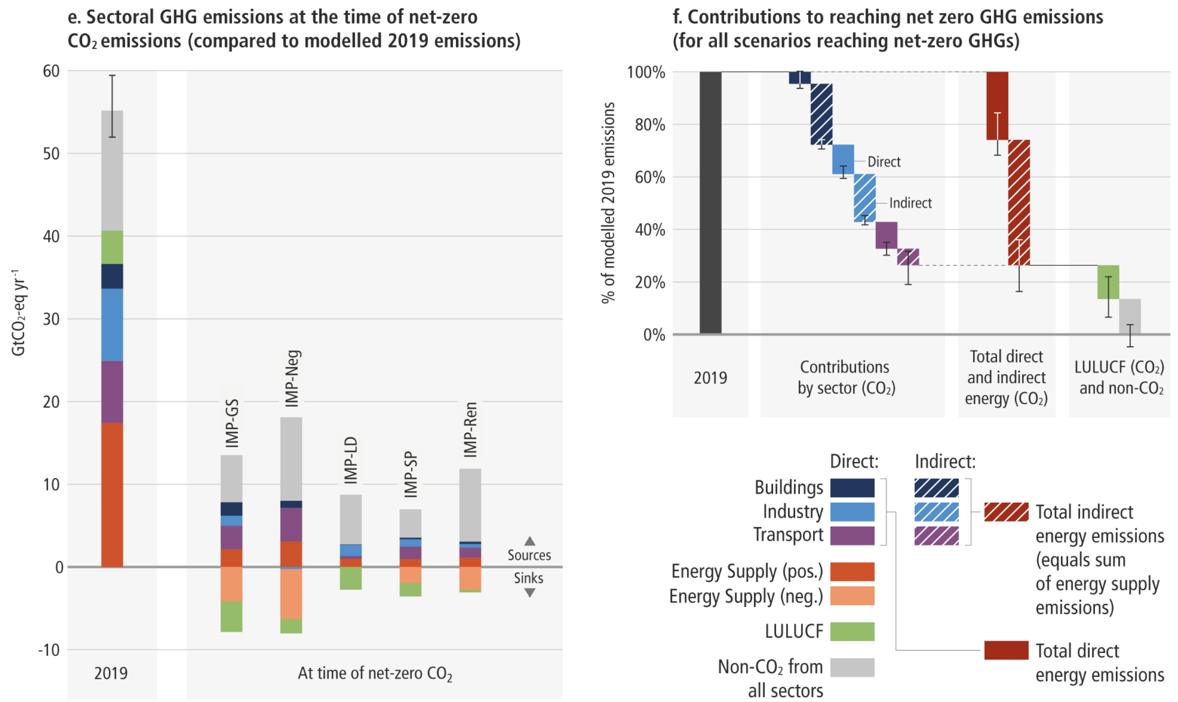


Figure SPM.5: Illustrative Mitigation Emissions Pathways (IMPs) and net zero CO_2 and GHG emissions strategies

Panel a and b show the development of global GHG and CO_2 emissions in modelled global pathways (upper sub-panels) and the associated timing of when GHG and CO_2 emissions reach net zero (lower sub-panels). Panels c and d show the development of global CH_4 and N_2O emissions, respectively. Coloured ranges denote the 5th to 95th percentile across pathways. The red ranges depict emissions pathways assuming policies that were implemented by the end of 2020 and pathways assuming implementation of NDCs (announced prior to COP26). Ranges of modelled pathways that limit warming to 1.5ºC (>50%) with no or limited overshoot are shown in light blue (category C1) and pathways that limit warming to 2ºC (>67%) are shown in light purple (category C3). The grey range comprises all assessed pathways (C1-C8) from the 5th percentile of the lowest warming category (C1) to the 95th percentile of the highest warming category (C8). The modelled pathway ranges are compared to the emissions from two pathways illustrative of high emissions (CurPol and ModAct) and five Illustrative Mitigation Pathways (IMPs): IMP-LD, IMP-Ren, IMP-SP, IMP-Neg and IMP-GS. Emissions are harmonised to the same 2015 base year. The vertical error bars in 2015 show the 5-95th percentile uncertainty range of the non-harmonised emissions across the pathways, and the uncertainty range, and median value, in emission estimates for 2015 and 2019. The vertical error bars in 2030 (panel a) depict the assessed range of the NDCs,as announced prior to COP26 (see Figure SPM.4, FOOTNOTE 24) .

Panel e shows the sectoral contributions of CO_2 and non-CO_2 emissions sources and sinks at the time when net zero CO_2 emissions are reached in the IMPs. Positive and negative emissions for different IMPs are compared to the GHG emissions from the year 2019. Energy supply (neg.) includes BECCS and DACCS. DACCS features in only two of the five IMPs (IMP-REN, IMP-GS) and contributes <1 % and 64%, respectively, to the net negative emissions in Energy Supply (neg.).

Panel f shows the contribution of different sectors and sources to the emissions reductions from a 2019 baseline for reaching net zero GHG emissions. Bars denote the median emissions reductions for all pathways that reach net zero GHG emissions. The whiskers indicate the p5-p95 range. The contributions of the service sectors (transport, buildings, industry) are split into direct (demand-side) as well as indirect (supply-side) CO_2 emissions

reductions. Direct emissions represent demand-side emissions due to the fuel use in the respective demand sector. Indirect emissions represent upstream emissions due to industrial processes and energy conversion, transmission and distribution. In addition, the contributions from the LULUCF sector and reductions from non-CO_2 emissions sources (green and grey bars) are displayed.
{3.3, 3.4}

C.4 Reducing GHG emissions across the full energy sector requires major transitions, including a substantial reduction in overall fossil fuel use, the deployment of low-emission energy sources, switching to alternative energy carriers, and energy efficiency and conservation. The continued installation of unabated fossil fuel [FOOTNOTE 55] infrastructure will 'lock-in' GHG emissions. (*high confidence*) {2.7, 6.6, 6.7, 16.4}

C.4.1 Net-zero CO_2 energy systems entail: a substantial reduction in overall fossil fuel use, minimal use of unabated fossil fuels, and use of CCS in the remaining fossil system [FOOTNOTE 55]; electricity systems that emit no net CO_2; widespread electrification of the energy system including end uses; energy carriers such as sustainable biofuels, low-emissions hydrogen, and derivatives in applications less amenable to electrification; energy conservation and efficiency; and greater physical, institutional, and operational integration across the energy system. CDR will be needed to counter-balance residual emissions in the energy sector. The most appropriate strategies depend on national and regional circumstances, including enabling conditions and technology availability. (*high confidence*) {3.4, 6.6, 11.3, 16.4}

FOOTNOTE 55: In this context, 'unabated fossil fuels' refers to fossil fuels produced and used without interventions that substantially reduce the amount of GHG emitted throughout the life-cycle; for example, capturing 90% or more from power plants, or 50-80% of fugitive methane emissions from energy supply. {Box 6.5, 11.3}

C.4.2 Unit cost reductions in key technologies, notably wind power, solar power, and storage, have increased the economic attractiveness of low-emission energy sector transitions through 2030. Maintaining emission-intensive systems may, in some regions and sectors, be more expensive than transitioning to low emission systems. Low-emission energy sector transitions will have multiple co-benefits, including improvements in air quality and health. The long-term economic attractiveness of deploying energy system mitigation options depends, *inter alia*, on policy design and implementation, technology availability and performance, institutional capacity, equity, access to finance, and public and political support. (*high confidence*) {Figure SPM3, 3.4, 6.4, 6.6, 6.7, 13.7}

C.4.3 Electricity systems powered predominantly by renewables are becoming increasingly viable. Electricity systems in some countries and regions are already predominantly powered by renewables. It will be more challenging to supply the entire energy system with renewable energy. Even though operational, technological, economic, regulatory, and social challenges remain, a variety of systemic solutions to accommodate large shares of renewables in the energy system have emerged. A broad portfolio of options such as, integrating systems, coupling sectors, energy storage, smart grids, demand-side management, sustainable biofuels, electrolytic hydrogen and derivatives, and others will ultimately be needed to accommodate large shares of renewables in energy systems. (*high confidence*) {Box 6.8, 6.4, 6.6}

C.4.4 Limiting global warming to 2ºC or below will leave a substantial amount of fossil fuels unburned and could strand considerable fossil fuel infrastructure *(high confidence)*. Depending on its availability, CCS could allow fossil fuels to be used longer, reducing stranded assets (*high confidence*). The combined global discounted value of the unburned fossil fuels and stranded fossil fuel infrastructure has been projected to be around 1–4 trillion dollars from 2015 to 2050 to limit global warming to approximately 2ºC, and it will be higher if global warming is limited to approximately 1.5ºC *(medium confidence)*. In this context, coal assets are projected to be at risk of being stranded before 2030, while oil and gas assets are projected to be more at risk of being stranded toward mid-century. A low-emission energy sector transition is projected to reduce international trade in fossil fuels. (*high confidence*) {6.7, Figure 6.35}

C.4.5 Global methane emissions from energy supply, primarily fugitive emissions from production and transport of fossil fuels, accounted for about 18% [13%-23%] of global GHG emissions from energy supply, 32% [22%-42%] of global methane emissions, and 6% [4%-8%] of global GHG emissions in 2019 (*high confidence*). About 50–80% of CH_4 emissions from these fossil fuels could be avoided with currently available technologies at less than USD50 $tCO_2\text{-eq}^{-1}$ (*medium confidence*). {6.3, 6.4.2, Box 6.5, 11.3, 2.2.2, Table 2.1, Figure 2.5; Annex1 Glossary}

C.4.6 CCS is an option to reduce emissions from large-scale fossil-based energy and industry sources, provided geological storage is available. When CO_2 is captured directly from the atmosphere (DACCS), or from biomass (BECCS), CCS provides the storage component of these CDR methods. CO_2 capture and subsurface injection is a mature technology for gas processing and enhanced oil recovery. In contrast to the oil and gas sector, CCS is less mature in the power sector, as well as in cement and chemicals production, where it is a critical mitigation option. The technical geological CO_2 storage capacity is estimated to be on the order of 1000 gigatonnes of CO_2, which is more than the CO_2 storage requirements through 2100 to limit global warming to 1.5°C, although the regional availability of geological storage could be a limiting factor. If the geological storage site is appropriately selected and managed, it is estimated that the CO_2 can be permanently isolated from the atmosphere. Implementation of CCS currently faces technological, economic, institutional, ecological-environmental and socio-cultural barriers. Currently, global rates of CCS deployment are far below those in modelled pathways limiting global warming to 1.5°C or 2°C. Enabling conditions such as policy instruments, greater public support and technological innovation could reduce these barriers. (*high confidence*) {2.5, 6.3, 6.4, 6.7, 11.3, 11.4, Cross-Chapter Box 8 in Chapter 12, Figure TS.31, SRCCS Chapter 5}

C.5 Net-zero CO_2 emissions from the industrial sector are challenging but possible. Reducing industry emissions will entail coordinated action throughout value chains to promote all mitigation options, including demand management, energy and materials efficiency, circular material flows, as well as abatement technologies and transformational changes in production processes. Progressing towards net zero GHG emissions from industry will be enabled by the adoption of new production processes using low and zero GHG electricity, hydrogen, fuels, and carbon management. (*high confidence*) {11.2, 11.3, 11.4, Box TS.4}

C.5.1 The use of steel, cement, plastics, and other materials is increasing globally, and in most regions. There are many sustainable options for demand management, materials efficiency, and circular material flows that can contribute to reduced emissions, but how these can be applied will vary across regions and different materials. These options have a potential for being more used in industrial practice and would need more attention from industrial policy. These options, as well as new production technologies, are generally not considered in recent global scenarios nor in national economy-wide scenarios due to relative newness. As a consequence, the mitigation potential in some scenarios is underestimated compared to bottom-up industry-specific models. (*high confidence*) {3.4, 5.3, Figure 5.7, 11.2, Box 11.2, 11.3, 11.4, 11.5.2, 11.6}

C.5.2 For almost all basic materials – primary metals [FOOTNOTE 56], building materials and chemicals – many low- to zero- GHG intensity production processes are at the *pilot* to *near-commercial* and in some cases *commercial* stage but not yet established industrial practice. Introducing new sustainable basic materials production processes could increase production costs but, given the small fraction of consumer cost based on materials, are expected to translate into minimal cost increases for final consumers. Hydrogen direct reduction for primary steelmaking is *near-commercial* in some regions. Until new chemistries are mastered, deep reduction of cement process emissions will rely on already commercialised cementitious material substitution and the availability of CCS. Reducing emissions from the production and use of chemicals would need to rely on a life cycle approach, including increased plastics recycling, fuel and feedstock switching, and carbon sourced through biogenic sources, and, depending on availability, CCU, direct air CO_2 capture, as well as CCS. Light industry, mining and manufacturing have the potential to be decarbonised through available abatement technologies (e.g., material efficiency, circularity), electrification (e.g., electrothermal heating, heat pumps) and low- or zero- GHG emitting fuels (e.g., hydrogen, ammonia, and bio-based & other synthetic fuels). (*high confidence*) {Table 11.4, Box 11.2, 11.3, 11.4}

FOOTNOTE 56: Primary metals refers to virgin metals produced from ore.

C.5.3 Action to reduce industry sector emissions may change the location of GHG intensive industries and the organisation of value chains. Regions with abundant low GHG energy and feedstocks have the potential to become exporters of hydrogen-based chemicals and materials processed using low-carbon electricity and hydrogen. Such reallocation will have global distributional effects on employment and economic structure. (*medium confidence*) {Box 11.1}

C.5.4 Emissions intensive and highly traded basic materials industries are exposed to international competition, and international cooperation and coordination may be particularly important in enabling change. For sustainable industrial transitions, broad and sequential national and sub-national policy strategies reflecting regional contexts will be required. These may combine policy packages including: transparent GHG accounting and standards; demand management; materials and energy efficiency policies; R&D and niche markets for commercialisation of low emission materials and products; economic and regulatory instruments to drive market uptake; high quality recycling, low-emissions energy and other abatement infrastructure (e.g., for CCS); and socially inclusive phase-out plans of emissions intensive facilities within the context of just transitions. The coverage of mitigation policies could be expanded nationally and sub-nationally to include all industrial emission sources, and both available and emerging mitigation options. (*high confidence*) {11.6}

C.6 Urban areas can create opportunities to increase resource efficiency and significantly reduce GHG emissions through the systemic transition of infrastructure and urban form through low-emission development pathways towards net-zero emissions. Ambitious mitigation efforts for established, rapidly growing and emerging cities will encompass 1) reducing or changing energy and material consumption, 2) electrification, and 3) enhancing carbon uptake and storage in the urban environment. Cities can achieve net-zero emissions, but only if emissions are reduced within and outside of their administrative boundaries through supply chains, which will have beneficial cascading effects across other sectors. (*very high confidence*) {8.2, 8.3, 8.4, 8.5, 8.6, Figure 8.21, 13.2}

C.6.1 In modelled scenarios, global consumption-based urban CO_2 and CH_4 emissions [FOOTNOTE 15] are projected to rise from 29 $GtCO_2$-eq in 2020 to 34 $GtCO_2$-eq in 2050 with moderate mitigation efforts (intermediate GHG emissions, SSP2-4.5), and up to 40 $GtCO_2$-eq in 2050 with low mitigation efforts (high GHG emissions, SSP 3-7.0). With ambitious and immediate mitigation efforts, including high levels of electrification and improved energy and material efficiency, global consumption-based urban CO_2 and CH_4 emissions could be reduced to 3 $GtCO_2$-eq in 2050 in the modelled scenario with very low GHG emissions (SSP1-1.9). [FOOTNOTE 57] (*medium confidence*) {8.3}

FOOTNOTE 15: This estimate is based on consumption-based accounting, including both direct emissions from within urban areas, and indirect emissions from outside urban areas related to the production of electricity, goods and services consumed in cities. These estimates include all CO_2 and CH_4 emission categories except for aviation and marine bunker fuels, land-use change, forestry and agriculture. {8.1, Annex I: Glossary}

FOOTNOTE 57: These scenarios have been assessed by WGI to correspond to intermediate, high and very low GHG emissions.

C.6.2 The potential and sequencing of mitigation strategies to reduce GHG emissions will vary depending on a city's land use, spatial form, development level, and state of urbanisation (*high confidence*). Strategies for established cities to achieve large GHG emissions savings include efficiently improving, repurposing or retrofitting the building stock, targeted infilling, and supporting non-motorised (e.g., walking, bicycling) and public transport. Rapidly growing cities can avoid future emissions by co-locating jobs and housing to achieve compact urban form, and by leapfrogging or transitioning to low-emissions technologies. New and emerging cities will have significant infrastructure development needs to achieve high quality of life, which can be met through energy efficient infrastructures and services, and people-centred urban design. (*high confidence).* For cities, three broad mitigation strategies have been found to be effective when implemented concurrently: i) reducing or changing energy and material use towards more sustainable production and consumption; ii) electrification in combination with switching to low-emission energy sources; and iii) enhancing carbon uptake and storage in the urban environment, for example through bio-based building materials, permeable surfaces, green roofs, trees, green spaces, rivers, ponds and lakes [FOOTNOTE 58]. (*very high confidence*) {5.3, Figure 5.7, Table SM5.2, 8.2, 8.4, 8.6, Figure 8.21, 9.4, 9.6, 10.2}

FOOTNOTE 58: These examples are considered to be a subset of nature-based solutions or ecosystem-based approaches.

C.6.3 The implementation of packages of multiple city-scale mitigation strategies can have cascading effects across sectors and reduce GHG emissions both within and outside a city's administrative boundaries. The capacity of cities to develop and implement mitigation strategies varies with the broader regulatory and institutional settings, as well as enabling conditions, including access to financial and technological resources, local governance capacity, engagement of civil society, and municipal budgetary powers. (*very high confidence*). {Figure 5.7, Table SM5.2, 8.4, 8.5, 8.6, 13.2, 13.3, 13.5, 13.7, Cross-Chapter Box 9}

C.6.4 A growing number of cities are setting climate targets, including net-zero GHG targets. Given the regional and global reach of urban consumption patterns and supply chains, the full potential for reducing consumption-based urban emissions to net-zero GHG can be met only when emissions beyond cities' administrative boundaries are also addressed. The effectiveness of these strategies depends on cooperation and coordination with national and sub-national governments, industry, and civil society, and whether cities have adequate capacity to plan and implement mitigation strategies. Cities can play a positive role in reducing emissions across supply chains that extend beyond cities' administrative boundaries, for example through building codes and the choice of construction materials. (*very high confidence*) {8.4, Box 8.4, 8.5, 9.6, 9.9, 13.5, 13.9}

C.7. In modelled global scenarios, existing buildings, if retrofitted, and buildings yet to be built, are projected to approach net zero GHG emissions in 2050 if policy packages, which combine ambitious sufficiency, efficiency, and renewable energy measures, are effectively implemented and barriers to decarbonisation are removed. Low ambitious policies increase the risk of lock-in buildings in carbon for decades while well-designed and effectively implemented mitigation interventions, in both new buildings and existing ones if retrofitted, have significant potential to contribute to achieving SDGs in all regions while adapting buildings to future climate. (*high confidence*) {9.1, 9.3, 9.4, 9.5, 9.6, 9.9}

C.7.1 In 2019, global direct and indirect GHG emissions from buildings and emissions from cement and steel use for building construction and renovation were 12 $GtCO_2$-eq. These emissions include indirect emissions from offsite generation of electricity and heat, direct emissions produced onsite and emissions from cement and steel used for building construction and renovation. In 2019, global direct and indirect emissions from non-residential buildings increased by about 55% and those from residential buildings increased by about 50% compared to 1990. The latter increase, according to the decomposition analysis, was mainly driven by the increase of the floor area per capita, population growth and the increased use of emission-intensive electricity and heat while efficiency improvements have partly decreased emissions. There are great differences in the contribution of each of these drivers to regional emissions. (*high confidence*) {9.3}

C.7.2 Integrated design approaches to the construction and retrofit of buildings have led to increasing examples of zero energy or zero carbon buildings in several regions. However, the low renovation rates and low ambition of retrofitted buildings have hindered the decrease of emissions. Mitigation interventions at the design stage include buildings typology, form, and multi-functionality to allow for adjusting the size of buildings to the evolving needs of their users and repurposing unused existing buildings to avoid using GHG-intensive materials and additional land. Mitigation interventions include: at the construction phase, low-emission construction materials, highly efficient building envelope and the integration of renewable energy solutions[FOOTNOTE 59]; at the use phase, highly efficient appliances/ equipment, the optimisation of the use of buildings and the supply with low-emission energy sources; and at the disposal phase, recycling and re-using construction materials. (*high confidence*) {9.4, 9.5, 9.6, 9.7}

FOOTNOTE 59: Integration of renewable energy solutions refers to the integration of solutions such as solar photovoltaics, small wind turbines, solar thermal collectors, and biomass boilers.

C.7.3 By 2050, bottom-up studies show that up to 61% (8.2 $GtCO_2$) of global building emissions could be mitigated. Sufficiency policies [FOOTNOTE 60] that avoid the demand for energy and materials contribute 10% to this potential, energy efficiency policies contribute 42%, and renewable energy policies 9%. The largest share of the mitigation potential of new buildings is available in developing countries while in developed countries the highest mitigation potential is within the retrofit of existing buildings. The 2020-2030 decade is critical for accelerating the learning of know-how, building the technical and institutional capacity, setting the appropriate governance structures, ensuring the flow of finance, and in developing the skills needed to fully capture the mitigation potential of buildings. *(high confidence)* {9.3, 9.4, 9.5, 9.6, 9.7, 9.9}

FOOTNOTE 60: Sufficiency policies are a set of measures and daily practices that avoid demand for energy , materials, land and water while delivering human wellbeing for all within planetary boundaries.

C.8 Demand-side options and low-GHG emissions technologies can reduce transport sector emissions in developed countries and limit emissions growth in developing countries (*high confidence*). Demand-focused interventions can reduce demand for all transport services and support the shift to more energy efficient transport modes (*medium confidence*). Electric vehicles powered by low emissions electricity offer the largest decarbonisation potential for land-based transport, on a life cycle basis (*high confidence*). Sustainable biofuels can offer additional mitigation benefits in land-based transport in the short and medium term (*medium confidence*). Sustainable biofuels, low emissions hydrogen, and derivatives (including synthetic fuels) can support mitigation of CO_2 emissions from shipping, aviation, and heavy-duty land transport but require production process improvements and cost reductions (*medium confidence*). Many mitigation strategies in the transport sector would have various co-benefits, including air quality improvements, health benefits, equitable access to transportation services, reduced congestion, and reduced material demand *(high confidence)*. {10.2, 10.4, 10.5, 10.6, 10.7}

C.8.1 In scenarios that limit warming to 1.5°C (>50%) with no or limited overshoot, global transport-related CO_2 emissions fall by 59% [42–68% interquartile range] by 2050 relative to modelled 2020 emissions, but with regionally differentiated trends (*high confidence*). In global modelled scenarios that limit warming to 2°C (>67%), transport related CO_2 emissions are projected to decrease by 29% [14-44% interquartile range] by 2050 compared to modelled 2020 emissions. In both categories of scenarios, the transport sector *likely* does not reach zero CO_2 emissions by 2100 so negative emissions are *likely* needed to counterbalance residual CO_2 emissions from the sector *(high confidence)*. {3.4, 10.7}

C.8.2 Changes in urban form (e.g., density, land use mix, connectivity, and accessibility) in combination with programmes that encourage changes in consumer behaviour (e.g., transport pricing) could reduce transport related greenhouse gas emissions in developed countries and slow growth in emissions in developing countries (*high confidence*). Investments in public inter- and intra-city transport and active transport infrastructure (e.g., bike and pedestrian pathways) can further support the shift to less GHG-intensive transport modes (*high confidence*). Combinations of systemic changes including, teleworking, digitalisation, dematerialisation, supply chain management, and smart and shared mobility may reduce demand for passenger and freight services across land, air, and sea (*high confidence*). Some of these changes could lead to induced demand for transport and energy services, which may decrease their GHG emissions reduction potential (*medium confidence*). {5.3, 10.2, 10.8}

C.8.3 Electric vehicles powered by low-GHG emissions electricity have large potential to reduce land-based transport GHG emissions, on a life cycle basis (*high confidence*). Costs of electrified vehicles, including automobiles, two and three wheelers, and buses are decreasing and their adoption is accelerating, but they require continued investments in supporting infrastructure to increase scale of deployment (*high confidence*). Advances in battery technologies could facilitate the electrification of heavy-duty trucks and complement conventional electric rail systems (*medium confidence*). There are growing concerns about critical minerals needed for batteries. Material and supply diversification strategies, energy and material efficiency improvements, and circular material flows can reduce the environmental footprint and material supply risks for battery production (*medium confidence*). Sourced sustainably and with low-GHG emissions feedstocks, bio-based fuels, blended or unblended with fossil fuels, can provide mitigation benefits, particularly in the short- and medium-term (*medium confidence*). Low-GHG emissions hydrogen and hydrogen derivatives, including synthetic fuels, can offer mitigation potential in some contexts and land-based transport segments (*medium confidence*). {3.4, 6.3, 10.3, 10.4, 10.7, 10.8, Box 10.6}

C.8.4 While efficiency improvements (e.g., optimised aircraft and vessel designs, mass reduction, and propulsion system improvements) can provide some mitigation potential, additional CO_2 emissions mitigation technologies for aviation and shipping will be required (*high confidence*). For aviation, such technologies include high energy density biofuels (*high confidence*), and low-emission hydrogen and synthetic fuels (*medium confidence*). Alternative fuels for shipping include low-emission hydrogen, ammonia, biofuels, and other synthetic fuels (*medium confidence*). Electrification could play a niche role for aviation and shipping for short trips (*medium confidence*) and can reduce emissions from port and airport operations (*high confidence*). Improvements to national and international governance structures would further enable the decarbonisation of shipping and aviation (*medium confidence*). Such improvements could include, for example, the implementation of stricter efficiency and carbon intensity standards for the sectors (*medium confidence*). {10.3. 10.5, 10.6, 10.7, 10.8, Box 10.5}

C.8.5 Substantial potential for GHG reductions, both direct and indirect, for the transport sector largely depends on power sector decarbonisation, and low emissions feedstocks and production chains *(high confidence)*. Integrated transport and energy infrastructure planning and operations can enable sectoral synergies and reduce the environmental, social, and economic impacts of decarbonising the transport and energy sectors *(high confidence)*. Technology transfer and financing can support developing countries leapfrogging or transitioning to low emissions transport systems thereby providing multiple co-benefits (*high confidence*). {10.2, 10.3, 10.4, 10.5, 10.6, 10.7, 10.8}

C.9 AFOLU mitigation options, when sustainably implemented, can deliver large-scale GHG emission reductions and enhanced removals, but cannot fully compensate for delayed action in other sectors. In addition, sustainably sourced agricultural and forest products can be used instead of more GHG intensive products in other sectors. Barriers to implementation and trade-offs may result from the impacts of climate change, competing demands on land, conflicts with food security and livelihoods, the complexity of land ownership and management systems, and cultural aspects. There are many country-specific opportunities to provide co-benefits (such as biodiversity conservation, ecosystem services, and livelihoods) and avoid risks (for example, through adaptation to climate change). (*high confidence*) {7.4, 7.6, 7.7, 12.5, 12.6}

C.9.1 The projected economic mitigation potential of AFOLU options between 2020 and 2050, at costs below USD100 tCO_2-eq^{-1}, is 8-14 $GtCO_2$-eq yr^{-1} [FOOTNOTE 61] (*high confidence*). 30-50% of this potential is available at less than USD20/tCO_2-eq and could be upscaled in the near term across most regions (*high confidence*). The largest share of this economic potential [4.2-7.4 $GtCO_2$-eq yr^{-1}] comes from the conservation, improved management, and restoration of forests and other ecosystems (coastal wetlands, peatlands, savannas and grasslands), with reduced deforestation in tropical regions having the highest total mitigation. Improved and sustainable crop and livestock management, and carbon sequestration in agriculture, the latter includes soil carbon management in croplands and grasslands, agroforestry and biochar, can contribute 1.8-4.1 $GtCO_2$-eq yr^{-1} reduction. Demand-side and material substitution measures, such as shifting to balanced, sustainable healthy diets [FOOTNOTE 62], reducing food loss and waste, and using bio-materials, can contribute 2.1 [1.1-3.6]$GtCO_2$-eq yr^{-1} reduction. In addition, demand-side measures together with the sustainable intensification of agriculture can reduce ecosystem conversion and CH_4 and N_2O emissions, and free-up land for reforestation and restoration, and the producing of renewable energy. The improved and expanded use of wood products sourced from sustainably managed forests also has potential through the allocation of harvested wood to longer-lived products, increasing recycling or material substitution. AFOLU mitigation measures cannot compensate for delayed emission reductions in other sectors. Persistent and region-specific barriers continue to hamper the economic and political feasibility of deploying AFOLU mitigation options. Assisting countries to overcome barriers will help to achieve significant mitigation (*medium confidence*). (Figure SPM.6) {7.1, 7.4, 7.5, 7.6}

FOOTNOTE 61: The global top-down estimates and sectoral bottom-up estimates described here do not include the substitution of emissions from fossil fuels and GHG-intensive materials. 8-14 $GtCO_2$-eq yr^{-1} represents the mean of the AFOLU economic mitigation potential estimates from top-down estimates (lower bound of range) and global sectoral bottom-up estimates (upper bound of range). The full range from top-down estimates is 4.1-17.3 $GtCO_2$-eq yr^{-1} using a "no policy" baseline. The full range from global sectoral studies is 6.7-23.4 $GtCO_2$-eq yr^{-1} using a variety of baselines. (*high confidence*)

FOOTNOTE 62: 'Sustainable healthy diets' promote all dimensions of individuals' health and wellbeing; have low environmental pressure and impact; are accessible, affordable, safe and equitable; and are culturally acceptable, as described in FAO and WHO. The related concept of balanced diets refers to diets that feature plant-based foods, such as those based on coarse grains, legumes, fruits and vegetables, nuts and seeds, and animal-sourced food produced in resilient, sustainable and low-GHG emission systems, as described in SRCCL.

C.9.2 AFOLU carbon sequestration and GHG emission reduction options have both co-benefits and risks in terms of biodiversity and ecosystem conservation, food and water security, wood supply, livelihoods and land tenure and land-use rights of Indigenous Peoples, local communities and small land owners. Many options have co-benefits but those that compete for land and land-based resources can pose risks. The scale of benefit or risk largely depends on the type of activity undertaken, deployment strategy (e.g., scale, method), and context (e.g., soil, biome, climate, food system, land ownership) that vary geographically and over time. Risks can be avoided when AFOLU mitigation is pursued in response to the needs and perspectives of multiple stakeholders to achieve outcomes that maximize co-benefits while limiting trade-offs. (*high confidence)* {7.4, 7.6, 12.3}

C.9.3 Realising the AFOLU potential entails overcoming institutional, economic and policy constraints and managing potential trade-offs (*high confidence*). Land-use decisions are often spread across a wide range of landowners; demand-side measures depend on billions of consumers in diverse contexts. Barriers to the implementation of AFOLU mitigation include insufficient institutional and financial support, uncertainty over long-term additionality and trade-offs, weak governance, insecure land ownership, the low incomes and the lack of access to alternative sources of income, and the risk of reversal. Limited access to technology, data, and know-how is a barrier to implementation. Research and development are key for all measures. For example, measures for the mitigation of agricultural CH_4 and N_2O emissions with emerging technologies show promising results. However the mitigation of agricultural CH_4 and N_2O emissions is still constrained by cost, the diversity and complexity of agricultural systems, and by increasing demands to raise agricultural yields, and increasing demand for livestock products. (*high confidence*) {7.4, 7.6}

C.9.4 Net costs of delivering 5-6 Gt CO_2 yr^{-1} of forest related carbon sequestration and emission reduction as assessed with sectoral models are estimated to reach to ~USD400 billion yr^{-1} by 2050. The costs of other AFOLU mitigation measures are highly context specific. Financing needs in AFOLU, and in particular in forestry, include both the direct effects of any changes in activities as well as the opportunity costs associated with land use change. Enhanced monitoring, reporting and verification capacity and the rule of law are crucial for land-based mitigation, in combination with policies also recognising interactions with wider ecosystem services, could enable engagement by a wider array of actors, including private businesses, NGOs, and Indigenous Peoples and local communities. (*medium confidence*) {7.6, 7.7}

C.9.5 Context specific policies and measures have been effective in demonstrating the delivery of AFOLU carbon sequestration and GHG emission reduction options but the above-mentioned constraints hinder large scale implementation (*medium confidence*). Deploying land-based mitigation can draw on lessons from experience with regulations, policies, economic incentives, payments (e.g., for biofuels, control of nutrient pollution, water regulations, conservation and forest carbon, ecosystem services, and rural livelihoods), and from diverse forms of knowledge such as Indigenous knowledge, local knowledge and scientific knowledge. Indigenous Peoples, private forest owners, local farmers and communities manage a significant share of global forests and agricultural land and play a central role in land-based mitigation options. Scaling successful policies and measures relies on governance that emphasises integrated land use planning and management framed by SDGs, with support for implementation. (*high confidence*) {7.4, Box 7.2, 7.6}

C.10 Demand-side mitigation encompasses changes in infrastructure use, end-use technology adoption, and socio-cultural and behavioural change. Demand-side measures and new ways of end-use service provision can reduce global GHG emissions in end use sectors by 40-70% by 2050 compared to baseline scenarios, while some regions and socioeconomic groups require additional energy and resources. Demand side mitigation response options are consistent with improving basic wellbeing for all. (*high confidence*) (Figure SPM.6) {5.3, 5.4, Figure 5.6, Figure 5.14, 8.2, 9.4, 10.2, 11.3, 11.4, 12.4, Figure TS.22}

C.10.1 Infrastructure design and access, and technology access and adoption, including information and communication technologies, influence patterns of demand and ways of providing services, such as mobility, shelter, water, sanitation, and nutrition. Illustrative global low demand scenarios, accounting for regional differences, indicate that more efficient end-use energy conversion can improve services while reducing the need for upstream energy by 45% by 2050 compared to 2020. Demand-side mitigation potential differs between and within regions, and some regions and populations require additional energy, capacity, and resources for human wellbeing. The lowest population quartile by income worldwide faces shortfalls in shelter, mobility, and nutrition. (*high confidence*) {5.2, 5.3, 5.4, 5.5, Figure 5.6, Figure 5.10, Figure TS.20, Figure TS.22, Table 5.2}

C.10.2 By 2050, comprehensive demand-side strategies across all sectors could reduce CO_2 and non-CO_2 GHG emissions globally by 40–70% compared to the 2050 emissions projection of two scenarios consistent with policies announced by national governments until 2020. With policy support, socio-cultural options, and behavioural change can reduce global GHG emissions of end-use sectors by at least 5% rapidly, with most of the potential in developed countries, and more until 2050, if combined with improved infrastructure design and access. Individuals with high socio-economic status contribute disproportionately to emissions and have the highest potential for emissions reductions, e.g., as citizens, investors, consumers, role models, and professionals. (*high confidence*) (Figure SPM.6){5.2, 5.3, 5.4, 5.5, 5.6, Table SM5.2, 8.4, 9.9, 13.2, 13.5, 13.8, Figure TS.20}

C.10.3 A range of 5-30% of global annual GHG emissions from end-use sectors are avoidable by 2050, compared to 2050 emissions projection of two scenarios consistent with policies announced by national governments until 2020, through changes in the built environment, new and repurposed infrastructures and service provision through compact cities, co-location of jobs and housing, more efficient use of floor space and energy in buildings, and reallocation of street space for active mobility (*high confidence*). (Figure SPM.6) {5.3.1, 5.3.3, 5.4, Figure 5.7, Figure 5.13, Table 5.1, Table 5.5, Table SM5.2, 8.4, 9.5, 10.2, 11.3, 11.4, Table 11.6, Box TS.12}

C.10.4 Choice architecture [FOOTNOTE 63] can help end-users adopt, as relevant to consumers, culture and country contexts, low GHG intensive options such as balanced, sustainable healthy diets[FOOTNOTE 62] acknowledging nutritional needs; food waste reduction; adaptive heating and cooling choices for thermal comfort; integrated building renewable energy; and electric light-duty vehicles, and shifts to walking, cycling, shared pooled and public transit; sustainable consumption by intensive use of longer-lived repairable products (*high confidence*). Addressing inequality and many forms of status consumption [FOOTNOTE 64] and focusing on wellbeing supports climate change mitigation efforts (*high confidence*). (Figure SPM.6) {2.4.3, 2.6.2, 4.2.5, 5.1, 5.2, 5.3, 5.4, Figure 5.4, Figure 5.10, Table 5.2, Table SM5.2, 7.4.5, 8.2, 8.4, 9.4, 10.2, 12.4, Figure TS.20}

FOOTNOTE 63: Choice architecture describes the presentation of choices to consumers, and the impact that presentation has on consumer decision-making.

FOOTNOTE 64: Status consumption refers to the consumption of goods and services which publicly demonstrates social prestige.

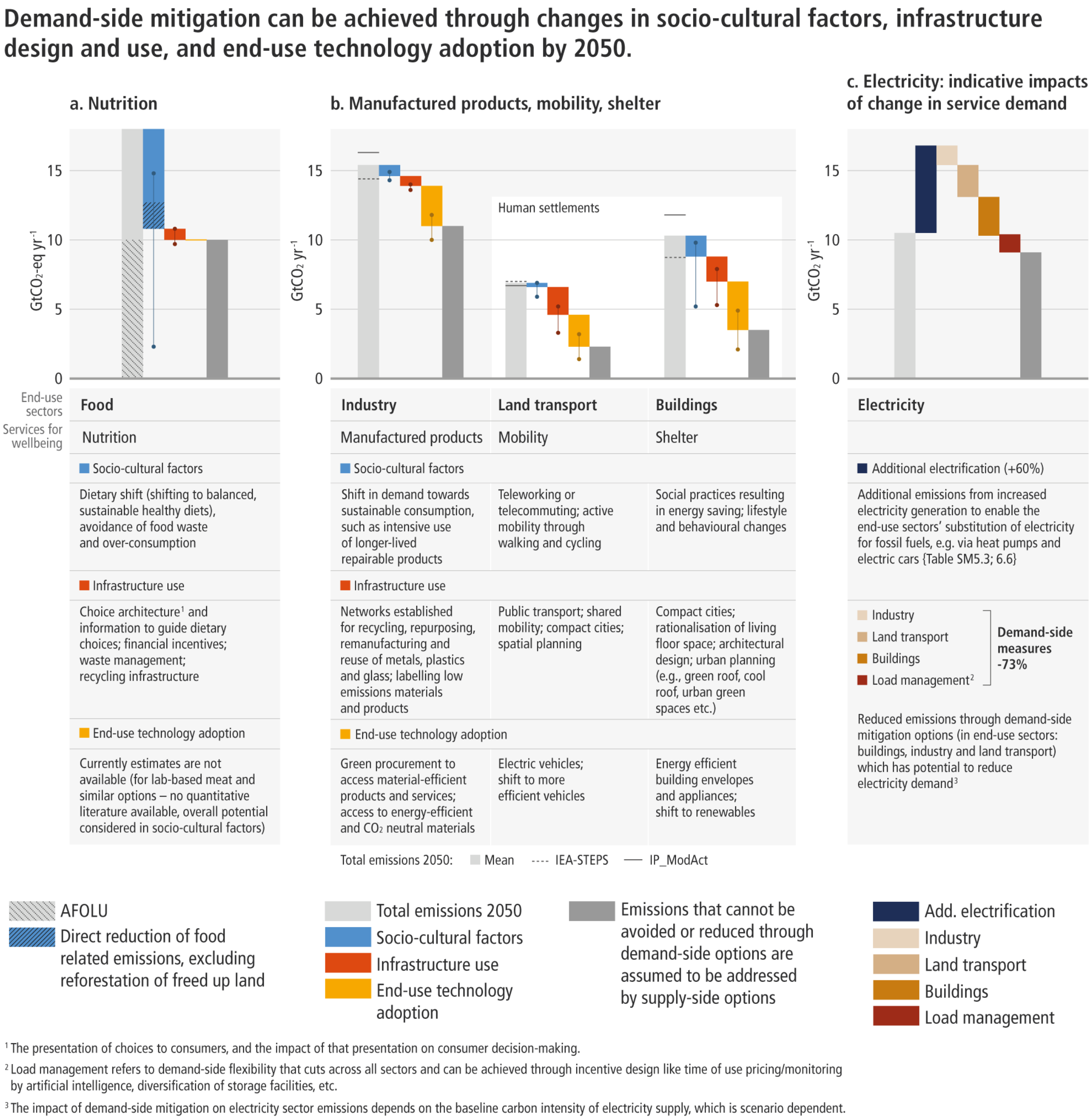


Figure SPM.6 Indicative potential of demand-side mitigation options by 2050

Figure SPM.6 covers the indicative potential of demand-side options for the year 2050. Figure SPM.7 covers cost and potentials for the year 2030. Demand-side mitigation response options are categorised into three broad domains: 'socio-cultural factors', associated with individual choices, behaviour; and lifestyle changes, social norms and culture; 'infrastructure use', related to the design and use of supporting hard and soft infrastructure that enables changes in individual choices and behaviour; and 'end-use technology adoption', refers to the uptake of technologies by end-users. Demand side mitigation is a central element of the IMP-LD and IMP-SP scenarios (Figure SPM.5).

Panel (a) (Nutrition) demand-side potentials in 2050 assessment is based on bottom-up studies and estimated following the 2050 baseline for the food sector presented in peer-reviewed literature (more information in Supplementary Material 5.II, and 7.4.5). Panel (b) (Manufactured products, mobility, shelter) assessment of potentials for total emissions in 2050 are estimated based on approximately 500 bottom up studies representing all global regions (detailed list is in Table SM5.2). Baseline is provided by the sectoral mean GHG emissions in 2050 of the two scenarios consistent with policies announced by national governments until 2020. The heights of the coloured columns represent the potentials represented by the median value. These are based on a range of values available in the case studies from literature shown in Chapter 5 Supplementary Material II. The range is shown by the dots connected by dotted lines representing the highest and the lowest potentials reported in the literature.

Panel (a) shows the demand side potential of socio-cultural factors and infrastructure use. The median value of direct emissions (mostly non-CO_2) reduction through socio-cultural factors is 1.9 $GtCO_2$-eq without considering land-use change through reforestation of freed up land. If changes in land use pattern enabled by this change in food demand are considered, the indicative potential could reach 7 $GtCO_2$-eq. Panel (b) illustrates mitigation potential in industry, land transport and buildings end-use sectors through demand-side options. Key options are presented in the summary table below the figure and the details are in Table SM5.2.

Panel (c) visualizes how sectoral demand-side mitigation options (presented in Panel (b)) change demand on the electricity distribution system. Electricity accounts for an increasing proportion of final energy demand in 2050 (additional electricity bar) in line with multiple bottom-up studies (detailed list is in Table SM5.3), and Chapters 6 (6.6). These studies are used to compute the impact of end-use electrification which increases overall electricity demand. Some of the projected increase in electricity demand can be avoided through demand-side mitigation options in the domains of socio-cultural factors and infrastructure use in end-use electricity use in buildings, industry, and land transport found in literature based on bottom-up assessments. Dark grey columns show the emissions that cannot be avoided through demand-side mitigation options.
{5.3, Figure 5.7, Supplementary Material 5.II}

C.11 The deployment of CDR to counterbalance hard-to-abate residual emissions is unavoidable if net zero CO_2 or GHG emissions are to be achieved. The scale and timing of deployment will depend on the trajectories of gross emission reductions in different sectors. Upscaling the deployment of CDR depends on developing effective approaches to address feasibility and sustainability constraints especially at large scales. (*high confidence*) {3.4, 7.4, 12.3, Cross-Chapter Box 8 in Chapter 12}

C.11.1 CDR refers to anthropogenic activities that remove CO_2 from the atmosphere and store it durably in geological, terrestrial, or ocean reservoirs, or in products. CDR methods vary in terms of their maturity, removal process, timescale of carbon storage, storage medium, mitigation potential, cost, co-benefits, impacts and risks, and governance requirements (*high confidence*). Specifically, maturity ranges from lower maturity (e.g., ocean alkalinisation) to higher maturity (e.g., reforestation); removal and storage potential ranges from lower potential (<1 Gt CO_2 yr^{-1}, e.g., blue carbon management) to higher potential (>3 Gt CO_2 yr^{-1}, e.g., agroforestry); costs range from lower cost (e.g., 45-100 USD/tCO_2 for soil carbon sequestration) to higher cost (e.g., 100-300 USD/tCO_2 for DACCS) (*medium confidence*). Estimated storage timescales vary from decades to centuries for methods that store carbon in vegetation and through soil carbon management, to ten thousand years or more for methods that store carbon in geological formations (*high confidence*). The processes by which CO_2 is removed from the atmosphere are categorised as biological, geochemical or chemical. Afforestation, reforestation, improved forest management, agroforestry and soil carbon sequestration are currently the only widely practiced CDR methods (*high confidence*). {7.4, 7.6, 12.3, Table 12.6, Table TS.7, Cross-Chapter Box 8 in Chapter 12, WG I 5.6}

C.11.2 The impacts, risks and co-benefits of CDR deployment for ecosystems, biodiversity and people will be highly variable depending on the method, site-specific context, implementation and scale (*high confidence*). Reforestation, improved forest management, soil carbon sequestration, peatland restoration and blue carbon management are examples of methods that can enhance biodiversity and ecosystem functions, employment and local livelihoods, depending on context (*high confidence*). In contrast, afforestation or production of biomass crops for BECCS or biochar, when poorly implemented, can have adverse socio-economic and environmental impacts, including on biodiversity, food and water security, local livelihoods and on the rights of Indigenous Peoples, especially if implemented at large scales and where land tenure is insecure (*high confidence*). Ocean fertilisation, if implemented, could lead to nutrient redistribution, restructuring of ecosystems, enhanced oxygen consumption and acidification in deeper waters (*medium confidence*). {7.4, 7.6, 12.3, 12.5}

C.11.3 The removal and storage of CO_2 through vegetation and soil management can be reversed by human or natural disturbances; it is also prone to climate change impacts. In comparison, CO_2 stored in geological and ocean reservoirs (via BECCS, DACCS, ocean alkalinisation) and as carbon in biochar is less prone to reversal. (*high confidence*) {6.4, 7.4, 12.3}

C11.4 In addition to deep, rapid, and sustained emission reductions CDR can fulfil three different complementary roles globally or at country level: lowering net CO_2 or net GHG emissions in the near-term; counterbalancing 'hard-to-abate' residual emissions (e.g., emissions from agriculture, aviation, shipping, industrial processes) in order to help reach net zero CO_2 or net zero GHG emissions in the mid-term; achieving net negative CO_2 or GHG emissions in the long-term if deployed at levels exceeding annual residual emissions (*high confidence*) {3.3, 7.4, 11.3, 12.3, Cross-Chapter Box 8 in Chapter 12}

C.11.5 Rapid emission reductions in all sectors interact with future scale of deployment of CDR methods, and their associated risks, impacts and co-benefits. Upscaling the deployment of CDR methods depends on developing effective approaches to address sustainability and feasibility constraints, potential impacts, co-benefits and risks. Enablers of CDR include accelerated research, development and demonstration, improved tools for risk assessment and management, targeted incentives and development of agreed methods for measurement, reporting and verification of carbon flows. (*high confidence*) {3.4, 7.6, 12.3}

C.12 Mitigation options costing USD100 tCO_2-eq^{-1} or less could reduce global GHG emissions by at least half the 2019 level by 2030 (*high confidence*). Global GDP continues to grow in modelled pathways [FOOTNOTE 65] but, without accounting for the economic benefits of mitigation action from avoided damages from climate change nor from reduced adaptation costs, it is a few percent lower in 2050 compared to pathways without mitigation beyond current policies. The global economic benefit of limiting warming to 2°C is reported to exceed the cost of mitigation in most of the assessed literature. (*medium confidence*) (Figure SPM.7) {3.6, 3.8, Cross-Working Group Box 1 in Chapter 3, 12.2, Box TS.7}

FOOTNOTE 65: In modelled pathways that limit warming to 2°C (>67%) or lower.

C.12.1 Based on a detailed sectoral assessment of mitigation options, it is estimated that mitigation options costing USD100 tCO_2-eq^{-1} or less could reduce global GHG emissions by at least half of the 2019 level by 2030 (options costing less than USD20 tCO_2-eq^{-1} are estimated to make up more than half of this potential) [FOOTNOTE 66]. For a smaller part of the potential, deployment leads to net cost savings. Large contributions with costs less than USD20 tCO_2-eq^{-1} come from solar and wind energy, energy efficiency improvements, reduced conversion of natural ecosystems, and CH_4 emissions reductions (coal mining, oil and gas, waste). The mitigation potentials and mitigation costs of individual technologies in a specific context or region may differ greatly from the provided estimates. The assessment of the underlying literature suggests that the relative contribution of the various options could change beyond 2030. (*medium confidence*) (Figure SPM.7) {12.2}

FOOTNOTE 66. The methodology underlying the assessment is described in the caption to Figure SPM.7.

C.12.2 The aggregate effects of climate change mitigation on global GDP are small compared to global projected GDP growth in assessed modelled global scenarios that quantify the macroeconomic implications of climate change mitigation, but that do not account for damages from climate change nor adaptation costs (*high confidence*). For example, compared to pathways that assume the continuation of policies implemented by the end of 2020, assessed global GDP reached in 2050 is reduced by 1.3–2.7% in modelled pathways assuming coordinated global action starting between now and 2025 at the latest to limit warming to 2°C (>67%). The corresponding average reduction in annual global GDP growth over 2020-2050 is 0.04–0.09 percentage points. In assessed modelled pathways, regardless of the level of mitigation action, global GDP is projected to at least double (increase by at least 100%) over 2020-2050. For modelled global pathways in other temperature categories, the reductions in global GDP in 2050 compared to pathways that assume the continuation of policies implemented by the end of 2020 are as follows: 2.6 - 4.2% (C1), 1.6 - 2.8% (C2), 0.8 - 2.1% (C4), 0.5 - 1.2% (C5). The corresponding reductions in average annual global GDP growth over 2020-2050, in percentage points, are as follows: 0.09 - 0.14 (C1), 0.05 - 0.09 (C2), 0.03 - 0.07 (C4), 0.02 - 0.04 (C5) [FOOTNOTE 67]. There are large variations in the modelled effects of mitigation on GDP across regions, depending notably on economic structure, regional emissions reductions, policy design and level of international cooperation [FOOTNOTE 68] (*high confidence*). Country level studies also show large variations in the effect of mitigation on GDP depending notably on the level of mitigation and on the way it is achieved (*high confidence*). Macroeconomic implications of mitigation co-benefits and trade-offs are not quantified comprehensively across the above scenarios and depend strongly on mitigation strategies (*high confidence*). {3.6, 4.2, Box TS.7, Annex III I.2, I.9, I.10 and II.3}

FOOTNOTE 67: These estimates are based on 311 pathways that report effects of mitigation on GDP and that could be classified in temperature categories, but that do not account for damages from climate change nor adaptation costs and that mostly do not reflect the economic impacts of mitigation co-benefits and trade-offs. The ranges given are interquartile ranges. The macroeconomic implications quantified vary largely depending on technology assumptions, climate/emissions target formulation, model structure and assumptions, and the extent to which pre-existing inefficiencies are considered. Models that produced the pathways classified in temperature categories do not represent the full diversity of existing modelling paradigms, and there are in the literature models that find higher mitigation costs, or conversely lower mitigation costs and even gains. {1.7, 3.2, 3.6, Annex III I.2 I.9 I.10 and II.3}

FOOTNOTE 68: In modelled cost-effective pathways with a globally uniform carbon price, without international financial transfers or complementary policies, carbon intensive and energy exporting countries are projected to bear relatively higher mitigation costs because of a deeper transformation of their economies and changes in international energy markets. {3.6}

C.12.3 Estimates of aggregate economic benefits from avoiding damages from climate change, and from reduced adaptation costs, increase with the stringency of mitigation (*high confidence*). Models that incorporate the economic damages from climate change find that the global cost of limiting warming to 2°C over the 21st century is lower than the global economic benefits of reducing warming, unless: i) climate damages are towards the low end of the range; or, ii) future damages are discounted at high rates (*medium confidence*) [FOOTNOTE 69]. Modelled pathways with a peak in global emissions between now and 2025 at the latest, compared to modelled pathways with a later peak in global emissions, entail more rapid near-term transitions and higher up-front investments, but bring long-term gains for the economy, as well as earlier benefits of avoided climate change impacts (*high confidence*). The precise magnitude of these gains and benefits is difficult to quantify. {1.7, 3.6, Cross-Working Group Box 1 in Chapter 3 Box TS.7, WGII SPM B.4}

FOOTNOTE 69: The evidence is too limited to make a similar robust conclusion for limiting warming to 1.5°C.

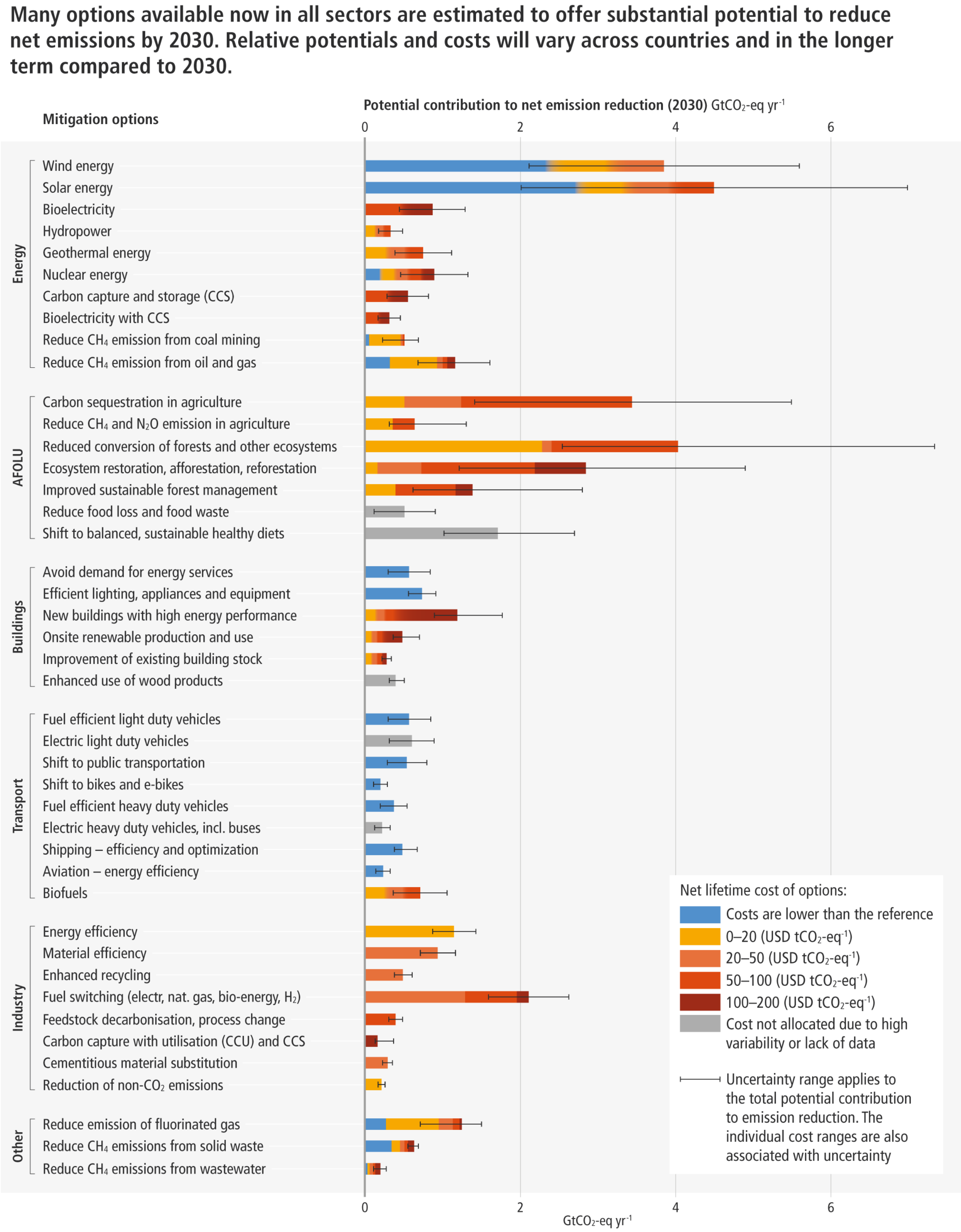


Figure SPM.7: Overview of mitigation options and their estimated ranges of costs and potentials in 2030.

Costs shown are net lifetime costs of avoided greenhouse gas emissions. Costs are calculated relative to a reference technology. The assessments per sector were carried out using a common methodology, including definition of potentials, target year, reference scenarios, and cost definitions. The mitigation potential (shown in the horizontal axis) is the quantity of net greenhouse gas emission reductions that can be achieved by a given mitigation option relative to a specified emission baseline. Net greenhouse gas emission reductions are the sum of reduced emissions and/or enhanced sinks. The baseline used consists of current policy (~ 2019) reference scenarios from the AR6 scenarios database (25/75 percentile values). The assessment relies on approximately 175 underlying sources, that together give a fair representation of emission reduction potentials across all regions. The mitigation potentials are assessed independently for each option and are not necessarily additive. {12.2.1, 12.2.2}

The length of the solid bars represents the mitigation potential of an option. The error bars display the full ranges of the estimates for the total mitigation potentials. Sources of uncertainty for the cost estimates include assumptions on the rate of technological advancement, regional differences, and economies of scale, among others. Those uncertainties are not displayed in the figure.

Potentials are broken down into cost categories, indicated by different colours (see legend). Only discounted lifetime monetary costs are considered. Where a gradual colour transition is shown, the breakdown of the potential into cost categories is not well known or depends heavily on factors such as geographical location, resource availability, and regional circumstances, and the colours indicate the range of estimates. Costs were taken directly from the underlying studies (mostly in the period 2015-2020) or recent datasets. No correction for inflation was applied, given the wide cost ranges used. The cost of the reference technologies were also taken from the underlying studies and recent datasets. Cost reductions through technological learning are taken into account (FOOTNOTE 70).

When interpreting this figure, the following should be taken into account:

- The mitigation potential is uncertain, as it will depend on the reference technology (and emissions) being displaced, the rate of new technology adoption, and several other factors.
- Cost and mitigation potential estimates were extrapolated from available sectoral studies. Actual costs and potentials would vary by place, context and time.
- Beyond 2030, the relative importance of the assessed mitigation options is expected to change, in particular while pursuing long-term mitigation goals, recognising also that the emphasis for particular options will vary across regions (for specific mitigation options see sections C4.1, C5.2, C7.3, C8.3 and C9.1).
- Different options have different feasibilities beyond the cost aspects, which are not reflected in the figure (cf. section E.1).
- The potentials in the cost range 100 to 200 USD tCO_2-eq^{-1} may be underestimated for some options.
- Costs for accommodating the integration of variable renewable energy sources in electricity systems are expected to be modest until 2030, and are not included because of complexities in attributing such costs to individual technology options.
- Cost range categories are ordered from low to high. This order does not imply any sequence of implementation.
- Externalities are not taken into account.

{12.2, Table 12.3, 6.4, Table 7.3, Supplementary Material Table 9.2, Supplementary Material Table 9.3, 10.6, 11.4, Fig 11.13, Supplementary Material 12.A.2.3}

FOOTNOTE 70: For nuclear energy, modelled costs for long-term storage of radio-active waste are included.

D. Linkages between mitigation, adaptation, and sustainable development

D.1 Accelerated and equitable climate action in mitigating, and adapting to, climate change impacts is critical to sustainable development. Climate change actions can also result in some trade-offs. The trade-offs of individual options could be managed through policy design. The Sustainable Development Goals (SDGs) adopted under the UN 2030 Agenda for Sustainable Development can be used as a basis for evaluating climate action in the context of sustainable development. (*high confidence*) (Figure SPM.8) {1.6, 3.7, 17.3, Figure TS.29}

D.1.1 Human-induced climate change is a consequence of more than a century of net GHG emissions from unsustainable energy use, land-use and land use change, lifestyle and patterns of consumption and production. Without urgent, effective and equitable mitigation actions, climate change increasingly threatens the health and livelihoods of people around the globe, ecosystem health and biodiversity. There are both synergies and trade-offs between climate action and the pursuit of other SDGs. Accelerated and equitable climate action in mitigating, and adapting to, climate change impacts is critical to sustainable development. (*high confidence*) {1.6, Cross-Chapter Box 5 in Chapter 4, 7.2, 7.3, 17.3, WGI, WGII}

D.1.2 Synergies and trade-offs depend on the development context including inequalities, with consideration of climate justice. They also depend on means of implementation, intra- and inter-sectoral interactions, cooperation between countries and regions, the sequencing, timing and stringency of mitigation actions, governance, and policy design. Maximising synergies and avoiding trade-offs pose particular challenges for developing countries, vulnerable populations, and Indigenous Peoples with limited institutional, technological and financial capacity, and with constrained social, human, and economic capital. Trade-offs can be evaluated and minimized by giving emphasis to capacity building, finance, governance, technology transfer, investments, and development and social equity considerations with meaningful participation of Indigenous Peoples and vulnerable populations. (*high confidence*) {1.6, 1.7, 3.7, 5.2, 5.6, 7.4, 7.6, 17.4}

D.1.3 There are potential synergies between sustainable development and energy efficiency and renewable energy, urban planning with more green spaces, reduced air pollution, and demand side mitigation including shifts to balanced, sustainable healthy diets (*high confidence*). Electrification combined with low GHG energy, and shifts to public transport can enhance health, employment, and can elicit energy security and deliver equity (*high confidence*). In industry, electrification and circular material flows contribute to reduced environmental pressures and increased economic activity and employment. However, some industrial options could impose high costs (*medium confidence*). (Figure SPM.8) {5.2, 8.2, 11.3, 11.5, 17.3, Figure TS.29}

D.1.4 Land-based options such as reforestation and forest conservation, avoided deforestation and restoration and conservation of natural ecosystems and biodiversity, improved sustainable forest management, agroforestry, soil carbon management and options that reduce CH_4 and N_2O emissions in agriculture from livestock and soil, can have multiple synergies with the SDGs. These include enhancing sustainable agricultural productivity and resilience, food security, providing additional biomass for human use, and addressing land degradation. Maximising synergies and managing trade-offs depend on specific practices, scale of implementation, governance, capacity building, integration with existing land-use, and the involvement of local communities and Indigenous Peoples and through benefit sharing supported by frameworks such as Land Degradation Neutrality within the UNCCD. (*high confidence*) {3.7, 7.4, 12.5, 17.3}

D.1.5 Trade-offs in terms of employment, water use, land use competition and biodiversity, as well as access to, and the affordability of, energy, food, and water can be avoided by well-implemented land-based mitigation options, especially those that do not threaten existing sustainable land uses and land rights, though more frameworks for integrated policy implementation are required. The sustainability of bioenergy and other biobased products is influenced by feedstock, land management practice, climatic region, the context of existing land management, and the timing, scale and speed of deployment. (*medium confidence*) {3.5, 3.7, 7.4, 12.4, 12.5, 17.1}

D.1.6 CDR methods such as soil carbon sequestration and biochar [FOOTNOTE 71] can improve soil quality and food production capacity. Ecosystem restoration and reforestation sequester carbon in plants and soil, and can enhance biodiversity and provide additional biomass, but can displace food production and livelihoods, which calls for integrated approaches to land use planning, to meet multiple objectives including food security. However, due to limited application of some of the options today, there are some uncertainties about potential benefits (*high confidence*) {3.7, 7.4, 7.6, 12.5, 17.3, Table TS.7}

FOOTNOTE 71: Potential risks, knowledge gaps due to the relative immaturity of use of biochar as soil amendment and unknown impacts of widespread application, and co-benefits of biochar are reviewed in 7.4.3.2.

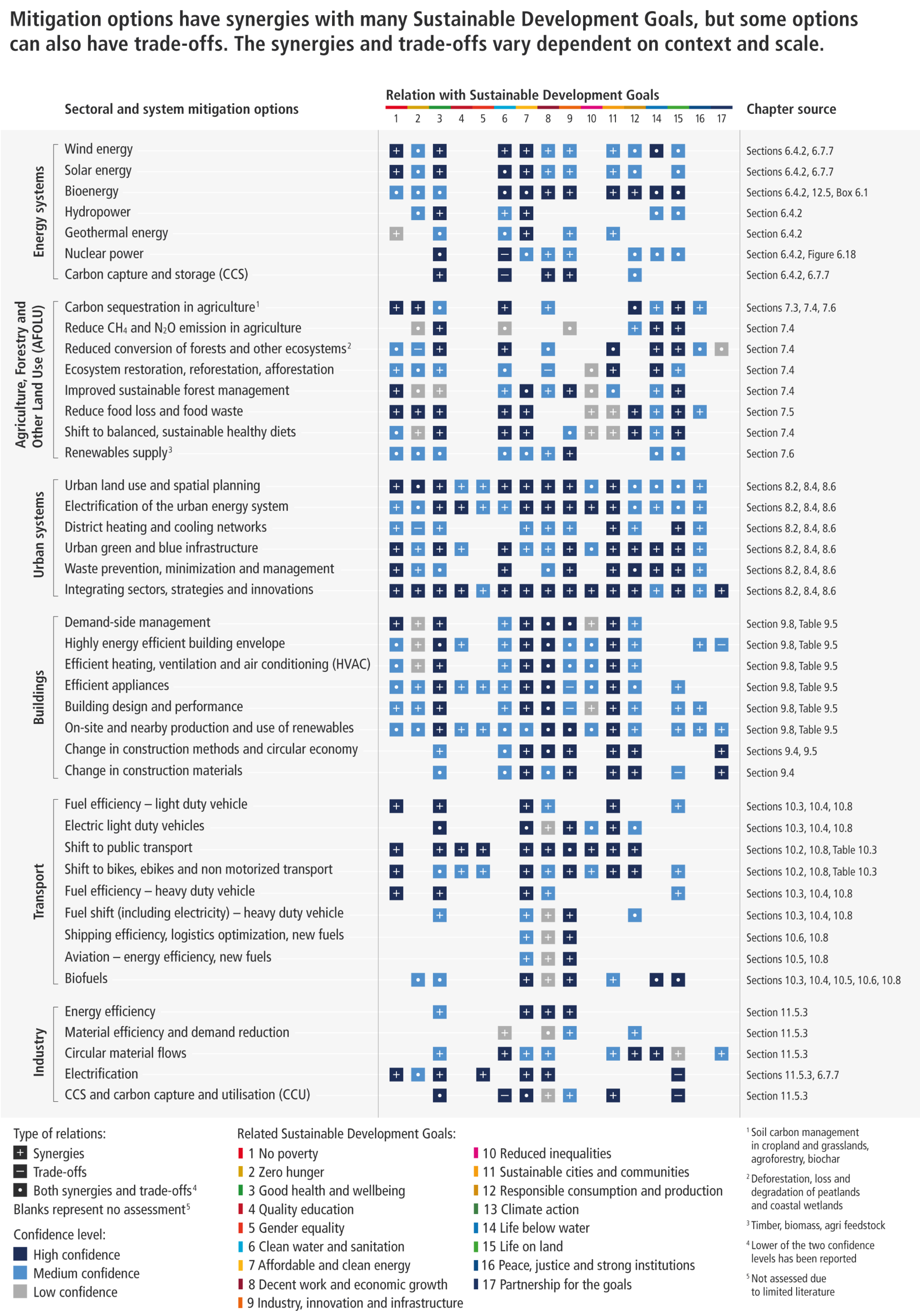


Figure SPM.8 Synergies and trade-offs between sectoral and system mitigation options and the SDGs

The sectoral chapters (Chapters 6–11) include qualitative assessments of synergies and trade-offs between sectoral mitigation options and the SDGs. Figure SPM.8 presents a summary of the chapter-level assessment for selected mitigation options (see Supplementary Material Table 17.1 for the underlying assessment). The last column provides a line of sight to the sectoral chapters, which provide details on context specificity and dependence of interactions on the scale of implementation. Blank cells indicate that interactions have not been assessed due to limited literature. They do not indicate the absence of interactions between mitigation options and the SDGs. Confidence levels depend on the quality of evidence and level of agreement in the underlying literature assessed by the sectoral chapters. Where both synergies and trade-offs exist, the lower of the confidence levels for these interactions is used.

Some mitigation options may have applications in more than one sector or system. The interactions between mitigation options and the SDGs might differ depending on the sector or system, and also on the context and the scale of implementation. Scale of implementation particularly matters when there is competition for scarce resources.

{6.3, 6.4, 6.7, 7.3, 7.4, 7.5, 7.6, 8.2, 8.4, 8.6, Figure 8.4, Table SM8.1, Table SM8.2, 9.4, 9.5, 9.8, Table 9.5, 10.3, 10.4, 10.5, 10.6, 10.8, Table 10.3, 11.5, 12.5, 17.3, Figure 17.1, Table SM17.1, Annex II Part IV Section 12}

D.2 There is a strong link between sustainable development, vulnerability and climate risks. Limited economic, social and institutional resources often result in high vulnerability and low adaptive capacity, especially in developing countries *(medium confidence)*. Several response options deliver both mitigation and adaptation outcomes, especially in human settlements , land management, and in relation to ecosystems. However, land and aquatic ecosystems can be adversely affected by some mitigation actions, depending on their implementation (*medium confidence*). Coordinated cross-sectoral policies and planning can maximise synergies and avoid or reduce trade-offs between mitigation and adaptation (*high confidence*). {3.7, 4.4, 13.8, 17.3, WG II}

D.2.1 Sustainable urban planning and infrastructure design including green roofs and facades, networks of parks and open spaces, management of urban forests and wetlands, urban agriculture, and water-sensitive design can deliver both mitigation and adaptation benefits in settlements (*medium confidence*). These options can also reduce flood risks, pressure on urban sewer systems, urban heat island effects, and can deliver health benefits from reduced air pollution (*high confidence*). There could also be trade-offs. For example, increasing urban density to reduce travel demand, could imply high vulnerability to heat waves and flooding (*high confidence*). (Figure SPM.8) {3.7, 8.2, 8.4, 12.5, 13.8, 17.3}

D.2.2 Land-related mitigation options with potential co-benefits for adaptation include agroforestry, cover crops, intercropping, and perennial plants, thus restoring natural vegetation and rehabilitating degraded land. These can enhance resilience by maintaining land productivity and protecting and diversifying livelihoods. Restoration of mangroves and coastal wetlands sequester carbon, while also reducing coastal erosion and protecting against storm surges, thus, reduce the risks from sea level rise and extreme weather. (*high confidence*) {4.4, 7.4, 7.6, 12.5, 13.8}

D.2.3 Some mitigation options can increase competition for scarce resources including land, water and biomass. Consequently, these can also reduce adaptive capacity, especially if deployed at larger scale and with high expansion rates thus exacerbating existing risks in particular where land and water resources are very limited. Examples include the large-scale or poorly planned deployment of bioenergy, biochar, and afforestation of naturally unforested land. (*high confidence*) {12.5, 17.3}

D.2.4 Coordinated policies, equitable partnerships and integration of adaptation and mitigation within and across sectors can maximise synergies and minimise trade-offs and thereby enhance the support for climate action (*medium confidence*). Even if extensive global mitigation efforts are implemented, there will be a large need for financial, technical, and human resources for adaptation. Absence or limited resources in social and institutional systems can lead to poorly coordinated responses, thus reducing the potential for maximising mitigation and adaptation benefits, and increasing risk (*high confidence*). {12.6, 13.8, 17.1, 17.3}

D.3 Enhanced mitigation and broader action to shift development pathways towards sustainability will have distributional consequences within and between countries. Attention to equity and broad and meaningful participation of all relevant actors in decision-making at all scales can build social trust, and deepen and widen support for transformative changes. (*high confidence*) {3.6, 4.2, 4.5, 5.2, 13.2, 17.3, 17.4}

D.3.1 Countries at all stages of economic development seek to improve the well-being of people, and their development priorities reflect different starting points and contexts. Different contexts include social, economic, environmental, cultural, or political conditions, resource endowment, capabilities, international environment, and history. The enabling conditions for shifting development pathways towards increased sustainability will therefore also differ, giving rise to different needs. (*high confidence*) (Figure SPM.2) {1.6, 1.7, 2.4, 2.6, Cross-Chapter Box 5 in Chapter 4, 4.3.2, 17.4}

D.3.2 Ambitious mitigation pathways imply large and sometimes disruptive changes in economic structure, with significant distributional consequences, within and between countries. Equity remains a central element in the UN climate regime, notwithstanding shifts in differentiation between states over time and challenges in assessing fair shares. Distributional consequences within and between countries include shifting of income and employment during the transition from high to low emissions activities. While some jobs may be lost, low-emissions development can also open more opportunities to enhance skills and create more jobs that last, with differences across countries and sectors. Integrated policy packages can improve the ability to integrate considerations of equity, gender equality and justice. (*high confidence*). {1.4, 1.6, 3.6, 4.2, 5.2, Box 11.1, 14.3, 15.2, 15.5, 15.6}

D.3.3 Inequalities in the distribution of emissions and in the impacts of mitigation policies within countries affect social cohesion and the acceptability of mitigation and other environmental policies. Equity and just transitions can enable deeper ambitions for accelerated mitigation. Applying just transition principles and implementing them through collective and participatory decision-making processes is an effective way of integrating equity principles into policies at all scales, in different ways depending on national circumstances. (*medium confidence*) This is already taking place in many countries and regions, as national just transition commissions or task forces, and related national policies, have been established in several countries. A multitude of actors, networks, and movements are engaged. (*high confidence*) {1.6, 1.7, 2.4, 2.6, 4.5, 13.2, 13.9, 14.3, 14.5}

D.3.4 Broadening equitable access to domestic and international finance, technologies that facilitate mitigation, and capacity, while explicitly addressing needs can further integrate equity and justice into national and international policies and act as a catalyst for accelerating mitigation and shifting development pathways (*medium confidence*). The consideration of ethics and equity can help address the uneven distribution of adverse impacts associated with 1.5°C and higher levels of global warming, in all societies (*high confidence*). Consideration of climate justice can help to facilitate shifting development pathways towards sustainability, including through equitable sharing of benefits and burdens of mitigation, increasing resilience to the impacts of climate change, especially for vulnerable countries and communities, and equitably supporting those in need (*high confidence*). {1.4, 1.6, 1.7, 3.6, 4.2, 4.5, Box 5.10, 13.4, 13.8, 13.9, 14.3, 14.5, 15.2, 15.5, 15.6, 16.5, 17.3, 17.4, SR1.5 SPM, WGII CH18}

E. Strengthening the response

E.1 There are mitigation options which are feasible [FOOTNOTE 72] to deploy at scale in the near term. Feasibility differs across sectors and regions, and according to capacities and the speed and scale of implementation. Barriers to feasibility would need to be reduced or removed, and enabling conditions [FOOTNOTE 73] strengthened to deploy mitigation options at scale. These barriers and enablers include geophysical, environmental-ecological, technological, and economic factors, and especially institutional and socio-cultural factors. Strengthened near-term action beyond the NDCs (announced prior to UNFCCC COP26) can reduce and/or avoid long-term feasibility challenges of global modelled pathways that limit warming to 1.5 °C (>50%) with no or limited overshoot. ***(high confidence)*** **{3.8, 6.4, 8.5, 9.9, 10.8, 12.3, Figure TS.31, Annex II Part IV Section 11}**

FOOTNOTE 72: In this report, the term 'feasibility' refers to the potential for a mitigation or adaptation option to be implemented. Factors influencing feasibility are context-dependent and may change over time. Feasibility depends on geophysical, environmental-ecological, technological, economic, socio-cultural and institutional factors that enable or constrain the implementation of an option. The feasibility of options may change when different options are combined and increase when enabling conditions are strengthened.

FOOTNOTE 73: In this report, the term 'enabling conditions' refers to conditions that enhance the feasibility of adaptation and mitigation options. Enabling conditions include finance, technological innovation, strengthening policy instruments, institutional capacity, multi-level governance and changes in human behaviour and lifestyles.

E.1.1 Several mitigation options, notably solar energy, wind energy, electrification of urban systems, urban green infrastructure, energy efficiency, demand side management, improved forest- and crop/grassland management, and reduced food waste and loss, are technically viable, are becoming increasingly cost effective, and are generally supported by the public. This enables deployment in many regions. (*high confidence*) While many mitigation options have environmental co-benefits, including improved air quality and reducing toxic waste, many also have adverse environmental impacts, such as reduced biodiversity, when applied at very large scale, for example very large scale bioenergy or large scale use of battery storage, that would have to be managed (*medium confidence*). Almost all mitigation options face institutional barriers that need to be addressed to enable their application at scale (*medium confidence*). {6.4, Figure 6.19, 7.4, 8.5, Figure 8.19, 9.9, Figure 9.20, 10.8, Figure 10.23, 12.3, Figure 12.4, Figure TS.31}

E.1.2 The feasibility of mitigation options varies according to context and time. For example, the institutional capacity to support deployment varies across countries; the feasibility of options that involve large-scale land use changes varies across regions; spatial planning has a higher potential at early stages of urban development; the potential of geothermal is site specific; and capacities, cultural and local conditions can either inhibit or enable demand-side responses. The deployment of solar and wind energy has been assessed to become increasingly feasible over time. The feasibility of some options can increase when combined or integrated, such as using land for both agriculture and centralised solar production. (*high confidence*) {6.4, 6.6, 7.4, 8.5, 9.9, 10.8, 12.3, Appendix 10.3, Table SM6, Table SM8.2, Table SM9.1, Table SM12.B}

E.1.3 Feasibility depends on the scale and speed of implementation. Most options face barriers when they are implemented rapidly at a large scale, but the scale at which barriers manifest themselves varies. Strengthened and coordinated near-term actions in cost-effective modelled global pathways that limit warming to 2°C (>67%) or lower, reduce the overall risks to the feasibility of the system transitions, compared to modelled pathways with relatively delayed or uncoordinated action.[FOOTNOTE 74] (*high confidence*) {3.8, 6.4, 10.8, 12.3}

FOOTNOTE 74: The future feasibility challenges described in the modelled pathways may differ from the real-world feasibility experiences of the past.

E.2 In all countries, mitigation efforts embedded within the wider development context can increase the pace, depth and breadth of emissions reductions (*medium confidence*). Policies that shift development pathways towards sustainability can broaden the portfolio of available mitigation responses, and enable the pursuit of synergies with development objectives (*medium confidence*). Actions can be taken now to shift development pathways and accelerate mitigation and transitions across systems (*high confidence*). {4.3, 4.4, Cross-Chapter Box 5 in Chapter 4, 5.2, 5.4, 13.9, 14.5, 15.6, 16.3, 16.4, 16.5}

E.2.1 Current development pathways may create behavioural, spatial, economic and social barriers to accelerated mitigation at all scales (*high confidence*). Choices made by policymakers, citizens, the private sector and other stakeholders influence societies' development pathways (*high confidence*). Actions that steer, for example, energy and land systems transitions, economy-wide structural change, and behaviour change, can shift development pathways towards sustainability [FOOTNOTE 75] (*medium confidence*). {4.3, Cross-Chapter Box 5 in Chapter 4, 5.4, 13.9}

FOOTNOTE 75: Sustainability may be interpreted differently in various contexts as societies pursue a variety of sustainable development objectives.

E.2.2 Combining mitigation with policies to shift development pathways, such as broader sectoral policies, policies that induce lifestyle or behaviour changes, financial regulation, or macroeconomic policies can overcome barriers and open up a broader range of mitigation options (*high confidence*). It can also facilitate the combination of mitigation and other development goals (*high confidence*). For example, measures promoting walkable urban areas combined with electrification and renewable energy can create health co-benefits from cleaner air and benefits from enhanced mobility (*high confidence*). Coordinated housing policies that broaden relocation options can make mitigation measures in transport more effective (*medium confidence*). {3.2, 4.3, 4.4, Cross-Chapter Box 5 in Chapter 4, 5.3, 8.2, 8.4}

E.2.3 Institutional and regulatory capacity, innovation, finance, improved governance and collaboration across scales, and multi-objective policies enable enhanced mitigation and shifts in development pathways. Such interventions can be mutually reinforcing and establish positive feedback mechanisms, resulting in accelerated mitigation. (*high confidence*) {4.4, 5.4, Figure 5.14, 5.6, 9.9, 13.9, 14.5, 15.6, 16.3, 16.4, 16.5, Cross-Chapter Box 12 in Chapter 16}

E.2.4 Enhanced action on all the above enabling conditions can be taken now (*high confidence*). In some situations, such as with innovation in technology at an early stage of development and some changes in behaviour towards low-emissions, because the enabling conditions may take time to be established, action in the near-term can yield accelerated mitigation in the mid-term (*medium* *confidence*). In other situations, the enabling conditions can be put in place and yield results in a relatively short time frame, for example the provision of energy related information, advice and feedback to promote energy saving behaviour (*high confidence*). {4.4, 5.4, Figure 5.14, 5.6, 6.7, 9.9, 13.9, 14.5, 15.6, 16.3, 16.4, 16.5, Cross-Chapter Box 12 in Chapter 16}

E.3 Climate governance, acting through laws, strategies and institutions, based on national circumstances, supports mitigation by providing frameworks through which diverse actors interact, and a basis for policy development and implementation (*medium confidence*). Climate governance is most effective when it integrates across multiple policy domains, helps realise synergies and minimize trade-offs, and connects national and sub-national policy-making levels (*high confidence*). Effective and equitable climate governance builds on engagement with civil society actors, political actors, businesses, youth, labour, media, Indigenous Peoples and local communities (*medium confidence).* {5.4, 5.6, 8.5, 9.9, 13.2, 13.7, 13.9}

E.3.1 Climate governance enables mitigation by providing an overall direction, setting targets, mainstreaming climate action across policy domains, enhancing regulatory certainty, creating specialised organisations and creating the context to mobilise finance *(medium confidence)*. These functions can be promoted by climate-relevant laws, which are growing in number, or climate strategies, among others, based on national and sub-national context (*medium confidence*). Framework laws set an overarching legal basis, either operating through a target and implementation approach, or a sectoral mainstreaming approach, or both, depending on national circumstance *(medium confidence)*. Direct national and sub-national laws that explicitly target mitigation and indirect laws that impact emissions through mitigation related policy domains have both been shown to be relevant to mitigation outcomes (*medium confidence*). {13.2}

E.3.2 Effective national climate institutions address coordination across sectors, scales and actors, build consensus for action among diverse interests, and inform strategy setting *(medium confidence)*. These functions are often accomplished through independent national expert bodies, and high-level coordinating bodies that transcend departmental mandates. Complementary sub-national institutions tailor mitigation actions to local context and enable experimentation but can be limited by inequities and resource and capacity constraints (*high confidence*). Effective governance requires adequate institutional capacity at all levels (*high confidence*). {4.4, 8.5, 9.9, 11.3, 11.5, 11.6, 13.2, 13.5, 13.7, 13.9}

E.3.3 The extent to which civil society actors, political actors, businesses, youth, labour, media, Indigenous Peoples, and local communities are engaged influences political support for climate change mitigation and eventual policy outcomes. Structural factors of national circumstances and capabilities (e.g., economic and natural endowments, political systems and cultural factors and gender considerations) affect the breadth and depth of climate governance. Mitigation options that align with prevalent ideas, values and beliefs are more easily adopted and implemented. Climate-related litigation, for example by governments, private sector, civil society and individuals is growing, with a large number of cases in some developed countries, and with a much smaller number in some developing countries, and in some cases, has influenced the outcome and ambition of climate governance. (*medium confidence*) {5.2, 5.4, 5.5, 5.6, 9.9, 13.3, 13.4}

E.4 Many regulatory and economic instruments have already been deployed successfully. Instrument design can help address equity and other objectives. These instruments could support deep emissions reductions and stimulate innovation if scaled up and applied more widely (*high confidence*). Policy packages that enable innovation and build capacity are better able to support

a shift towards equitable low-emission futures than are individual policies (*high confidence*). Economy-wide packages, consistent with national circumstances, can meet short-term economic goals while reducing emissions and shifting development pathways towards sustainability (*medium confidence*). {13.6, 13.7, 13.9, 16.3, 16.4, 16.6, Cross-Chapter Box 5 in Chapter 4}

E.4.1 A wide range of regulatory instruments at the sectoral level have proven effective in reducing emissions. These instruments, and broad-based approaches including relevant economic instruments[FOOTNOTE 76], are complementary. (*high confidence*) Regulatory instruments that are designed to be implemented with flexibility mechanisms can reduce costs (*medium confidence*). Scaling up and enhancing the use of regulatory instruments, consistent with national circumstances, could improve mitigation outcomes in sectoral applications, including but not limited to renewable energy, land-use and zoning, building codes, vehicle and energy efficiency, fuel standards, and low-emissions industrial processes and materials (*high confidence*). {6.7, 7.6, 8.4, 9.9, 10.4, 11.5, 11.6, 13.6}

FOOTNOTE 76: Economic instruments are structured to provide a financial incentive to reduce emissions and include, among others, market- and price-based instruments.

E.4.2 Economic instruments have been effective in reducing emissions, complemented by regulatory instruments mainly at the national and also sub-national and regional level (*high confidence*). Where implemented, carbon pricing instruments have incentivized low-cost emissions reduction measures, but have been less effective, on their own and at prevailing prices during the assessment period, to promote higher-cost measures necessary for further reductions (*medium confidence*). Equity and distributional impacts of such carbon pricing instruments can be addressed by using revenue from carbon taxes or emissions trading to support low-income households, among other approaches (*high confidence*). Practical experience has informed instrument design and helped to improve predictability, environmental effectiveness, economic efficiency, distributional goals and social acceptance (*high confidence*). Removing fossil fuel subsidies would reduce emissions, improve public revenue and macroeconomic performance, and yield other environmental and sustainable development benefits; subsidy removal may have adverse distributional impacts especially on the most economically vulnerable groups which, in some cases can be mitigated by measures such as re-distributing revenue saved, all of which depend on national circumstances (*high confidence*); fossil fuel subsidy removal is projected by various studies to reduce global CO_2 emissions by 1-4%, and GHG emissions by up to 10% by 2030, varying across regions (*medium confidence*). {6.3, 13.6}

E.4.3 Low-emission technological innovation is strengthened through the combination of dedicated technology-push policies and investments (e.g., for scientific training, R&D, demonstration), with tailored demand-pull policies (e.g., standards, feed-in tariffs, taxes), which create incentives and market opportunities. Developing countries' abilities to deploy low-emission technologies, seize socio-economic benefits and manage trade-offs would be enhanced with increased financial resources and capacity for innovation which are currently concentrated in developed countries, alongside technology transfer. *(high confidence)* {16.2, 16.3, 16.4, 16.5}

E.4.4 Effective policy packages would be comprehensive in coverage, harnessed to a clear vision for change, balanced across objectives, aligned with specific technology and system needs, consistent in terms of design and tailored to national circumstances. They are better able to realise synergies and avoid trade-offs across climate and development objectives. Examples include: emissions reductions from buildings through a mix of efficiency targets, building codes, appliance performance standards, information provision, carbon pricing, finance and technical assistance; and industrial GHG emissions reductions through innovation support, market creation and capacity building. (*high confidence*) {4.4, 6.7, 9.9, 11.6, 13.7, 13.9, 16.3, 16.4}

E.4.5 Economy-wide packages that support mitigation and avoid negative environmental outcomes include: long-term public spending commitments, pricing reform; and investment in education and training, natural capital, R&D and infrastructure (*high confidence*). They can meet short-term economic goals while reducing emissions and shifting development pathways towards sustainability (*medium confidence*). Infrastructure investments can be designed to promote low-emissions futures that meet development needs (*medium confidence*). {Cross Chapter Box 7 in Chapter 4, 5.4, 5.6, 8.5, 13.6, 13.9, 16.3, 16.5, 16.6}

E.4.6 National policies to support technology development and diffusion, and participation in international markets for emission reduction, can bring positive spill-over effects for other countries (*medium confidence*), although reduced demand for fossil fuels could result in costs to exporting countries (*high confidence*). There is no consistent evidence that current emission trading systems have led to significant emissions leakage, which can be attributed to design features aimed at minimising competitiveness effects among other reasons (*medium confidence*). {13.6, 13.7, 13.8, 16.2, 16.3, 16.4}

E.5 Tracked financial flows fall short of the levels needed to achieve mitigation goals across all sectors and regions. The challenge of closing gaps is largest in developing countries as a whole. Scaling up mitigation financial flows can be supported by clear policy choices and signals from governments and the international community. (*high confidence*) Accelerated international financial cooperation is a critical enabler of low-GHG and just transitions, and can address inequities in access to finance and the costs of, and vulnerability to, the impacts of climate change (*high confidence*). {15.2, 15.3, 15.4, 15.5, 15.6}

E.5.1 Average annual modelled investment requirements for 2020 to 2030 in scenarios that limit warming to 2°C or 1.5°C are a factor of three to six greater than current levels, and total mitigation investments (public, private, domestic and international) would need to increase across all sectors and regions (*medium confidence*). Mitigation investment gaps are wide for all sectors, and widest for the AFOLU sector in relative terms and for developing countries [FOOTNOTE 77] (*high confidence*). Financing and investment requirements for adaptation, reduction of losses and damages, general infrastructure, regulatory environment and capacity building, and climate-responsive social protection further exacerbate the magnitude of the challenges for developing countries to attract financing (*high confidence*). {3.2, 14.4, 15.1, 15.2, 15.3, 15.4, 15.5}

FOOTNOTE 77: In modelled pathways, regional investments are projected to occur when and where they are most cost-effective to limit global warming. The model quantifications help to identify high-priority areas for cost-effective investments, but do not provide any indication on who would finance the regional investments.

E.5.2 There is sufficient global capital and liquidity to close global investment gaps, given the size of the global financial system, but there are barriers to redirect capital to climate action both within and outside the global financial sector, and in the macroeconomic headwinds facing developing regions. Barriers to the deployment of commercial finance from within the financial sector as well as macroeconomic considerations include: inadequate assessment of climate-related risks and investment opportunities, regional mismatch between available capital and investment needs, home bias factors, country indebtedness levels, economic vulnerability, and limited institutional capacities (*high confidence*). Challenges from outside the financial sector include: limited local capital markets; unattractive risk-return profiles, in particular due to missing or weak regulatory environments consistent with ambition levels; limited institutional capacity to ensure safeguards; standardization, aggregation, scalability and replicability of investment opportunities and financing models; and, a pipeline ready for commercial investments. *(high confidence)* {15.2, 15.3, 15.5, 15.6}

E.5.3 Accelerated financial support for developing countries from developed countries and other sources is a critical enabler to enhance mitigation action and address inequities in access to finance, including its costs, terms and conditions and economic vulnerability to climate change for developing countries (*high confidence*). Scaled-up public grants for mitigation and adaptation funding for vulnerable regions, especially in Sub-Saharan Africa, would be cost-effective and have high social returns in terms of access to basic energy (*high confidence*). Options for scaling up mitigation in developing regions include: increased levels of public finance and publicly mobilised private finance flows from developed to developing countries in the context of the USD100 billion-a-year goal; increase the use of public guarantees to reduce risks and leverage private flows at lower cost; local capital markets development; and building greater trust in international cooperation processes (*high confidence*). A coordinated effort to make the post-pandemic recovery sustainable and increased flows of financing over the next decade can accelerate climate action, including in developing regions and countries facing high debt costs, debt distress and macro-economic uncertainty (*high confidence*). {15.2, 15.3, 15.4, 15.5, 15.6, Box 15.6}

E.5.4 Clear signalling by governments and the international community, including a stronger alignment of public sector finance and policy, and higher levels of public sector climate finance, reduces uncertainty and transition risks for the private sector. Depending on national contexts, investors and financial intermediaries, central banks, and financial regulators can support climate action and can shift the systemic underpricing of climate climate-related risk by increasing awareness, transparency and consideration of climate-related risk, and investment opportunities. Financial flows can also be aligned with funding needs through: greater support for technology development; a continued role for multilateral and national climate funds and development banks; lowering financing costs for underserved groups through entities such as green banks existing in some countries, funds and risk-sharing mechanisms; economic instruments which consider economic and social equity and distributional impacts; gender-responsive and women-empowerment programs as well as enhanced access to finance for local communities and Indigenous Peoples and small landowners; and greater public-private cooperation. (*high confidence*) {15.2, 15.5, 15.6}

E.6 International cooperation is a critical enabler for achieving ambitious climate change mitigation goals. The UNFCCC, Kyoto Protocol, and Paris Agreement are supporting rising levels of national ambition and encouraging development and implementation of climate policies, although gaps remain. Partnerships, agreements, institutions and initiatives operating at the sub-global and sectoral levels and engaging multiple actors are emerging, with mixed levels of effectiveness. (*high confidence*) {8.5, 14.2, 14.3, 14.5, 14.6, 15.6, 16.5}

E.6.1 Internationally agreed processes and goals, such as those in the UNFCCC, Kyoto Protocol, and Paris Agreement, including transparency requirements for national reporting on emissions, actions and support, and tracking progress towards the achievement of nationally determined contributions, are enhancing international cooperation, national ambition and policy development. International financial, technology and capacity building support to developing countries will enable greater implementation and encourage ambitious nationally determined contributions over time. (*medium confidence*) {14.3}

E.6.2 International cooperation on technology development and transfer accompanied by capacity building, knowledge sharing, and technical and financial support can accelerate the global diffusion of mitigation technologies, practices and policies at national and sub-national levels, and align these with other development objectives (*high confidence*). Challenges in and opportunities to enhance innovation cooperation exist, including in the implementation of elements of the UNFCCC and the Paris Agreement as per the literature assessed, such as in relation to technology development and transfer, and finance (*high confidence*). International cooperation on innovation works best when tailored to specific institutional and capability contexts, when it benefits local value chains, when partners collaborate equitably and on voluntary and mutually agreed terms, when all relevant voices are heard, and when capacity building is an integral part of the effort (*medium confidence*). Support to strengthen technological innovation systems and innovation capabilities, including through financial support in developing countries would enhance engagement in and improve international cooperation on innovation (*high confidence*). {4.4, 14.2, 14.4, 16.3, 16.5, 16.6}

E.6.3 Transnational partnerships can stimulate policy development, low-emissions technology diffusion and emission reductions by linking sub-national and other actors, including cities, regions, non-governmental organisations and private sector entities, and by enhancing interactions between state and non-state actors. While this potential of transnational partnerships is evident, uncertainties remain over their costs, feasibility, and effectiveness. Transnational networks of city governments are leading to enhanced ambition and policy development and a growing exchange of experience and best practices (*medium confidence*). {8.5, 11.6, 14.5, 16.5, Cross-Chapter Box 12 in Chapter 16}

E.6.4 International environmental and sectoral agreements, institutions, and initiatives are helping, and in some cases may help, to stimulate low GHG emissions investment and reduce emissions. Agreements addressing ozone depletion and transboundary air pollution are contributing to mitigation, and in other areas, such as atmospheric emissions of mercury, may contribute to mitigation (*high confidence)*. Trade rules have the potential to stimulate international adoption of mitigation technologies and policies, but may also limit countries' ability to adopt trade-related climate policies (*medium confidence*). Current sectoral levels of ambition vary, with emission reduction aspirations in international aviation and shipping lower than in many other sectors (*medium confidence*). {14.5, 14.6}

WORKING GROUP III CONTRIBUTION

TO THE IPCC SIXTH ASSESSMENT REPORT (AR6)

Technical Summary

Date of Draft: November 29th 2021

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TS. 1 Introduction

The Working Group III (WG III) contribution to the IPCC's Sixth Assessment Report (AR6) assesses the current state of knowledge on the scientific, technological, environmental, economic and social aspects of climate change mitigation. It builds on previous IPCC reports, including the WG III contribution to the IPCC's Fifth Assessment Report (AR5) and the three Special Reports of the Sixth Assessment cycle on: *Global warming of 1.5 °C (SR 1.5 °C); Climate Change and Land (SRCCL)*; and, *the Ocean and Cryosphere in a Changing Climate (SROCC)*.[1]

The report assesses new literature, methodological and recent developments, and changes in approaches towards climate change mitigation since the IPCC AR5 report was published in 2014.

The global science and policy landscape on climate change mitigation has evolved since AR5. The development of the literature reflects, among other factors, the UN Framework Convention on Climate Change (UNFCCC), the outcomes of its Kyoto Protocol and the goals of the Paris Agreement {13, 14, 15}, and the UN 2030 Agenda for Sustainable Development {1, 4, 17}. Literature further highlights the growing role of non-state and sub-national actors in the global effort to address climate change, including cities, businesses, citizens, transnational initiatives and public-private entities {5, 8, 13}. It draws attention to the decreasing cost of some low emission technologies {2, 6, 12} and the evolving role of international cooperation {14}, finance {15} and innovation {16}. Emerging literature examines the global spread of climate policies, strengthened mitigation actions in developing countries, sustained reductions in greenhouse gas (GHG) emissions in some developed countries and the continuing challenges for mitigation. {2, 13}

There are ever closer linkages between climate change mitigation, development pathways and the pursuit of sustainable development goals. Development pathways largely drive GHG emissions and hence shape the mitigation challenge and the portfolio of available responses {4}. The co-benefits and risks of mitigation responses also differ according to stages of development and national capabilities {1, 2, 3, 4, 13}. Climate change mitigation framed in the context of sustainable development, equity, and poverty eradication, and rooted in the development aspirations of the society within which they take place, will be more acceptable, durable and effective. {1, 4, 17}

This report includes new assessment approaches that go beyond those evaluated in the previous IPCC WG III reports. In addition to sectoral and systems chapters {6, 7, 8, 9, 10, 11}, this report includes, for the first time, chapters dedicated to cross-sectoral perspectives {12} demand, services and social aspects of mitigation (Box TS.11) {5} and innovation, technology development and transfer {16}. The assessment of future pathways combines a forward-looking assessment of near- to medium-term perspectives up to 2050, including ways of shifting development pathways towards sustainability {4}, with an assessment of long-term outcome-oriented pathways up to 2100 {3}. Collaboration between the IPCC Working Groups is reflected in Cross-Working Group boxes which address topics such as the economic benefits from avoided impacts along mitigation pathways {Cross-Working Group Box 1 in Chapter 3}, climate change and urban areas {Cross-Working Group Box 2 in Chapter 8}, mitigation and adaptation through the bioeconomy {Cross-Working Group Box 3 in Chapter 12} and Solar Radiation Modification {Cross-Working Group Box 4 in Chapter 14}. This assessment also gives

FOOTNOTE [1] The three Special Reports are: Global Warming of 1.5°C: an IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (2018); Climate Change and Land: an IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (2019); IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (2019).

greater attention than AR5 to social, economic and environmental dimensions of mitigation actions, and institutional, legal and financial aspects {5, 13, 14, 15}.

The report draws from literature on broad and diverse analytic frameworks across multiple disciplines. These include, inter alia: economic and environmental efficiency {1}; ethics and equity {4, 5, 17}; innovation and the dynamics of socio-technical transitions {16}; and, socio-political-institutional frameworks {1, 5, 13, 14, 17}. These help to identify synergies and trade-offs with sustainable development goals, challenges and windows of opportunity for action including co-benefits, and equitable transitions at local, national and global scales. {1, 5, 13, 14, 16}.

This Technical Summary (TS) of the WG III contribution to the IPCC's Sixth Assessment Report broadly follows the report chapter order and is structured as follows.

- TS Section 2 sets out how the global context for mitigation has changed and summarises signs of progress and continuing challenges.
- TS Section 3 evaluates emission trends and drivers including recent sectoral, financial, technological and policy developments.
- TS Section 4 identifies mitigation and development pathways in the near and medium- term to 2050, and in the longer term to 2100. This section includes an assessment of how mitigation pathways deploying different portfolios of mitigation responses are consistent with limiting global warming to different levels.
- TS Section 5 summarises recent advances in knowledge across sectors and systems including energy, urban and other settlements, transport, buildings, industry, and agriculture, forestry and other land use.
- TS Section 6 examines how enabling conditions including *behaviour and lifestyle, policy, governance and institutional capacity, international cooperation, finance*, and *innovation and technology* can accelerate mitigation in the context of sustainable development
- TS Section 7 evaluates how mitigation can be achieved in the context of sustainable development, while maximising co-benefits and minimising risks.

Throughout this Technical Summary the validity of findings, confidence in findings, and cross references to Technical Summary sections, figures and tables are shown in ( ) brackets.[2] *References to the underlying report are shown in { } brackets.*

FOOTNOTE [2] Each finding is grounded in an evaluation of the underlying evidence, typeset in italics. The validity of a finding is evaluated in terms of the evidence quality – *'limited', 'medium', 'robust'* – and the degree of agreement between sources – *'low', 'medium', 'high'*. A level of confidence is expressed using five qualifiers: *very low, low, medium, high and very high.* Generally, the level of confidence is highest where there is robust evidence from multiple sources and high agreement. For findings with, for example, '*robust evidence, medium agreement'*, a confidence statement may not always be appropriate. The assessed likelihood of an outcome or a result is described as: *virtually certain* 99–100% probability, *very likely* 90–100%, *likely* 66–100%, *about as likely as not* 33–66%, *unlikely* 0–33%, *very unlikely* 0–10%, *exceptionally unlikely* 0–1%. Additional terms may also be used when appropriate, consistent with the IPCC uncertainty guidance: https://www.ipcc.ch/site/assets/uploads/2018/05/uncertainty-guidance-note.pdf.

TS. 2 The changed global context, signs of progress and continuing challenges

Since the IPCC's Fifth Assessment Report (AR5), important changes that have emerged include the specific objectives established in the Paris Agreement of 2015 (for temperature, adaptation and finance), rising climate impacts, and higher levels of societal awareness and support for climate action (*high confidence*). Meeting the long-term temperature goal in the Paris Agreement, however, implies a rapid inflection in GHG emission trends and accelerating decline towards 'net zero'. This is implausible without urgent and ambitious action at all scales. {1.2, 1.3, 1.5, 1.6, Chapters 3 and 4}

Effective and equitable climate policies are largely compatible with the broader goal of sustainable development and efforts to eradicate poverty as enshrined in the UN 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals (SDGs), notwithstanding trade-offs in some cases (*high confidence*). Taking urgent action to combat climate change and its impacts is one of the 17 SDGs (SDG13). However, climate change mitigation also has synergies and/or trade-offs with many other SDGs. There has been a strong relationship between development and GHG emissions, as historically both per capita and absolute emissions have risen with industrialisation. However, recent evidence shows countries can grow their economies while reducing emissions. Countries have different priorities in achieving the SDGs and reducing emissions as informed by their respective national conditions and capabilities. Given the differences in GHG emissions contributions, degree of vulnerability and impacts, as well as capacities within and between nations, equity and justice are important considerations for effective climate policy and for securing national and international support for deep decarbonisation. Achieving sustainable development and eradicating poverty would involve effective and equitable climate policies at all levels from local to global scale. Failure to address questions of equity and justice over time can undermine social cohesion and stability. International co-operation can enhance efforts to achieve ambitious global climate mitigation in the context of sustainable development pathways towards fulfilling the SDGs are illustrated in Figure TS.1. {1.4, 1.6, Chapters 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 13 and 17}

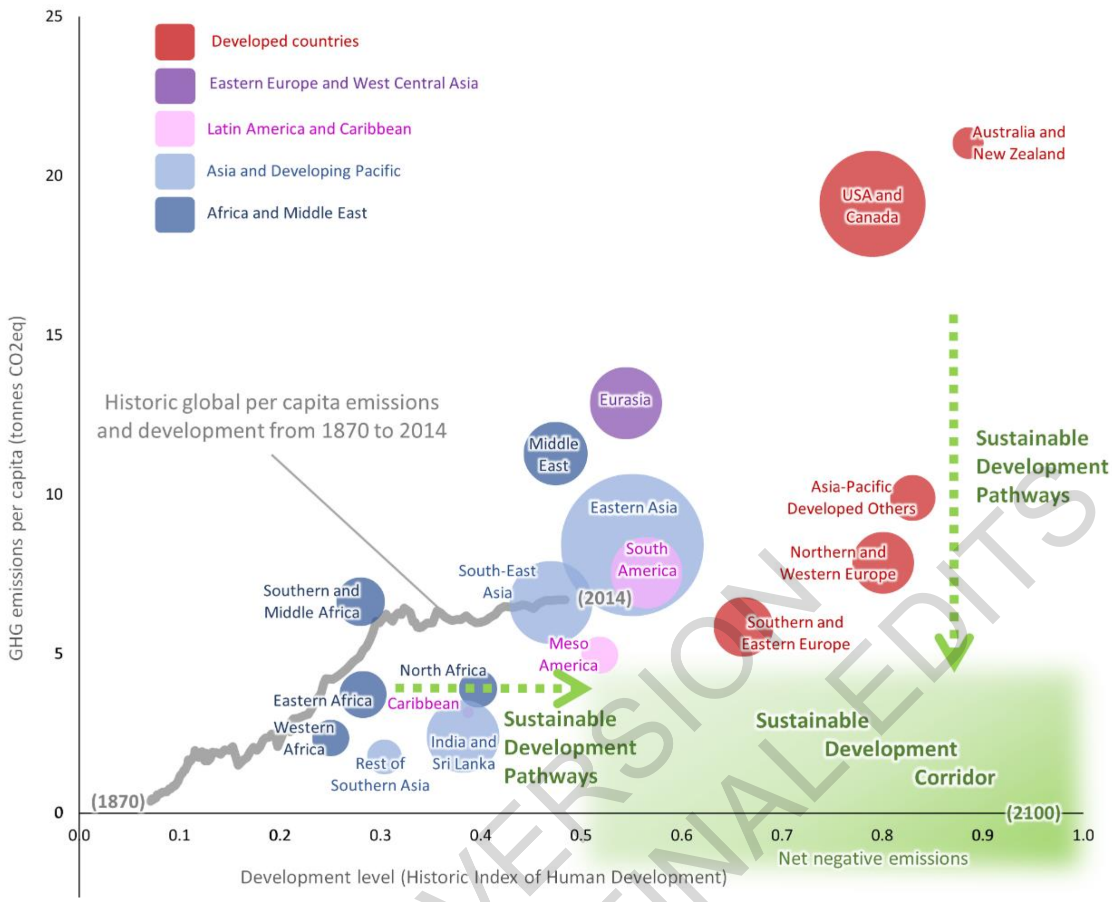


Figure TS.1: Sustainable development pathways towards fulfilling the Sustainable Development Goals

Figure TS.1 legend: The graph shows how global average per capita GHG emissions (vertical axis) and relative "Historic Index of Human Development" (HIHD) levels (horizonal axis) have increased globally since the industrial revolution (grey line). The bubbles on the graph show regional per capita GHG emissions and human development levels in the year 2015, illustrating large disparities. Pathways towards fulfilling the Paris Agreement and SDG 13 (Climate Action) involve global average per capita GHG emissions below around 5 tCO_2eq by 2030. Likewise, HIHD levels need to be at least 0.5 or greater to fulfil SDGs 3 (Good Health & Well-being), SDG 4 (Quality Education) and SDG 8 (Decent Work & Economic Growth). This suggests a 'sustainable development zone' for year 2030 (in green); the in-figure text also suggests a *sustainable development corridor*, where countries limit per capita GHG emissions while improving levels of human development over time. The emphasis of pathways into the sustainable development zone differ (green arrows) but in each case transformations are needed in how human development is attained while limiting GHG emissions. {Figure 1.6}

The transition to a low carbon economy depends on a wide range of closely intertwined drivers and constraints, including policies and technologies where notable advances over the past decade have opened up new and large-scale opportunities for deep decarbonisation, and for alternative development pathways which could deliver multiple social and developmental goals (*high confidence*). Drivers for-, and constraints on-, low carbon societal transitions comprise *economic and technological* factors (the means by which services such as food, heating and shelter are provided and for whom, the emissions intensity of traded products, finance and investment), *socio-political issues* (political economy, equity and fairness, social innovation and behaviour change), and *institutional factors* (legal framework and institutions, and the quality of international cooperation). In addition to being deeply intertwined, all the factors matter to varying degrees, depending on prevailing social, economic, cultural and political context. They often both drive and inhibit transitions at the same time, within and across different scales. The development and deployment of innovative technologies and systems at scale are important for achieving deep decarbonisation, and in recent years, the cost of several low carbon technologies has declined sharply as deployment has risen rapidly. (Figure TS.7) {1.3, 1.4, Chapters 2, 4, 5, 13,14}

Accelerating mitigation to prevent dangerous anthropogenic interference with the climate system will require the integration of broadened assessment frameworks and tools that combine multiple perspectives, applied in a context of multi-level governance (*high confidence*). Analysing a challenge on the scale of fully decarbonising our economies entails integration of multiple analytic frameworks. Approaches to risk assessment and resilience, established across IPCC Working Groups, are complemented by frameworks for probing the challenges in implementing mitigation. *Aggregate frameworks* include cost-effectiveness analysis towards given objectives, and cost-benefit analysis, both of which have been developing to take fuller account of advances in understanding risks and innovation, the dynamics of sectors and systems and of climate impacts, and welfare economic theory including growing consensus on long-term discounting. *Ethical frameworks* consider the fairness of processes and outcomes which can help ameliorate distributional impacts across income groups, countries and generations. *Transition and transformation frameworks* explain and evaluate the dynamics of transitions to low-carbon systems arising from interactions amongst levels. *Psychological, behavioural and political frameworks* outline the constraints (and opportunities) arising from human psychology and the power of incumbent interests. A comprehensive understanding of climate mitigation must combine these multiple frameworks. Together with established risk frameworks, these collectively help to explain potential synergies and trade-offs in mitigation, implying a need for a wide portfolio of policies attuned to different actors and levels of decision-making, and underpin 'just transition' strategies in diverse contexts. {1.2.2, 1.7, 1.8, Figure 1.7}

The speed, direction, and depth of any transition will be determined by choices in the environmental, technological, economic, socio-cultural and institutional realms (*high confidence*). Transitions in specific systems can be gradual or can be rapid and disruptive. The pace of a transition can be impeded by 'lock-in' generated by existing physical capital, institutions, and social norms. The interaction between politics, economics and power relationships is central to explaining why broad commitments do not always translate to urgent action. At the same time, attention to, and support for, climate policies and low carbon societal transitions has generally increased, as the impacts have become more salient. Both public and private financing and financial structures strongly affect the scale and balance of high and low carbon investments. Societal and behavioural norms, regulations and institutions are essential conditions to accelerate low carbon transitions in multiple sectors, whilst addressing distributional concerns endemic to any major transition. The COVID-19 pandemic has also had far-reaching impacts on the global economic and social system, and recovery will present both challenges and opportunities for climate mitigation. (Box TS.1){1.3, Box 1.1, 1.4, 1.8, Chapters 2, 3, 4, 5, 15, 17}

Achieving the global transition to a low-carbon, climate-resilient and sustainable world requires purposeful and increasingly coordinated planning and decisions at many scales of governance including local, subnational, national and global levels (*high confidence*). Accelerating mitigation globally would imply strengthening policies adopted to date, expanding the effort across options, sectors, and countries, and broadening responses to include more diverse actors and societal processes at multiple – including international – levels. The effective governance of climate change entails strong action across multiple jurisdictions and decision-making levels, including regular evaluation and learning. Choices that cause climate change as well as the processes for making and implementing relevant decisions involve a range of non-nation state actors such as cities, businesses, and civil society organisations. At global, national and subnational levels, climate change actions are interwoven with, and embedded in, the context of much broader social, economic and political goals. Therefore, the governance required to address climate change has to navigate power, political, economic, and social dynamics at all levels of decision making. Effective climate-governing institutions, and openness to experimentation on a variety of institutional arrangements, policies and programmes can play a vital role in engaging stakeholders and building momentum for effective climate action. {1.4, 1.9, Chapters 8, 13, 15, 17}

GHG emissions continued to rise to 2019, although the growth of global GHG emissions has slowed over the past decade *(high confidence)*. Delivering the updated Nationally Determined Contributions (NDCs) to 2030 would turn this into decline, but the implied global emissions by 2030, still exceed pathways consistent with 1.5°C by a large margin and are near the upper end of the range of modelled pathways that *likely* limit warming to 2°C or below. In all chapters of this report there is evidence of progress towards deeper mitigation, but there remain many obstacles to be overcome. Table TS.1 summarises some of the key signs of progress in emission trends, sectors, policies and investment, as well as the challenges that persist.

Table TS.1: Signs of Progress and Continuing Challenges

Signs of progress	**Continuing challenges**
Emissions trends	
The rate of global GHG emissions growth has slowed in recent years, from 2.1% per year between 2000 and 2009, to 1.3% per year in between 2010 and 2019. (TS.3) {2.2}	**GHG emissions have continued to grow at high absolute rates**. Emissions increased by 8.9 $GtCO_2eq$ from 2000-2009 and by 6.5 $GtCO_2eq$ 2010-2019, reaching 59 $GtCO_2eq$ in 2019. (TS.3) {2.2}
At least 24 countries have reduced both territorial carbon dioxide (CO_2) and GHG emissions and consumption-based CO_2 emissions in absolute terms for at least 10 years, including consumption-based CO_2 emissions. Of these, six are Western and Northern European countries that started reducing in the 1970s, six are former Eastern Bloc countries with consistent reductions since the 1990s, and 12 more have reduced since the mid-2000s. Some have done so at rapid sustained CO_2 reduction rates of 4% per year. (TS.3) {2.2}	**The combined emissions reductions of these 24 countries were outweighed by rapid emissions growth elsewhere**, particularly among developing countries that have grown from a much lower base of per capita emissions. Uncertainties in emissions levels and changes over time prevents a precise assessment of reductions in some cases. The per capita emissions of developed countries remain high, particularly in Australia, Canada, and the United States. {2.2}
Lockdown policies in response to COVID-19 led to an estimated global drop of 5.8% in CO_2 emissions in 2020 relative to 2019. Energy demand reduction occurred across sectors, except in residential buildings due to teleworking and homeschooling. The transport sector was particularly impacted and international aviation emissions declined by 45%. (Box TS.1) {2.2}	**Atmospheric CO_2 concentrations continued to rise in 2020 and emissions have already rebounded as lockdown policies are eased.** Economic recovery packages currently include support for fossil fuel industries. (Box TS.1; Box TS.8)
Sectors	
Multiple low-carbon electricity generation and storage technologies have made rapid progress: costs have reduced, deployment has scaled up, and performance has improved. These include solar photovoltaics (PV), onshore and offshore wind, and batteries. In many contexts solar PV and onshore wind power are now competitive with fossil-based generation. (TS.3) {2.5, 6.3}	**Although deployment is increasing rapidly, low-carbon electricity generation deployment levels and rates are currently insufficient to meet stringent climate goals.** The combined market share of solar PV and wind generation technologies are still below 10%. Global low-carbon electricity generation will have to reach 100% by 2050, which is challenged by the continuous global increase in electricity demand. The contribution of biomass has absolute limits. (TS.5, 2.5)
The rate of emissions growth from coal slowed since 2010 as coal power plants were retired in the United States and Europe, fewer new plants were added in China,	**Global coal emissions may not have peaked yet**, and a few countries and international development banks continue to fund and develop new coal capacity,

Signs of progress	**Continuing challenges**
and a large number of planned global plants were scrapped or converted to co-firing with biomass. (TS.3) {2.7, 6.3}	especially abroad. The lifetime emissions of current fossil-based energy infrastructures may already exceed the remaining carbon budget for keeping warming below 1.5°C. (TS.3) {2.2; 2.7, 6.7}
Deforestation has declined since 2010 and net forest cover increased. Government initiatives and international moratoria were successful in reducing deforestation in the Amazon between 2004 and 2015, while regrowth and regeneration occurred in Europe, Eurasia and North America. (TS.5.6.1) {7.3.1}	**The long-term maintenance of low deforestation rates is challenging.** Deforestation in the Amazon has risen again over the past four years. Other parts of the world also face steady, or rapidly increasing, deforestation. {7.3.1**}**
Electrification of public transport services is demonstrated as a feasible, scalable and affordable mitigation option to decarbonise mass transportation. Electric vehicles (e-vehicles) **are the fastest growing segment of the automobile industry, having achieved double-digit market share by 2020 in many countries.** When charged with low-carbon electricity, these vehicles can significantly reduce emissions. {10.4}	**Transport emissions have remained roughly constant, growing at an average of 2% per annum between 2010-2019** due to the persistence of high travel demand, heavier vehicles, low efficiencies, and car-centric development. The full decarbonisation of e-vehicles requires that they are charged with zero-carbon electricity, and that car production, shipping, aviation and supply chains are decarbonized. (TS.3) {2.4}
There has been a significant global transition from coal and biomass use in buildings towards modern energy carriers and efficient conversion technologies. This led to efficiency improvements and some emissions reductions in developed countries, as well as significant gains in health and well-being outcomes in developing regions. Nearly Zero Energy (NZE) Buildings or low-energy Buildings are achievable in all regions and climate zones for both new and existing buildings. {9.3; 9.8}	**There is a significant lock-in risk in all regions given the long lifespans of buildings and the low ambition of building policies.** This is the case for both existing buildings in developed countries, and also for new buildings in developing countries that are also challenged by the lack of technical capacity and effective governance. Emissions reductions in developed countries have been outweighed by the increase in population growth, floor area per capita and the demand for electricity and heat. {9.9; 9.3}
The decarbonisation of most industrial processes has been demonstrated using technologies that include electricity and hydrogen for energy and feedstocks, carbon capture and utilisation technologies, and innovation in circular material flows. (TS.5.5) {11.2}	**Industry emissions continue to increase, driven by a strong global demand for basic materials.** Without reductions in material demand growth and a very rapid scale-up of low-carbon innovations, the long lifetimes of industrial capital stock risks locking-in emissions for decades to come. (TS.5.5) {11.2}
Policies and investment	

Signs of progress	Continuing challenges
The Paris Agreement established a new global policy architecture to meet stringent climate goals, while avoiding many areas of deadlock that had arisen in trying to extend the Kyoto Protocol**.** (TS 6.3)	**Current national pledges under the Paris Agreement[3] are insufficient to limit warming to 1.5°C with no or limited overshoot, and would require an abrupt acceleration of mitigation efforts after 2030 to *likely* limit warming to 2°C.** (TS 6.3)
Most wealthy countries, and a growing list of developing countries, have signaled an intention to achieve net zero GHG (or net zero CO_2) emissions by mid-century. National economy-wide GHG emissions targets covered 90% of global emissions in 2020 compared to 49% in 2010. Direct and indirect climate legislation has also steadily increased and this is supported by a growing list of financial investors. (TS.6.2)	**Many net zero targets are ambiguously defined, and the policies needed to achieve them are not yet in place.** Opposition from status quo interests, as well as insufficient low-carbon financial flows, act as barriers to establishing and implementing stringent climate policies covering all sectors. (Box TS.6) {13.4}
The global coverage of mandatory policies – pricing and regulation – has increased, and sectoral coverage of mitigation policies has expanded. Emission trading and carbon taxes now cover over 20% of global CO_2 emissions (TS 6). Allowance prices as of April 1, 2021 ranged from just over USD1 to USD50, covering between 9 and 80% of a jurisdiction's emissions {13.6.3}. Many countries have introduced sectoral regulations that block new investment in fossil fuel technologies.	**There is incomplete global policy coverage of non-CO_2 gases, CO_2 from industrial processes, and emissions outside the energy sector**. Few of the world's carbon prices are at a level consistent with various estimates of the carbon price needed to limit warming to 2°C or 1.5°C {13.6}
There has been a marked increase in civic and private engagement with climate governance. This includes business measures to limit emissions, invest in reforestation and develop carbon-neutral value chains such as using wood for construction. There is an upsurge in climate activism, and growing engagement of groups such as labour unions {1.3.3, 5.2.3}. The media coverage of climate change has also grown steadily across platforms and has generally become more accurate over time. (TS 6.2)	**There is no conclusive evidence that an increase in engagement results in overall pro-mitigation outcomes**. A broad group of actors influence how climate governance develop over time, including a range of civic organisations, encompassing both pro-and anti-climate action groups. Accurate transference of the climate science has been undermined significantly by climate change counter-movements, in both legacy and new/social media environments through misinformation. (TS 6.2)

FOOTNOTE [3] Current NDCs refer to nationally determined contributions submitted to the UNFCCC, as well as publicly announced but not yet submitted mitigation pledges with sufficient detail on targets, reflected in studies published up to 11 October 2021. Revised NDCs submitted or announced after 11 October 2021 are not included. Intended nationally determined contributions (INDCs) were converted to NDCs as countries ratified the Paris Agreement. Original INDCs and NDCs refer to those submitted to the UNFCCC in 2015 and 2016

TS. 3 Emission trends and drivers

Global net anthropogenic GHG emissions during the decade (2010-2019) were higher than any previous time in human history *(high confidence)*. Since 2010, GHG emissions have continued to grow reaching 59±6.6 $GtCO_2$-eq in 2019,[4] but the average annual growth in the last decade (1.3%, 2010-2019) was lower than in the previous decade (2.1%, 2000-2009) (*high confidence*). Average annual GHG emissions were 56 $GtCO_2$-eq yr^{-1} for 2010-2019 (the highest decadal average on record) growing by about 9.1 $GtCO_2$-eq yr^{-1} from the previous decade (2000-2009) (*high confidence*). (Figure TS.2) {2.2.2, Table 2.1, Figure 2.5}

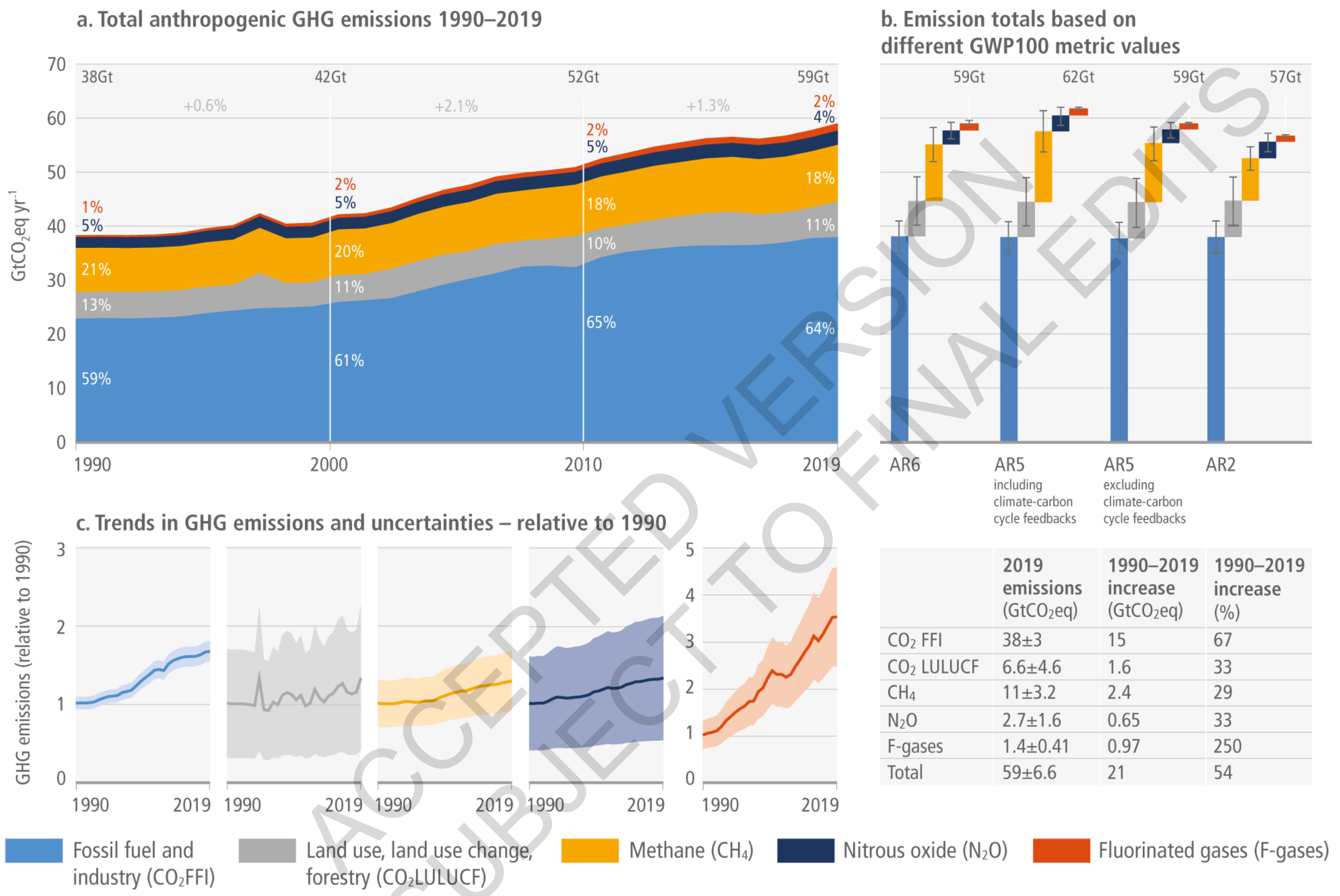
Emissions growth has varied, but has persisted, across all groups of greenhouse gases *(high confidence)*. The average annual emission levels of the last decade (2010-2019) were higher than in any previous decade for each group of greenhouse gases (*high confidence*). In 2019, CO_2 emissions were 45±5.5 $GtCO_2$,[5] methane (CH_4) 11±3.2 $GtCO_2$-eq, nitrous oxide (N_2O) 2.7±1.6 $GtCO_2$-eq and fluorinated gases (F-gases[6]) 1.4±0.41 $GtCO_2$-eq. Compared to 1990, the magnitude and speed of these increases differed across gases: CO_2 from fossil fuel and industry (FFI) grew by 15 $GtCO_2$-eq yr^{-1} (67%), CH_4 by 2.4 $GtCO_2$-eq yr^{-1} (29%), F-gases by 0.97 $GtCO_2$-eq yr^{-1} (250%), N_2O by 0.65 $GtCO_2$-eq yr^{-1} (33%). CO_2 emissions from net land use, land-use change and forestry (LULUCF) have shown little long-term change, with large uncertainties preventing the detection of statistically significant trends. F-gases excluded from GHG emissions inventories such as *chlorofluorocarbons* and *hydrochlorofluorocarbons* are about the same size as those included (*high confidence*). (Figure TS.2) {2.2.1, 2.2.2, Table 2.1, Figure 2.2, Figure 2.3, Figure 2.5}

Globally, Gross Domestic Product (GDP) per capita and population growth remained the strongest drivers of CO_2 emissions from fossil fuel combustion in the last decade (*high confidence*). Trends since 1990 continued in the years 2010 to 2019 with GDP per capita and population growth increasing emissions by 2.3% and 1.2% yr^{-1}, respectively. This growth outpaced the reduction in the use of energy per unit of GDP (-2% yr^{-1}, globally) as well as improvements in the carbon intensity of energy (-0.3% yr^{-1}). {2.4.1, Figure 2.19}

FOOTNOTE [4] Emissions of GHGs are weighed by Global Warming Potentials with a 100 year time horizon (GWP100) from the Sixth Assessment Report. GWP100 is commonly used in wide parts of the literature on climate change mitigation and is required for reporting emissions under the United Nations Framework Convention on Climate Change (UNFCCC). All metrics have limitations and uncertainties. {Cross-Chapter Box 2, Annex II Part II Section 8}

FOOTNOTE [5] In 2019, CO_2 from fossil fuel and industry (FFI) were 38±3.0 Gt, CO_2 from net land use, land-use change and forestry (LULUCF) 6.6±4.6 Gt.

FOOTNOTE [6] Fluorinated gases, also known as 'F-gases', include: hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluouride (SF_6), nitrogen trifluouride (NF_3).



	2019 emissions ($GtCO_2eq$)	1990–2019 increase ($GtCO_2eq$)	1990–2019 increase (%)
CO_2 FFI	38±3	15	67
CO_2 LULUCF	6.6±4.6	1.6	33
CH_4	11±3.2	2.4	29
N_2O	2.7±1.6	0.65	33
F-gases	1.4±0.41	0.97	250
Total	59±6.6	21	54

Figure TS.2: **Global anthropogenic emissions have continued to rise across all major groups of greenhouse gases ($GtCO_2$-eq yr^{-1}) 1990-2019**

Figure TS.2 Legend: Total anthropogenic GHG emissions include CO_2 from fossil fuel combustion and industrial processes (CO_2-FFI); CO_2 from Land use, land use change and forestry (CO_2-LULUCF); methane (CH_4); nitrous oxide (N_2O); fluorinated gases (F-gases: HFCs; PFCs, SF6, NF3). CO_2-LULUCF emissions include gross removals as well as emissions. F-gas emissions do not include some important species covered by the Montreal Protocol such as (chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs).

Panel a: Aggregate GHG emission trends by groups of gases reported in $GtCO_2$-eq converted based on global warming potentials with a 100-year time horizon (GWP100) from the IPCC Sixth Assessment Report Working Group I (Chapter 7).

Panel b: GHG emissions for the year 2019 in Gt of CO_2-eq units using GWP100 values from the IPCC's Sixth, Fifth and Second Assessment Reports, respectively. Error bars show emissions uncertainties at a 90% confidence interval.

Panel c: Individual trends in CO_2-FFI, CO_2-LULUCF, CH_4, N_2O and F-gas emissions for the period 1990–2019, normalised relative to 1 in 1990. Note the different scale for F-gas emissions compared to other gases, highlighting its rapid growth from a low base. The table shows absolute emissions in 2019 as well as emissions growth between 1990 and 2019, expressed as absolute change in CO_2-eq and as percentage change relative to 1990. Note that these changes therefore include interannual variability for these individual years as well as longer term trends. {2.2, Figure 2.5}

START BOX TS.1 HERE

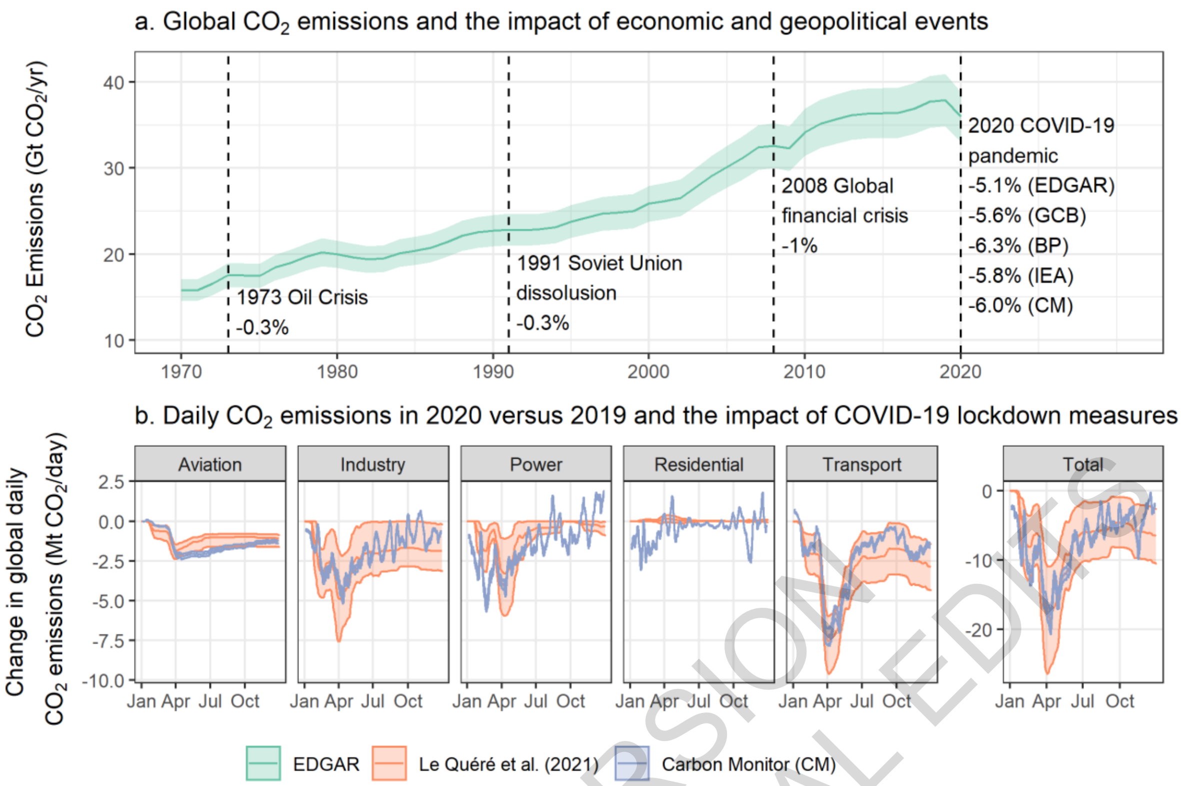
Box TS.1: The COVID-19 pandemic: Impact on emissions and opportunities for mitigation

The COVID-19 pandemic triggered the deepest global economic contraction as well as CO_2 emission reductions since the Second World War {2.2.2}. While emissions and most economies rebounded in 2020, some impacts of the pandemic could last well beyond this. Owing to the very recent nature of this event, it remains unclear what the exact short and long-term impacts on global emissions drivers, trends, macroeconomics and finance will be.

Starting in the spring of 2020 a major break in global emissions trends was observed due to lockdown policies implemented in response to the pandemic. Overall, global CO_2-FFI emissions are estimated to have declined by 5.8% (5.1%-6.3%) in 2020, or about 2.2 (1.9-2.4) $GtCO_2$ in total. This exceeds any previous global emissions decline since 1970 both in relative and absolute terms (Box TS.1 Figure 1). During periods of economic lockdown, daily emissions, estimated based on activity and power-generation data, declined substantially compared to 2019, particularly in April 2020 –as shown in Box TS.1 Figure 1 – but rebounded by the end of 2020. Impacts were differentiated by sector, with road transport and aviation particularly affected. Different databases estimate the total power sector CO_2 reduction from 2019 to 2020 at 3% (IEA[7]) and 4.5% (EDGAR[8]). Approaches that predict near real-time estimates of the power sector reduction are more uncertain and estimates range more widely between 1.8%, 4.1% and 6.8%, the latter taking into account the over-proportional reduction of coal generation due to low gas prices and merit order effects.

FOOTNOTE [7] IEA: International Energy Agency

FOOTNOTE [8] EDGAR: Emissions Database for Global Atmospheric Research



Box TS.1 Figure 1: Global carbon emissions in 2020 and the impact of COVID-19

Box TS.1 Figure 1 legend: Panel a depicts carbon emissions from fossil fuel and industry over the past five decades. The single year declines in emissions following major economic and geopolitical events are shown, as well as the decline recorded in five different datasets for emissions in 2020 compared to 2019. Panel b depicts the perturbation of daily carbon emissions in 2020 compared to 2019, showing the impact of COVID-19 lockdown policies. {Figure 2.6}

The lockdowns implemented in many countries accelerated some specific trends, such as the uptake in urban cycling. The acceptability of collective social change over a longer term towards less resource-intensive lifestyles, however, depends on the social mandate for change. This mandate can be built through public participation, discussion and debate, to produce recommendations that inform policymaking. {Box 5.2}

Most countries were forced to undertake unprecedented levels of short-term public expenditures in 2021. This is expected to slow economic growth and may squeeze financial resources for mitigation and relevant investments in the near future. Pandemic responses have increased sovereign debt across countries in all income bands and the sharp increase in most developing economies and regions has caused debt distress, widening the gap in developing countries' access to capital. {15.6.3}

The wider overall reduction in energy investment has prompted a relative shift towards low carbon investment particularly for major future investment decisions by the private sector {15.2.1, 15.3.1, 15.6.1}. Some countries and regions have prioritised green stimulus expenditures for example as part of a 'Green New Deal' {Box 13.1}. This is motivated by assessments that investing in new growth industries can boost the macroeconomic effectiveness ('multipliers') of public spending, crowd-in and revive private investment, whilst also delivering on mitigation commitments. {15.2.3}

The impacts of COVID-19 may have temporarily set back development and the delivery of many SDGs. It also distracts political and financial capacity away from efforts to accelerate climate change mitigation and shift development pathways to increased sustainability. Yet, studies of previous post-shock periods suggest that waves of innovation that are ready to emerge can be accelerated by crises, which may prompt new behaviours, weaken incumbent systems, and initiate rapid reform. {1.6.5}

Institutional change can be slow but major economic dislocation can create significant opportunities for new ways of financing and enabling 'leapfrogging' investment {10.8}. Given the unambiguous risks of climate change, and consequent stranded asset risks from new fossil fuel investments {Box 6.11}, the most robust recoveries may well be those which align with lower carbon and resilient development pathways.

END BOX TS.1 HERE

Cumulative net CO_2 emissions over the last decade (2010-2019) are about the same size as the remaining carbon budget *likely* to limit warming to 1.5°C *(medium confidence)*. 62% of total cumulative CO_2 emissions from 1850 to 2019 occurred since 1970 (1500±140 $GtCO_2$), about 43% since 1990 (1000±90 $GtCO_2$), and about 17% since 2010 (410±30 $GtCO_2$). For comparison, the remaining carbon budget for keeping warming to 1.5°C with a 67% (50%) probability is about 400 (500) ±220 $GtCO_2$ (Figure TS.3). {2.2.2, Figure 2.7, WG I Chapter 5.5, WG I Chapter 5 Table 5.8}

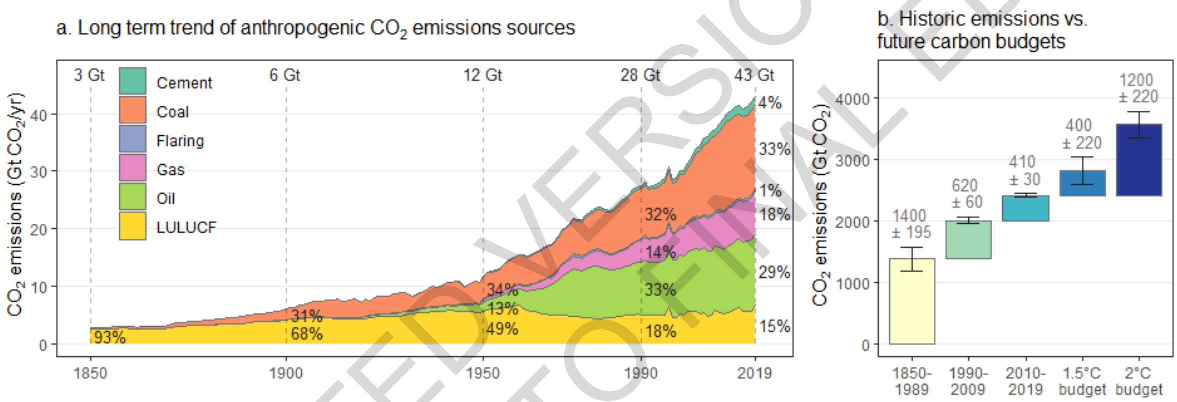


Figure TS.3: Historic anthropogenic CO_2 emission and cumulative CO_2 emissions (1850-2019) as well as remaining carbon budgets for *likely* limiting warming to 1.5°C and 2°C

Figure TS.3 legend: Panel a shows historic annual anthropogenic CO_2 emissions ($GtCO_2$ yr^{-1}) by fuel type and process. Panel b shows historic cumulative anthropogenic CO_2 emissions for the periods 1850-1989, 1990-2009, and 2010-2019 as well as remaining future carbon budgets as of 1 January 2020 to limit warming to 1.5°C and 2°C at the 67th percentile of the transient climate response to cumulative CO_2 emissions. The whiskers indicate a budget uncertainty of ±220 $GtCO_2$-eq for each budget and the aggregate uncertainty range at one standard deviation for historical cumulative CO_2 emissions, consistent with Working Group I. **{**Figure 2.7}

A growing number of countries have achieved GHG emission reductions over periods longer than 10 years – a few at rates that are broadly consistent with the global rates described in climate change mitigation scenarios that likely to limit warming to 2°C *(high confidence)*. At least 24 countries have reduced CO_2 and GHG emissions for longer than 10 years. Reduction rates in a few countries have reached 4% in some years, in line with global rates observed in pathways that *likely* limit warming to 2°C. However, the total reduction in annual GHG emissions of these countries is small (about 3.2 $GtCO_2$-eq yr^{-1}) compared to global emissions growth observed over the last decades. Complementary evidence suggests that countries have decoupled territorial CO_2 emissions from GDP, but fewer have decoupled consumption-based emissions from GDP. Decoupling has mostly occurred in countries with high per capita GDP and high per capita CO_2 emissions. (Figure TS.4, Box TS.2) {2.2.3, 2.3.3, Figure 2.11, Table 2.3, Table 2.4}

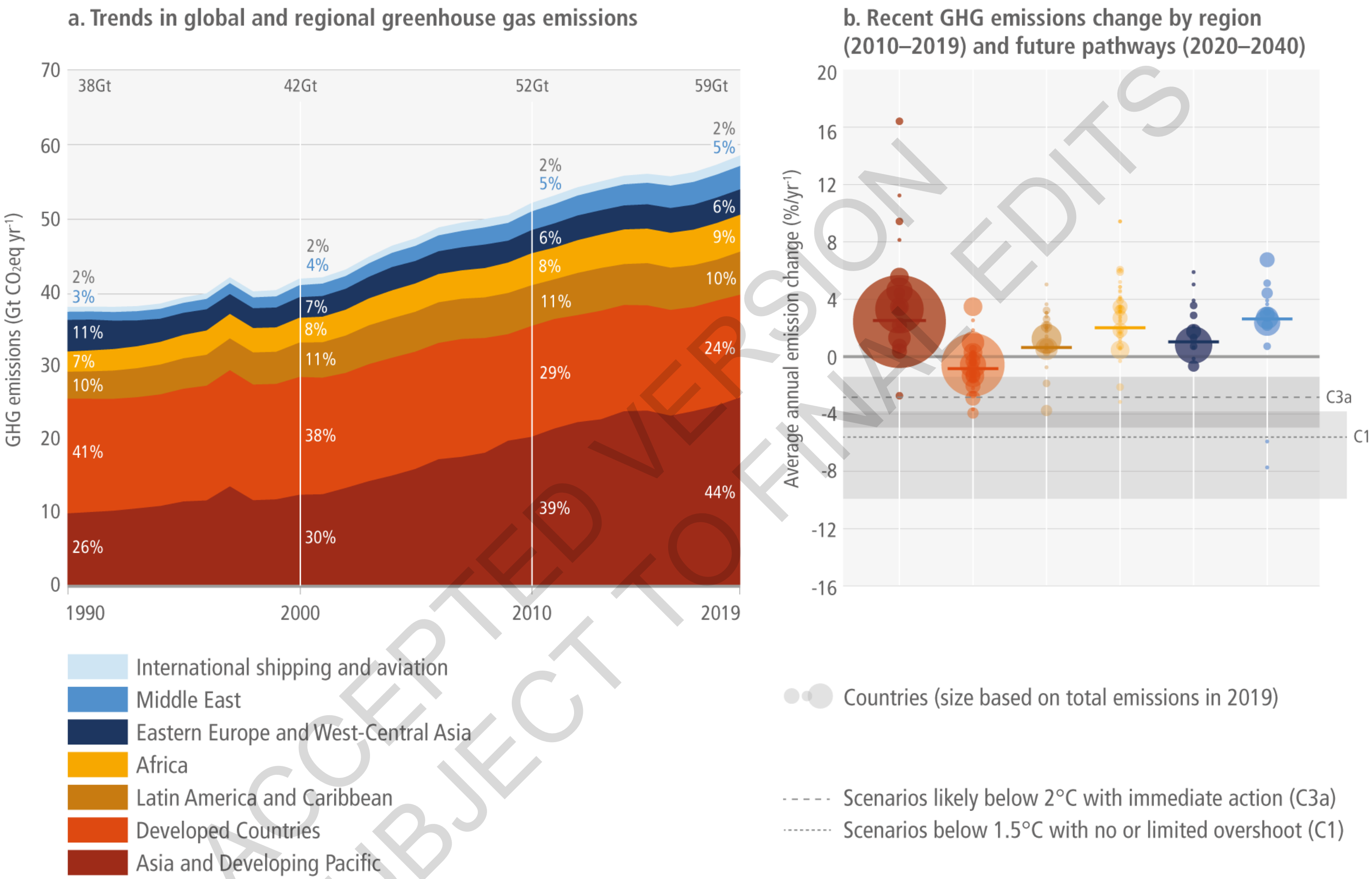


Figure TS.4: Emissions have grown in most regions, although some countries have achieved sustained emission reductions in line with 2 °C scenarios

Figure TS.4 legend: Change in regional GHG emissions and rates of change compatible with warming targets.

Panel a: Regional GHG emission trends (in $GtCO_2$-eq yr^{-1} (GWP100 AR6)) for the time period 1990–2019.

Panel b: Historical GHG emissions change by region (2010–2019). Circles depict countries, scaled by total emissions in 2019, short horizontal lines depict the average change by region. Also shown are global rates of reduction over the period 2020-2040 in scenarios assessed in the AR6 that limit global warming to 1.5°C and 2°C with different probabilities. The 5^{th}–95^{th} percentile range of emissions changes for scenarios below 1.5°C with no or limited overshoot (scenario category C1) and scenarios *likely* below 2°C with immediate action (scenario category C3a) are shown as a shaded area with a horizontal line at the mean value. Panel b excludes CO_2 LULUCF due to a lack of consistent historical national data, and International Shipping and Aviation, which cannot be allocated to regions. Global rates of reduction in scenarios are shown for illustrative purposes only and do not suggest rates of reduction at the regional or national level**.** {Figure 2.9, Figure 2.11}

START BOX TS.2 HERE

Box TS.2: GHG emission metrics provide simplified information about the effects of different greenhouse gases

Comprehensive mitigation policy relies on consideration of all anthropogenic forcing agents, which differ widely in their atmospheric lifetimes and impacts on the climate system. GHG emission metrics provide simplified information about the effect that emissions of different gases have on global temperature or other aspects of climate, usually expressed relative to the effect of emitting CO_2[‡]. This information can support choices about priorities, trade-offs and synergies in mitigation policies and emission targets for non-CO_2 gases relative to CO_2 as well as baskets of gases expressed in CO_2-eq.

The choice of metric can affect the timing and emphasis placed on reducing emissions of Short-Lived Climate Forcers (SLCFs) relative to CO_2 within multi-gas abatement strategies as well as the costs of such strategies. Different metric choices can also alter the time at which net zero GHG emissions are calculated to be reached for any given emissions scenario. A wide range of GHG emission metrics has been published in the scientific literature, which differ in terms of: (i) the key measure of climate change they consider, (ii) whether they consider climate outcomes for a specified point in time or integrated over a specified time horizon, (iii) the time horizon over which the metric is applied, (iv) whether they apply to a single emission pulse, to emissions sustained over a period of time, or to a combination of both, and (v) whether they consider the climate effect from an emission compared to the absence of that emission, or compared to a reference emissions level or climate state {Annex I}.

Parties to the Paris Agreement decided to report aggregated emissions and removals (expressed as CO_2-eq) based on the Global Warming Potential with a time horizon of 100 years (GWP100) using values from IPCC AR5 or from a subsequent IPCC report as agreed upon by the CMA[†], and to account for future nationally determined contributions (NDCs) in accordance with this approach. Parties may also report supplemental information on aggregate emissions and removals, expressed as CO_2-eq, using other GHG emission metrics assessed by the IPCC.

The WG III contribution to AR6 uses updated GWP100 values from AR6 WG I to report aggregate emissions and removals unless stated otherwise. These reflect updated scientific understanding of the response of the climate system to emissions of different gases and include a methodological update to incorporate climate-carbon cycle feedbacks associated with the emission of non-CO_2 gases (see Annex II Part II Section 8 for a list of GWP100 metric values). The choice of GWP100 was made inter alia for consistency with decisions under the Rulebook for the Paris Agreement and because it is the dominant metric used in the literature assessed by WG III. Furthermore, for mitigation pathways that *likely* limit global warming to 2°C or lower, using GWP100 to inform cost-effective abatement choices between gases would achieve such long-term temperature goals at close to least global cost within a few percent (*high confidence*).

However, GWP100 is not well suited to estimate the cumulative effect on climate from sustained SLCF emissions and the resulting warming at specific points in time. This is because the warming caused by an individual SLCF emission pulse is not permanent, and hence, unlike CO_2, the warming from successive SLCF emission pulses over multiple decades or centuries depends mostly on their ongoing rate of emissions rather than cumulative emissions. Recently developed step/pulse metrics such as the CGTP (Combined Global Temperature Change Potential) and GWP* (referred to as GWP-star and indicated by asterisk) recognise that a sustained increase/decrease in the rate of SLCF emissions has indeed a similar effect on global surface temperature as one-off emission/removal of CO_2. These metrics use this relationship to calculate the CO_2 emissions or removals that would result in roughly the same temperature change as a sustained change in the rate of SLCF emissions (CGTP) over a given time period, or as a varying time series of CH_4 emissions (GWP*). From a mitigation perspective, this makes these metrics well suited in principle to estimate the effect on the remaining carbon budget from more, or less, ambitious SLCF mitigation over multiple decades compared to a given reference scenario (*high confidence*). However, potential application in wider climate policy (e.g., to inform equitable and ambitious emission targets or to support sector-specific mitigation policies) is contested and relevant literature still limited.

All metrics have limitations and uncertainties, given that they simplify the complexity of the physical climate system and its response to past and future GHG emissions. For this reason, the WG III contribution to the AR6 reports emissions and mitigation options for individual gases where possible; CO_2-equivalent emissions are reported in addition to individual gas emissions where this is judged to be policy-relevant. This approach aims to reduce the ambiguity regarding actual climate outcomes over time arising from the use of any specific GHG emission metric. {Cross-Chapter Box 2 in Chapter 2, Supplementary Material 2.3, Annex II Part II Section 8; WG I Chapter 7.6}

[ǂ] *Emission metrics also exist for aerosols, but these are not commonly used in climate policy. This assessment focuses on GHG emission metrics only.*

[†] *The CMA is the Conference of the Parties serving as the Meeting of the Parties to the Paris Agreement. See 18/CMA.1 (Annex, para 37) and 4/CMA.1 (Annex II, para 1) regarding the use of GHG emission metrics in reporting of emissions and removals and accounting for Parties' NDCs.*

END BOX TS.2 HERE

Consumption-based CO_2 emissions in developed countries and the Asia and Developing Pacific region are higher than in other regions *(high confidence).* In developed countries, consumption-based CO_2 emissions peaked at 15 $GtCO_2$ in 2007, declining to about 13 $GtCO_2$ in 2018. The Asia and Developing Pacific region, with 52% of current global population, has become a major contributor to consumption-based CO_2 emission growth since 2000 (5.5% yr^{-1} for 2000-2018); in 2015 it exceeded the *developed countries* region, with 16% of global population, as the largest emitter of consumption-based CO_2. {2.3.2, Figure 2.14}

Carbon intensity improvements in the production of traded products has led to a net reduction in CO_2 emissions embodied in international trade (*high confidence*). A decrease in the carbon intensity of traded products has offset increased trade volumes between 2006 and 2016. Emissions embodied in internationally traded products depend on the composition of the global supply chain across sectors and countries and the respective carbon intensity of production processes (emissions per unit of economic output). {2.3, 2.4}

Developed countries tend to be net CO_2 emission importers, whereas developing countries tend to be net emission exporters (*high confidence*). Net CO_2 emission transfers from developing to developed countries via global supply chains have decreased between 2006 and 2016**.** Between 2004 and 2011, CO_2 emission embodied in trade between developing countries have more than doubled (from 0.47 to 1.1 Gt) with the centre of trade activities shifting from Europe to Asia. {2.3.4, Figure 2.15}

Territorial emissions from developing country regions continue to grow, mostly driven by increased consumption and investment, albeit starting from a low base of per capita emissions and with a lower historic contribution to cumulative emissions than developed countries (*high confidence*). Average 2019 per capita CO_2-FFI emissions in three developing regions Africa (1.2 tCO_2), Asia and developing Pacific (4.4 tCO_2), and Latin America and Caribbean (2.7 tCO_2) remained less than half of Developed Countries 2019 CO_2-FFI emissions (9.5 tCO_2). In these three developing regions together, CO_2-FFI emissions grew by 26% between 2010 and 2019 (compared to 260% between 1990 and 2010). In contrast, in Developed Countries emissions contracted by 9.9% between 2010-2019 and by 9.6% between 1990-2010. Historically, these three developing regions together contributed 28% to cumulative CO_2-FFI emissions between 1850 and 2019, whereas Developed Countries contributed 57%, and least developed countries contributed 0.4%. (Figure TS.5) {2.2, Figure 2.9, Figure 2.10}

Globally, households with income in the top 10% contribute about 36-45% of global GHG emissions *(robust evidence, medium agreement)*. About two thirds of the top 10% live in developed countries and one third in other economies. The lifestyle consumption emissions of the middle income and poorest citizens in emerging economies are between 5-50 times below their counterparts in high-income countries *(medium confidence)*. Increasing inequality within a country can exacerbate dilemmas of redistribution and social cohesion and affect the willingness of the rich and poor to accept policies to protect the environment, and to accept and afford lifestyle changes that favour mitigation *(medium confidence)*. {2.6.1, 2.6.2, Figure 2.29}

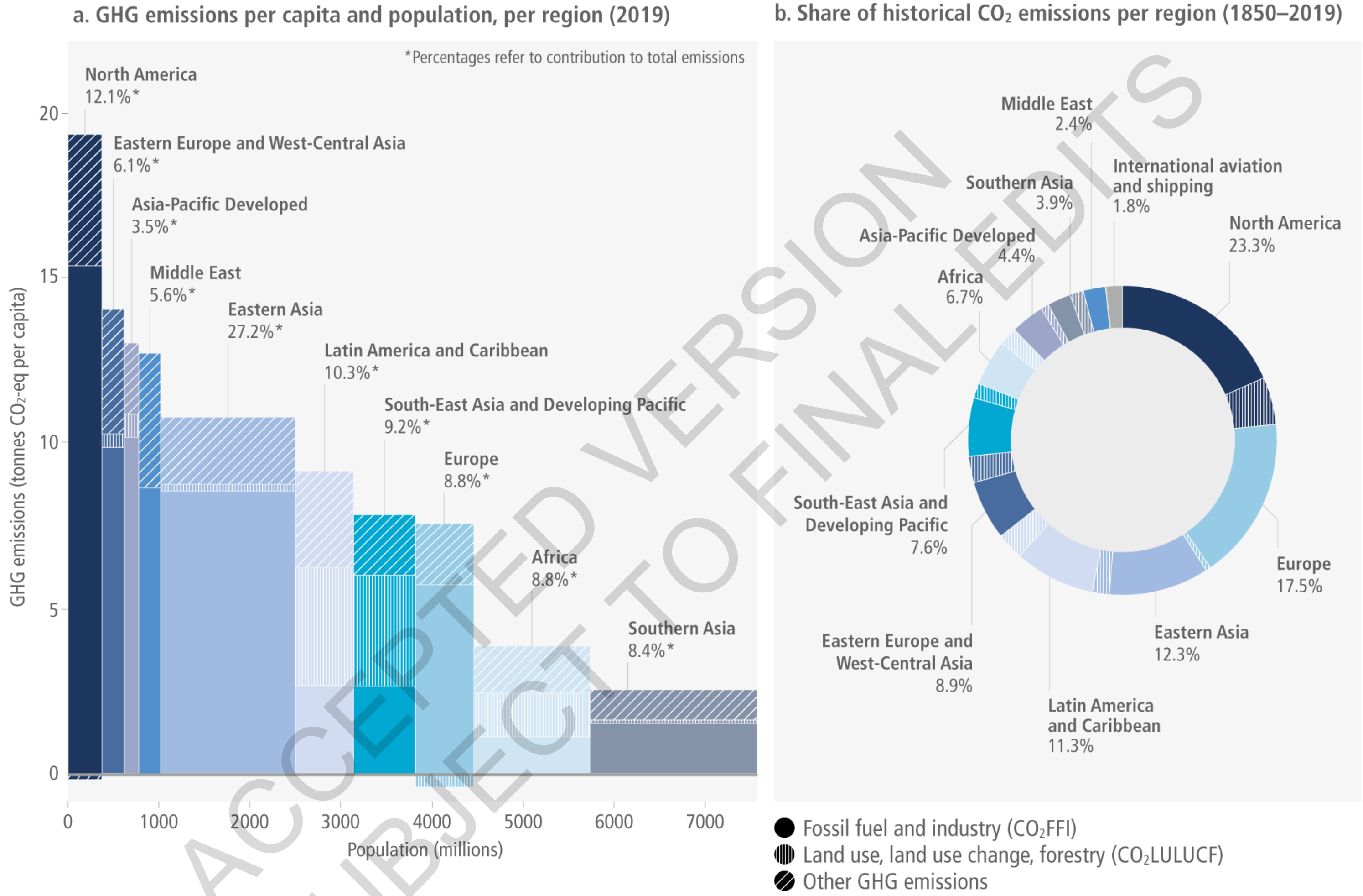


Figure TS.5: Global emissions are distributed unevenly, both in the present day and cumulatively since 1850

Figure TS.5 legend: Panel a shows the distribution of regional GHG emissions in tonnes CO_2-eq per capita by region in 2019. GHG emissions are categorised into: CO_2 Fossil fuel and industry (CO_2-FFI), CO_2 Land use, land use change, forestry (CO_2-LULUCF) and other GHG emissions (CH_4, nitrous oxide, F-gas, expressed in CO_2-eq using GWP100). The height of each rectangle shows per-capita emissions, the width shows the population of the region, so that the area of the rectangles refers to the total emissions for each regional. Percentages refer to overall GHG contributions to total global emissions in 2019. Emissions from international aviation and shipping are not included.
Panel b shows the share of historical net CO_2 emissions per region from 1850 to 2019. This includes CO_2-FFI and CO_2-LULUCF ($GtCO_2$). Other GHG emissions are not included. Emissions from international aviation and shipping are included. {1.3, Figure 1.2a, 2.2, Figure 2.10}

Globally, GHG emissions continued to rise across all sectors and subsectors, and most rapidly in transport and industry (*high confidence*). In 2019, 34% (20 $GtCO_2$-eq) of global GHG emissions came from the energy sector, 24% (14 $GtCO_2$-eq) from industry, 22% (13 $GtCO_2$-eq) from agriculture, forestry and other land use (AFOLU), 15% (8.7 $GtCO_2$-eq) from transport, and 5.6% (3.3 $GtCO_2$-eq) from buildings. Once indirect emissions from energy use are considered, the relative shares of industry and buildings emissions rise to 34% and 17%, respectively. Average annual GHG emissions growth during 2010-2019 slowed compared to the previous decade in energy supply (from 2.3% to 1.0%) and industry (from 3.4% to 1.4%, direct emissions only), but remained roughly constant at about 2% per year in the transport sector *(high confidence)*. Emission growth in AFOLU is more uncertain due to the high share of CO_2-LULUCF emissions. (Figure TS.8) {2.2.4, Figures 2.13, Figures 2.16-2.21}

There is a discrepancy, equating to 5.5 $GtCO_2$ yr^{-1}, between alternative methods of accounting for anthropogenic land CO_2 fluxes. Accounting for this discrepancy would assist in assessing collective progress in a global stocktake (*high confidence*). The principal accounting approaches are National GHG inventories (NGHGI) and global modelling[9] approaches. NGHGI, based on IPCC guidelines, consider a much larger area of forest to be under human management than global models. NGHGI consider the fluxes due to human-induced environmental change on this area to be anthropogenic and are thus reported. Global models, in contrast, consider these fluxes to be natural and are excluded from the total reported anthropogenic land CO_2 flux. The accounting method used will affect the assessment of collective progress in a global stocktake {Cross-Chapter Box 6 in Chapter 7} (*medium confidence*). In the absence of these adjustments, allowing a like with like comparison, collective progress would appear better than it is. {7.2}

This accounting discrepancy also applies to Integrated Assessment Models (IAMs), with the consequence that anthropogenic land CO_2 fluxes reported in IAM pathways cannot be compared directly with those reported in national GHG inventories (*high confidence*). Methodologies enabling a more like-for-like comparison between models' and countries' approaches would support more accurate assessment of the collective progress achieved under the Paris Agreement. {3.4, 7.2.2}

Average annual growth in GHG emissions from energy supply decreased from 2.3% for 2000–2009 to 1.0% for 2010–2019 (*high confidence*). This slowing of growth is attributable to further improvements in energy efficiency and reductions in the carbon intensity of energy supply driven by fuel switching from coal to gas, reduced expansion of coal capacity, particularly in Eastern Asia, and the increased use of renewables (*medium confidence*). (Figure TS.6) {2.2.4, 2.4.2.1, Figure 2.17}

The industry, buildings and transport sectors make up 44% of global GHG emissions, or 66% when the emissions from electricity and heat production are reallocated as *indirect emissions* (*high confidence*). This reallocation makes a substantial difference to overall industry and buildings

FOOTNOTE [9] Bookkeeping models and dynamic global vegetation models emissions as shown in Figure TS.6. Industry, buildings, and transport emissions are driven, respectively, by the large rise in demand for basic materials and manufactured products, a global trend of increasing floor space per capita, building energy service use, travel distances, and vehicle size and weight. Between 2010-2019, aviation grew particularly fast on average at ~3.3% per annum. Globally, energy efficiency has have improved in all three demand sectors, but carbon intensities have not. (Figure TS.6) {2.2.4, Figure 2.18, Figure 2.19, Figure 2.20}

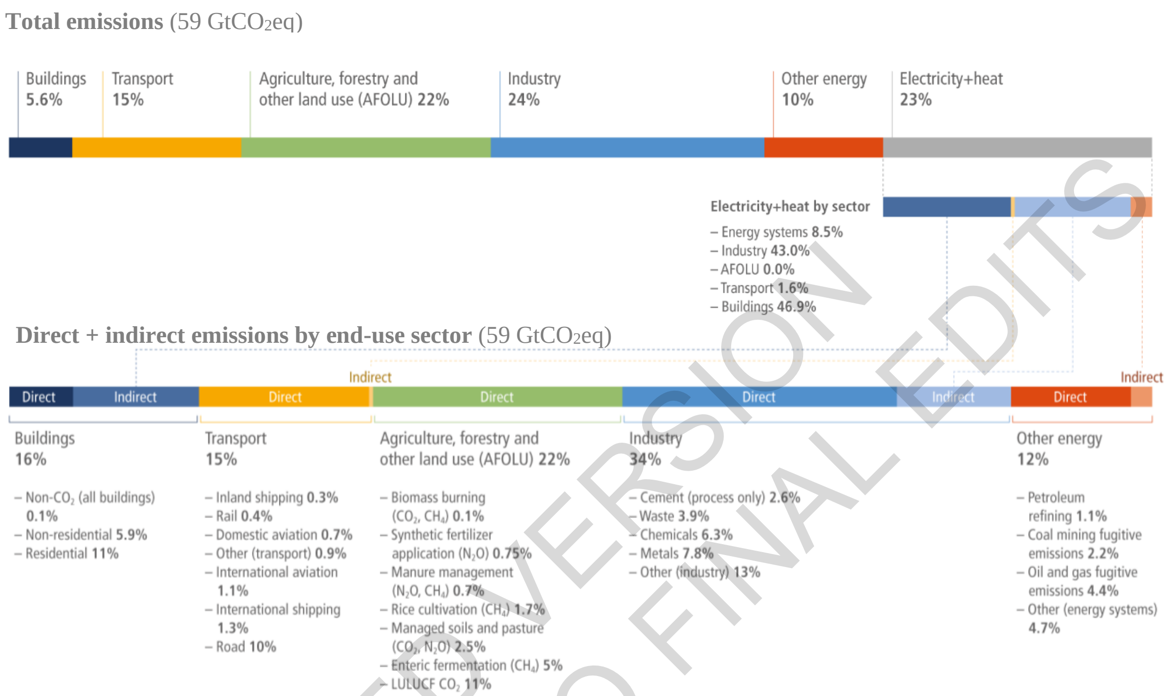


Figure TS.6: Total anthropogenic direct and indirect GHG emissions for the year 2019 (in $GtCO_2eq$) by sector and sub-sector

Figure TS.6 legend: Direct emissions estimates assign emissions to the sector in which they arise (scope 1 reporting). Indirect emissions – as used here - refer to the reallocation of emissions from electricity and heat to the sector of final use (scope 2 reporting). Note that cement refers to process emissions only, as a lack of data prevents the full reallocation of indirect emissions to this sector. More comprehensive conceptualisations of indirect emissions including all products and services (scope 3 reporting) are discussed in Chapter 2 section 2.3. Emissions are converted into CO_2-equivalents based on global warming potentials with a 100-year time horizon (GWP100) from the IPCC Sixth Assessment Report. Percentages may not add up to 100 across categories due to rounding at the second significant digit. {Figure 2.12, 2.3}

Providing access to modern energy services universally would increase global GHG emissions by a few percent at most (*high confidence*). The additional energy demand needed to support *decent living standards*[10] for all is estimated to be well below current average energy consumption (*medium evidence, high agreement*). More equitable income distribution could also reduce carbon emissions, but

FOOTNOTE [10] Decent Living Standards (DLS) – a benchmark of material conditions for human well-being – overlaps with many Sustainable Development Goals (SDGs). Minimum requirements of energy use consistent with enabling well-being for all is between 20 and 50 GJ cap-1 yr-1 23 depending on the context. (Figure TS.22) {5.2.2, 5.2.2, Box 5.3} the nature of this relationship can vary by level of income and development (*limited evidence, medium agreement*). {2.4.3}

Evidence of rapid energy transitions exists in some case studies *(medium confidence)*. Emerging evidence since AR5 on past energy transitions identifies a growing number of cases of accelerated technology diffusion at sub-global scales and describes mechanisms by which future energy transitions may occur more quickly than those in the past. Important drivers include technology transfer and cooperation, international policy and financial support, and harnessing synergies among technologies within a sustainable energy system perspective *(medium confidence)*. A fast global low-carbon energy transition enabled by finance to facilitate low-carbon technology adoption in developing and particularly in least developed countries can facilitate achieving climate stabilisation targets (*high confidence*). {2.5.2, Table 2.5}

Multiple low-carbon technologies have shown rapid progress since AR5 – in cost, performance, and adoption – enhancing the feasibility of rapid energy transitions (*high confidence*). The rapid deployment and unit cost decrease of modular technologies like solar, wind, and batteries have occurred much faster than anticipated by experts and modelled in previous mitigation scenarios, as shown in Figure TS.7 (*high confidence*). The political, economic, social, and technical feasibility of solar energy, wind energy and electricity storage technologies has improved dramatically over the past few years. In contrast, the adoption of nuclear energy and CO_2 capture and storage (CCS) in the electricity sector has been slower than the growth rates anticipated in stabilisation scenarios. Emerging evidence since AR5 indicates that small-scale technologies (e.g., solar, batteries) tend to improve faster and be adopted more quickly than large-scale technologies (nuclear, CCS) *(medium confidence)*. (Figure TS.7, Box TS.15) {2.5.3, 2.5.4, Figure 2.22, Figure 2.23}

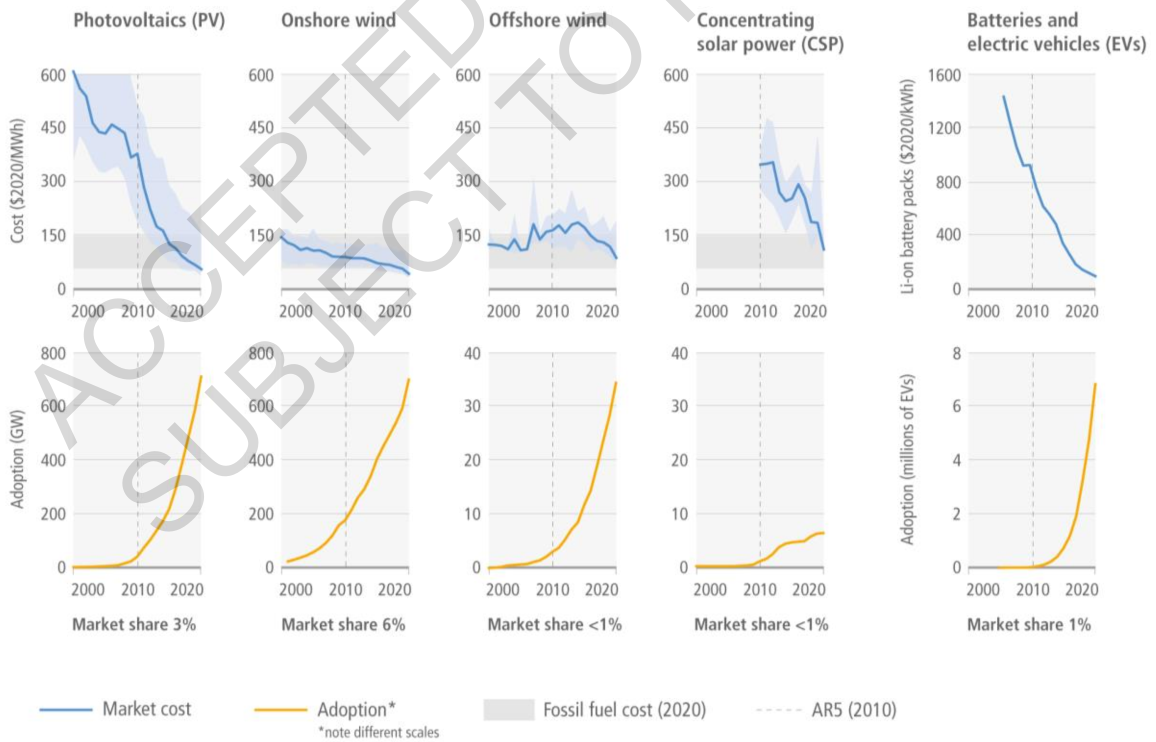


Figure TS.7: The unit costs of batteries and some forms of renewable energy have fallen significantly, and their adoption continues to increase

Figure TS.7 legend: The upper panel shows levelised costs of electricity (LCOE) for rapidly changing mitigation technologies. Solid blue lines indicate average market cost in each year. Light blue shaded areas show the range between the 5th and 95th percentiles in each year. Grey shading indicates the range of fossil fuel (coal and gas) LCOE in 2020 (corresponding to USD55-148 per MWh). LCOE allows consistent comparisons of cost trends across a diverse set of energy technologies to be made; it does not include environmental externalities and does not reflect variation in the value of electricity over time and space (see Chapter 6).

The lower panel shows cumulative global adoption for each technology, in GW of installed capacity for renewable energy and in millions of vehicles for electric vehicles. A vertical dashed line is placed in 2010 to indicate change since AR5. The market share percentages shown are the 2020 shares based on provisional data, i.e., percentage of total electricity production (for PV, Onshore wind, Offshore wind, concentrating solar power (CSP)) and of passenger total vehicles (for electric vehicles). The electricity market share is generally lower than the share of production capacity given lower capacity factors for these renewable technologies. {2.5, 6.4}

Robust incentives for investment in innovation, especially incentives reinforced by national policy and international agreements, are central to accelerating low-carbon technological change *(robust evidence, medium agreement)*. Policies have driven innovation, including instruments for technology push (e.g., scientific training, research and development (R&D)) and demand pull (e.g., carbon pricing, adoption subsidies), as well as those promoting knowledge flows and especially technology transfer. The magnitude of the scale-up challenge elevates the importance of rapid technology development and adoption. This includes ensuring participation of developing countries in an enhanced global flow of knowledge, skills, experience, equipment, and technology itself requires strong financial, institutional, and capacity building support. {2.5.4, 2.5, 2.8}

Estimates of future CO_2 emissions from existing fossil fuel infrastructures already exceed remaining cumulative net CO_2 emissions in pathways limiting warming to 1.5°C with no or limited overshoot (*high confidence*). Assuming variations in historic patterns of use and decommissioning, estimated future CO_2 emissions from existing fossil fuel infrastructure alone are 660 (460-890) $GtCO_2$ and from existing and currently planned infrastructure 850 (600-1100) $GtCO_2$. This compares to overall cumulative net CO_2 emissions until reaching net zero CO_2 of 510 (330-710) $GtCO_2$ in pathways that limit warming to 1.5°C with no or limited overshoot, and 890 (640-1160) $GtCO_2$ in pathways that *likely* limit warming to 2°C (*high confidence*). While most future CO_2 emissions from existing and currently planned fossil fuel infrastructure are situated in the power sector, most remaining fossil fuel CO_2 emissions in pathways that *likely* limit warming to 2°C and below are from non-electric energy – most importantly from the industry and transportation sectors (*high confidence*). Decommissioning and reduced utilisation of existing fossil fuel installations in the power sector as well as cancellation of new installations are required to align future CO_2 emissions from the power sector with projections in these pathways (*high confidence*). (Figure TS.8) {2.7.2, 2.7.3, Figure 2.26, Table 2.6, Table 2.7}

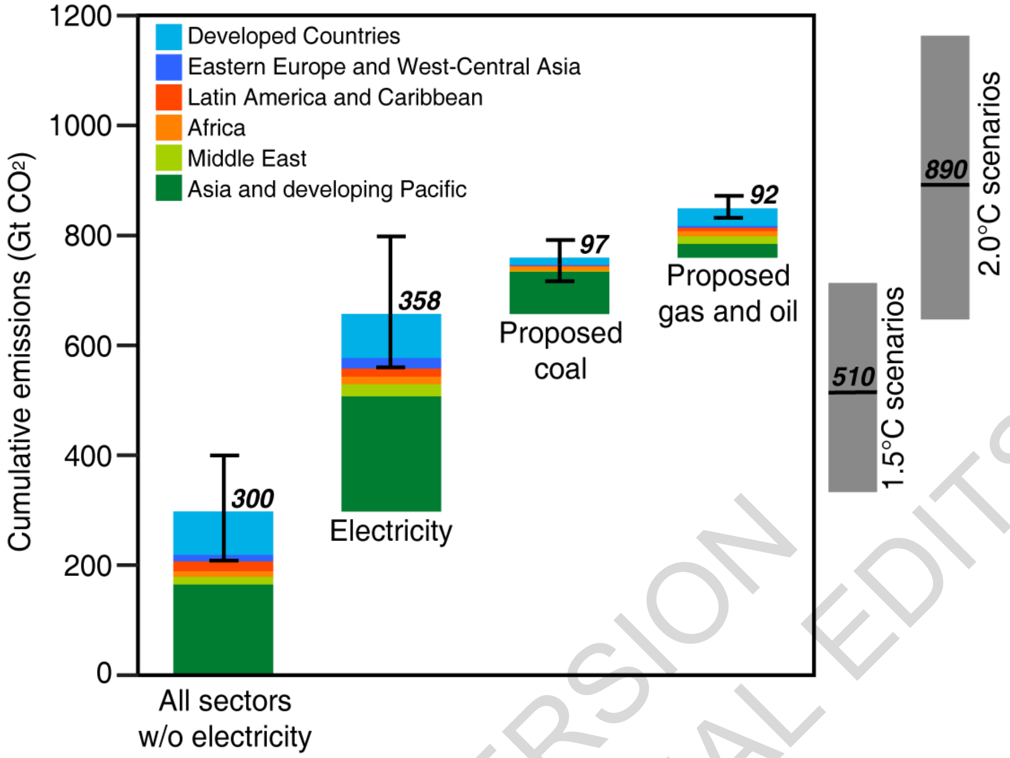


Figure TS.8: Future CO_2 emissions from existing and currently planned fossil fuel infrastructure in the context of Paris carbon budgets in $GtCO_2$ based on historic patterns of infrastructure lifetimes and capacity utilisation

Figure TS.8 legend: Future CO_2 emissions estimates of existing infrastructure for the electricity sector as well as all other sectors (industry, transport, buildings, other fossil fuel infrastructures) and of proposed infrastructures for coal power as well as gas and oil power. Grey bars on the right depict the range (5^{th} – 95^{th} percentile) in overall cumulative net CO_2 emissions until reaching net zero CO_2 in pathways that limit warming to 1.5°C with no or limited overshoot (1.5°C scenarios), and in pathways that limit *likely* warming to 2°C (2°C scenarios). {Figure 2.26}

TS. 4 Mitigation and development pathways

While previous WG III assessments have explored mitigation pathways, since AR5 there has been an increasing emphasis in the literature on development pathways, and in particular at the national scale. Chapter 4 assesses near-term (2019-2030) to mid-term (2030- 2050) pathways, complementing Chapter 3 which focusses on long-term pathways (up to 2100). While there is considerable literature on country-level mitigation pathways, including but not limited to NDCs, the country distribution of this literature is very unequal (*high confidence*). {4.2.1, Cross-Chapter Box 4 in Chapter 4}

TS. 4.1 Mitigation and development pathways in the near- to mid-term

An emissions gap persists, exacerbated by an implementation gap, despite mitigation efforts including those in nationally determined contributions (NDCs). In this report the *emissions gap* is understood as the difference between projected global emissions with national determined contributions (NDCs) in 2030, and emissions in 2030 if mitigation pathways consistent with the Paris temperature goals were achieved. The term *implementation gap* refers to the gap between NDC mitigation pledges, and the expected outcome of existing policies.

Pathways consistent with the implementation and extrapolation of countries' current[11] policies see GHG emissions reaching 57 (52-60) $GtCO_2$-eq yr^{-1} by 2030 and to 46-67 $GtCO_2$-eq yr^{-1} by 2050, leading to a median global warming of 2.4°C to 3.5°C by 2100 (*medium confidence*). NDCs with unconditional and conditional elements[12] lead to 53 (50-57) and 50 (47-55) $GtCO_2$-eq, respectively *(medium confidence)*. {Table 4.1}. This leaves median estimated *emissions gaps* of 14-23 $GtCO_2$-eq to limit warming to 2°C and 25-34 $GtCO_2$-eq to limit warming to 1.5°C relative to mitigation pathways. (Figure TS.9) {Cross-Chapter Box 4 Figure 1 in Chapter 4}

FOOTNOTE [11] Current NDCs refers to the most recent nationally determined contributions submitted to the UNFCCC as well as those publicly announced (with sufficient detail on targets, but not yet submitted) up to 11 October 2021, and reflected in literature published up to 11 October 2021. Original INDCs and NDCs refer to those submitted to the UNFCCC in 2015 and 2016.

FOOTNOTE [12] See {4.2.1} for description of 'unconditional' and 'conditional' elements of NDCs.

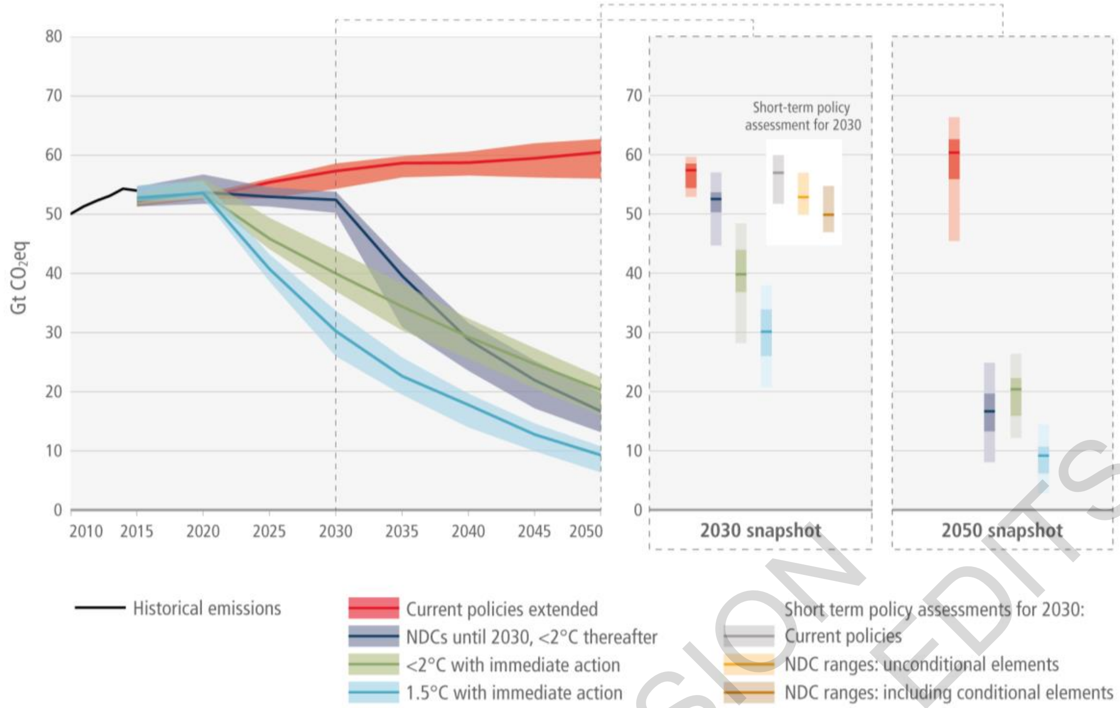


Figure TS.9 Aggregate GHG emissions of global mitigation pathways (coloured funnels and bars) and projected emission outcomes from current policies and emissions implied by unconditional and conditional elements of NDCs, based on updates available by 11 October 2021 (grey bars).

Figure TS.9 legend: Shaded areas show GHG emission medians and 25th–75th percentiles over 2020–2050 for four types of pathways in the AR6 scenario database: i) Pathways with near-term emissions developments in line with current policies and extended with comparable ambition levels beyond 2030; ii) Pathways *likely* to limit warming to 2°C with near term emissions developments reflecting 2030 emissions implied by current NDCs followed by accelerated emissions reductions; iii) Pathways *likely* to limit warming to 2°C based on immediate actions from 2020 onwards; iv) Pathways that limit warming to 1.5°C with no or limited overshoot. Right hand panels show two snapshots of the 2030 and 2050 emission ranges of the pathways in detail (median, 25th–75th and 5th–95th percentiles). The 2030 snapshot includes the projected emissions from the implementation of the NDCs as assessed in Chapter 4.2 (Table 4.1; median and full range). Historic GHG emissions trends as used in model studies are shown for 2010–2015. GHG emissions are in CO_2-equivalent using GWP100 values from AR6. {3.5, Table 4.1, Cross-Chapter Box 4 in Chapter 4}

Projected global emissions from aggregated NDCs place limiting global warming to 1.5°C beyond reach and make it harder after 2030 to limit warming to 2°C *(high confidence)*. Pathways following NDCs until 2030 show a smaller reduction in fossil fuel use, slower deployment of low carbon alternatives, and a smaller reduction in CO_2, CH_4 and overall GHG emissions in 2030 compared to immediate action scenarios. This is followed by a much faster reduction of emissions and fossil fuels after 2030, and a larger increase in the deployment of low carbon alternatives during the medium term in order to get close to the levels of the immediate action pathways in 2050. Those pathways also deploy a larger amount of Carbon Dioxide Removal (CDR) to compensate for higher emissions before 2030. The faster transition during 2030-2050 entails greater investment in fossil fuel infrastructure and lower deployment of low carbon alternatives in 2030 which adds to the socio-economic challenges in realising the higher transition rates. (TS 4.2) {3.5}

Studies evaluating up to 105 updated NDCs[13] indicate that emissions in NDCs with conditional elements have been reduced by 4.5 (2.7-6.3) $GtCO_2$-eq. This closes the emission gaps by about one-third to 2°C and about 20% to 1.5°C compared to the original NDCs submitted in 2015/16 *(medium confidence)*. 4.2.2, Cross-Chapter Box 4 in Chapter 4}. An *implementation gap* also exists between the projected emissions with 'current policies' and the projected emissions resulting from the implementation of the unconditional and conditional elements of NDCs; this is estimated to be around 4 and 7 $GtCO_2$-eq in 2030, respectively {4.2.2} *(medium confidence)*. Many countries would therefore require additional policies and associated action on climate change to meet their autonomously determined mitigation targets as specified under the first NDCs (*limited evidence*). The disruptions triggered by the COVID-19 pandemic increase uncertainty over the range of projections relative to pre-COVID-19 literature. As indicated by a growing number of studies at the national and global level, how large near- to mid-term emissions implications of the COVID-19 pandemic are, to a large degree depends on how stimulus or recovery packages are designed. {4.2}

FOOTNOTE [13] Submitted by 11 October 2021.

Table TS.2: Comparison of key characteristics of mitigation pathways with immediate action towards limiting warming to 1.5-2°C vs. pathways following current NDCs until 2030.

Global indicators	**Mitigation pathways** *median (interquartile range)*			
	<1.5°C Immediate action, no or limited overshoot	**1.5°C by 2100** NDCs until 2030, with high overshoot of 1.5°C	***Likely* < 2°C**	
			Immediate action	NDCs until 2030
	Scenarios category: C1	subset of scenarios category: C2	Scenarios category:C3a	Scenarios category: C3b
Cumulative net negative CO_2 until 2100 ($GtCO_2$)	190 (0,385)	320 (250,440)	10 (0,120)	70 (0,200)
Kyoto GHG emissions in 2030 (% rel to 2019) in 2050 (% rel to 2019)	-45 (-50,-40) -85 (-90,-80)	-5 (-5,0) -75 (-85,-70)	-25 (-35,-20) -65 (-70,-60)	-5 (-10,0) -70 (-70,-60)
CO_2 emissions change in 2030 (% rel to 2019) in 2050 (% rel to 2019)	-50 (-60,-40) -100 (-105,-95)	-5 (-5,0) -85 (-95,-80)	-25 (-35,-20) -70 (-80,-65)	-5 (-5,0) -75 (-80,-65)
CH_4 emissions in 2030 (% rel to 2019) in 2050 (% rel to 2019)	-35 (-40,-30) -50 (-60,-45)	-5 (-5,0) -50 (-60,-45)	-25 (-35,-20) -45 (-50,-40)	-10 (-15,-5) -50 (-65,-45)
Primary energy from coal in 2030 (% rel to 2019) in 2050 (% rel to 2019)	-75 (-80,-65) -95 (-100,-80)	-10 (-20,-5) -90 (-100,-85)	-50 (-65,-35) -85 (-100,-65)	-15 (-20,-10) -80 (-90,-70)
Primary energy from oil in 2030 (% rel to 2019) in 2050 (% rel to 2019)	-10 (-25,0) -60 (-75,-40)	5 (5,10) -50 (-65,-30)	0 (-10,10) -30 (-45,-15)	10 (5,10) -40 (-55,-20)
Primary energy from gas in 2030 (% rel to 2019) in 2050 (% rel to 2019)	-10 (-30,0) -45 (-60,-20)	15 (10,25) -45 (-55,-25)	10 (0,15) -10 (-35,15)	15 (10,15) -30 (-45,-5)
Primary energy from nuclear in 2030 (% rel to 2019) in 2050 (% rel to 2019)	40 (5,70) 90 (10,305)	10 (0,25) 100 (40,135)	35 (5,50) 85 (30,200)	10 (0,30) 75 (30,120)
Primary energy from biomass in 2030 (% rel to 2019) in 2050 (% rel to 2019)	75 (55,130) 290 (215,430)	45 (20,75) 230 (170,440)	60 (35,105) 240 (130,355)	45 (10,80) 260 (95,435)
Primary energy from non-biomass renewables in 2030 (% rel to 2019) in 2050 (% rel to 2019)	225 (150,270) 725 (540,955)	100 (85,145) 665 (515,925)	150 (115,190) 565 (415,765)	115 (85,130) 625 (545,705)
Carbon intensity of electricity in 2030 (% rel to 2019) in 2050 (% rel to 2019)	-75 (-85,-70) -100 (-100,-100)	-30 (-40,-30) -100 (-100,-100)	-60 (-70,-50) -95 (-100,-95)	-35 (-40,-30) -100 (-100,-95)

Table TS.2 legend: Key characteristics are reported for four groups of mitigation pathways: (i) immediate action to limit warming to 1.5°C with no or limited overshoot (C1 in Table TS.3; 97 scenarios), (ii) near team action following the NDCs until 2030 and returning warming to below 1.5°C (50% chance) by 2100 with high overshoot (subset of 42 scenarios following the NDCs until 2030 in C2), (iii) immediate action to *likely* limit warming to 2°C, (C3a in Table TS.3; 204 scenarios) and (iv) near term action following the NDCs until 2030 followed by post-2030 action to *likely* limit warming to 2°C (C3b in Table TS.3; 97 scenarios). The groups (i), (iii), and (iv) are depicted in Figure TS.9. Reported are median and interquartile ranges (in brackets) for selected global indicators. Numbers are rounded to the nearest five. Changes from 2019 are relative to modelled 2019 values. Emissions reductions are based on harmonised model emissions used for the climate assessment. (Section 3.5) {Table 3.6}

There is a need to explore how accelerated mitigation – relative to NDCs and current policies – could close both e*mission gaps*, and *implementation gaps*. There is increasing understanding of the technical content of accelerated mitigation pathways, differentiated by national circumstances, with considerable, though uneven, literature at country-level (*medium evidence, high agreement*). Transformative technological and institutional changes for the near-term include demand reductions through efficiency and reduced activity, rapid decarbonisation of the electricity sector and low-carbon electrification of buildings, industry and transport (*robust evidence, medium agreement*). A focus on energy use and supply is essential, but not sufficient on its own – the land sector and food systems deserve attention. The literature does not adequately include demand-side options and systems analysis, and captures the impact from non-CO_2 GHGs with *medium confidence*. {4.2.5}

If obstacles to accelerated mitigation are rooted in underlying structural features of society, then transforming such structures can support emission reductions {4.2.6}. Countries and regions will have different starting points for transition pathways. Some critical differences between countries include climate conditions resulting in different heating and cooling needs, endowments with different energy resources, patterns of spatial development, and political and economic conditions {4.2.5}. The way countries develop determines their capacity to accelerate mitigation and achieve other sustainable development objectives simultaneously (*medium confidence)* {4.3.1, 4.3.2}. Yet meeting ambitious mitigation and development goals cannot be achieved through incremental change (*robust evidence, medium agreement*). Though development pathways result from the actions of a wide range of actors, it is possible to shift development pathways through policies and enhancing enabling conditions (*limited evidence, medium agreement*).

***Shifting development pathways towards sustainability* offers ways to broaden the range of levers and enablers that a society can use to accelerate mitigation and increases the likelihood of making progress simultaneously on climate action and other development goals (Box TS.3) {Cross-Chapter Box 5 in Chapter 4, Figure 4.7, 4.3}.** There are practical options to shift development pathways in ways that advance mitigation and other sustainable development objectives, supporting political feasibility, increase resources to meet multiple goals, and reduce emissions (*limited evidence, high agreement*). Concrete examples, assessed in chapter 4 of this report, include high employment and low emissions structural change, fiscal reforms for mitigation and social contract, combining housing policies to deliver both housing and transport mitigation, and change economic, social and spatial patterns of development of the agriculture sector provide the basis for sustained reductions in emissions from deforestation. {4.4.1, 4.4, 1.10}

START BOX TS.3 HERE

Box TS.3: **Shifting development pathways to increase sustainability and broaden mitigation options**

In this report, *development pathways* refer to the patterns of development resulting from multiple decisions and choices made by many actors in the national and global contexts. Each society whether in developing or developed regions follows its own pattern of growth (Figure TS.13). Development pathways can also be described at smaller scales (e.g., for regions or cities) and for sectoral systems.

Development pathways are major drivers of GHG emissions {1, 2}. There is compelling evidence to show that continuing along existing development pathways will not achieve rapid and deep emission reductions. In the absence of shifts in development pathways, conventional mitigation policy instruments may not be able to limit global emissions to a degree sufficient to meet ambitious mitigation goals or they may only be able to do so at very high economic and social costs.

Policies to shift development pathways, on the other hand, make mitigation policies more effective. Shifting development pathways broadens the scope for synergies between sustainable development objectives and mitigation. Development pathways also determine the enablers and levers available for adaptation {AR6 WG II TS E.1.2} and for achieving other SDGs.

There are many instances in which reducing GHG emissions and moving towards the achievement of other development objectives can go hand in hand {Chapter 3, Fig 3.33, Chapters 6-12, 17}. Integrated policies can support the creation of synergies between *action to combat climate change and its impacts* (SDG 13) and other SDGs. For example, when measures promoting walkable urban areas are combined with electrification and clean renewable energy, there are several co-benefits to be attained. These include reduced pressures on agricultural land from reduced urban growth, health co-benefits from cleaner air and benefits from enhanced mobility {8.2, 8.4, 4.4.1}. Energy efficiency in buildings and energy poverty alleviation through improved access to clean fuels also deliver significant health benefits. {9.8.1 and 9.8.2}

However, decisions about mitigation actions, and their timing and scale, may entail trade-offs with the achievement of other national development objectives in the near-, mid- and long-term {Chapter 12}. In the near-term, for example, regulations may ban vehicles from city centres to reduce congestion and local air pollution but reduce mobility and choice. Increasing green spaces within cities without caps on housing prices may involve trade-offs with affordable housing and push low-income residents outside the city {8.2.2}. In the mid- and long-term, large-scale deployment of biomass energy raises concerns about food security and biodiversity conservation {3.7.1, 3.7.5, 7.4.4, 9.8.1, 12.5.2, 12.5.3}. Prioritising is one way to manage these trade-offs, addressing some national development objectives earlier than others. Another way is to adopt policy packages aimed at shifting development pathways towards sustainability (SDPS) as they expand the range of tools available to simultaneously achieve multiple development objectives and accelerate mitigation. (Box TS.3 Figure 1)

What does *shifting development pathways towards sustainability* entail?

Shifting development pathways towards sustainability implies making transformative changes that disrupt existing developmental trends. Such choices would not be marginal, but include technological, systemic and socio-behavioural changes {4.4}. Decision points also arise with new infrastructure, sustainable supply chains, institutional capacities for evidence-based and integrated decision-making, financial alignment towards low-carbon socially responsible investments, just transitions and shifts in behaviour and norms to support shifts away from fossil fuel consumption. Adopting multi-level governance modes, tackling corruption where it inhibits shifts to sustainability, and improving social and political trust are also key for aligning and supporting long-term environmentally just policies and processes. {4.4, Cross-Chapter Box 5 in Chapter 4}

How to shift development pathways?

Shifting development paths is complex. Changes that involve 'dissimilar, unfamiliar and more complex science-based components' take more time, acceptance and legitimation and involve complex social learning, even when they promise large gains. Despite the complexities of the interactions that result in patterns of development, history also shows that societies can influence the direction of development pathways based on choices made by decision-makers, citizens, the private sector, and social stakeholders. Shifts in development pathways result from both sustained political interventions and bottom-up changes in public opinion. Collective action by individuals as part of social movements or lifestyle changes underpins system change. {5.2.3, 5.4.1, 5.4.5}.

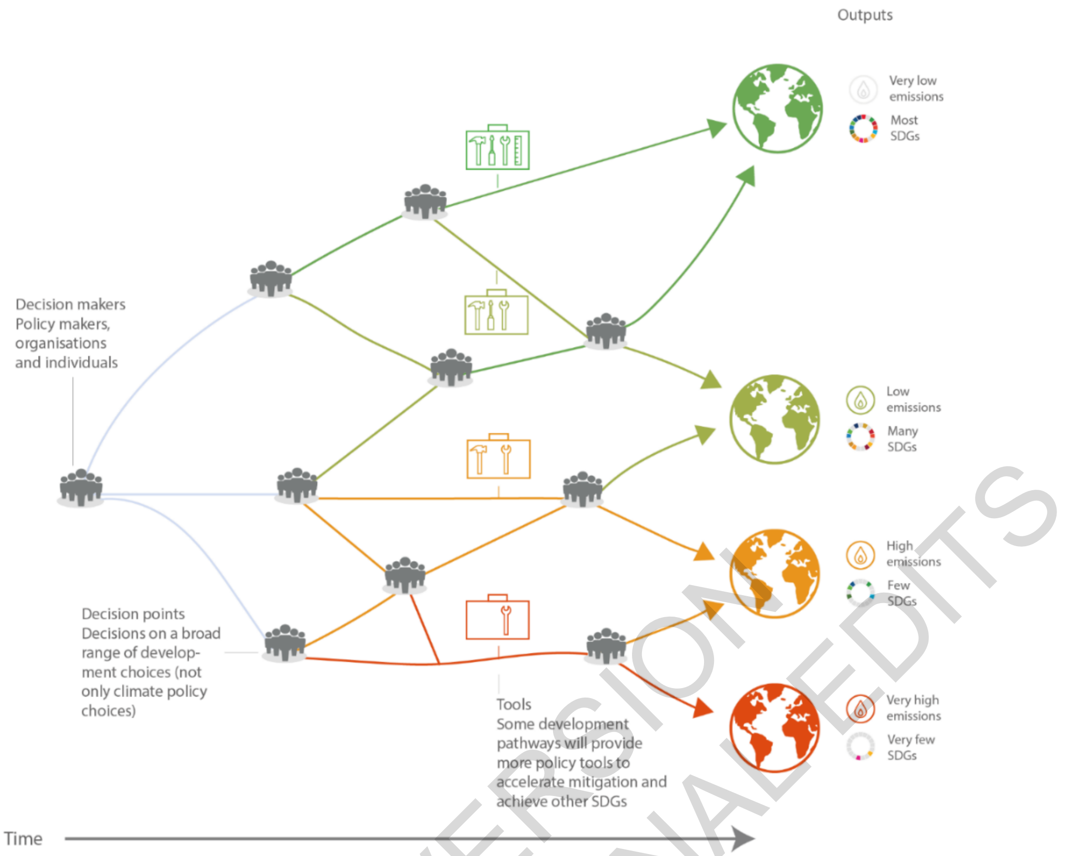
Sectoral transitions that aim to shift development pathways often have multiple objectives and deploy a diverse mix of policies and institutional measures. Context specific governance conditions can significantly enable or disable sectoral transitions {Cross-Chapter Box 12 in Chapter 16}.

The necessary transformational changes are anticipated to be more acceptable if rooted in the development aspirations of the economy and society within which they take place and may enable a new social contract to address a complex set of inter-linkages across sectors, classes, and the whole economy. Taking advantage of windows of opportunity and disruptions to mindsets and socio-technical systems could advance deeper transformations.

How can shifts in development pathways be implemented by actors in different contexts?

Shifting development pathways to increased sustainability is a shared aspiration. Yet since countries differ in starting points (e.g., social, economic, cultural, political) and historical backgrounds, they have different urgent needs in terms of facilitating the economic, social, and environmental dimensions of sustainable development and, therefore, give different priorities {4.3.2, 17.1}. The appropriate set of policies to shift development pathways thus depends on national circumstances and capacities.

Shifting development pathways towards sustainability needs to be supported by multilateral partnerships to strengthen suitable capacity, technological innovation (TS 6.5), and financial flows (TS. 6.4). The international community can play a particularly key role by helping ensure the necessary broad participation in climate-mitigation efforts, including by countries at different development levels, through sustained support for policies and partnerships that support shifting development pathways towards sustainability while promoting equity and being mindful of different transition capacities. {Chapter 4.3, 16.5, 16.6}



Box TS.3 Figure 1 Shifting development pathways to increased sustainability: Choices by a wide range of actors at key decision points on development pathways can reduce barriers and provide more tools to accelerate mitigation and achieve other Sustainable Development Goals. {4.7}

END BOX TS.3 HERE

Policies can *shift* development pathways. There are examples of policies implemented in the pursuit of overall societal development objectives, such as job creation, macro-economic stability, economic growth, and public health and welfare. In some countries, such policies are framed as part of a *just transition* (Box TS.3), however, they can have major influence on mitigative capacity, and hence can be seen as tools to broaden mitigation options *(medium confidence)* {4.3.3}. Coordinated policy mixes would need to orchestrate multiple actors – individuals, groups and collectives, corporate actors, institutions and infrastructure actors – to deepen decarbonisation and shift pathways towards sustainability. Shifts in one country may spill over to other countries. Shifting development pathways can jointly support mitigation and adaptation {4.4.2}. Some studies explore the risks of high complexity and potential delay attached to shifting development pathways. (Box TS.4, Figure TS.11) {4.4.3}

An increasing number of mitigation strategies up to 2050 (mid-term) have been developed by various actors. A growing number of such strategies aim at net zero GHG or CO_2 emissions, but it is not yet possible to draw global implications due to the limited size of sample (*medium evidence; low agreement*) {4.2.4}. Non-state actors are also engaging in a wide range of mitigation initiatives. When adding up emission reduction potentials, sub-national and non-state international cooperative initiatives could reduce emissions by up to about 20 $GtCO_2$-eq in 2030 (*limited evidence, medium agreement*) {4.2.3}. Yet perceived or real conflicts between mitigation and other SDGs can impede such action. If undertaken without precaution, accelerated mitigation is found to have significant implications for development objectives and macroeconomic costs at country level. The literature shows that employment effect of mitigation policies tends to be limited on aggregate but can be significant at sectoral level (*limited evidence, medium agreement*). Detailed design of mitigation policies is critical for distributional impacts and avoiding lock-in (*high confidence*), though further research is needed in that direction. {4.2.6}

The literature identifies a broad set of enabling conditions that can both foster *shifting development pathways* and *accelerated mitigation* (*medium evidence, high agreement*). Policy integration is a necessary component of shifting development pathways, addressing multiple objectives. To this aim, mobilising a range of policies is preferable to single policy instruments (*high confidence*). {4.4.1}. Governance for climate mitigation and shifting development pathways is enhanced when tailored to national and local contexts. Improved institutions and effective governance enable ambitious action on climate and can help bridge implementation gaps (*medium evidence, high agreement*). Given that strengthening institutions may be a long-term endeavour, it needs attention in the near-term {4.4.1}. Accelerated mitigation and shifting development pathways necessitates both re-directing existing financial flows from high- to low-emissions technologies and systems and to provide additional resources to overcome current financial barriers (*high confidence*) {4.4.1}. Opportunities exist in the near-term to close the finance gap {15.2.2}. At the national level, public finance for actions promoting sustainable development helps broaden the scope of mitigation *(medium confidence)*. Changes in behaviour and lifestyles are important to move beyond mitigation as incremental change, and when supporting shifts to more sustainable development pathways will broaden the scope of mitigation *(medium confidence)*. {4.4.1, Figure 4.8}

Some enabling conditions can be put in place relatively quickly while some others may take time to establish underscoring the importance of early action (*high confidence*). Depending on context, some enabling conditions such as such as promoting innovation may take time to establish. Other enabling conditions, such as improved access to financing, can be put in place in a relatively short time frame, and can yield rapid results {4.4, Figure 5.14, 13.9, 14.5, 15.6, 16.3, 16.4, 16.5, Cross-Chapter Box 12 in Chapter 16}. Focusing on development pathways and considering how to shift them may also yield rapid results by providing tools to accelerate mitigation and achieve other sustainable development goals. {4.4.1}. Charting just transitions to net zero may provide a vision, which policy measures can help achieve (Box TS.4, Box TS.8).

Equity can be an important enabler, increasing the level of ambition for accelerated mitigation (*high confidence*) {4.5}. Equity deals with the distribution of costs and benefits and how these are shared, as per social contracts, national policy and international agreements. Transition pathways have distributional consequences such as large changes in employment and economic structure (*high confidence*). The *just transition* concept has become an international focal point tying together social movements, trade unions, and other key stakeholders to ensure equity is better accounted for in low-carbon transitions (Box TS.4). The effectiveness of cooperative action and the perception of fairness of such arrangements are closely related in that pathways that prioritise equity and allow broad stakeholder participation can enable broader consensus for the transformational change implicit in the need for deeper mitigation (*robust evidence, medium agreement*). (Box TS.4) {4.5, Figure 4.9}

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Box TS. 4: Just Transition

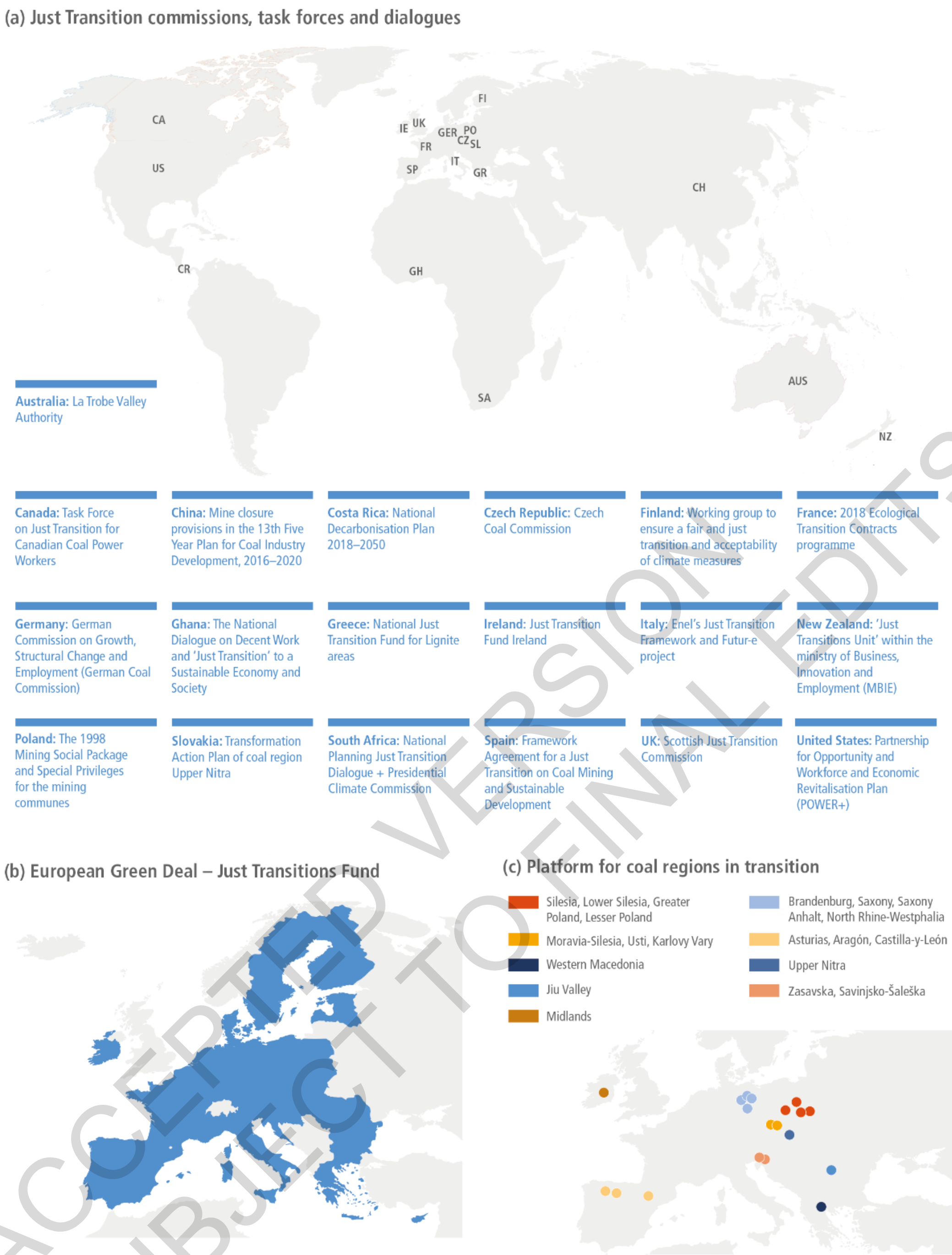
The Just Transition framework refers to a set of principles, processes and practices aimed at ensuring that no people, workers, places, sectors, countries or regions are left behind in the move from a high-carbon to a low-carbon economy. It includes respect and dignity for vulnerable groups; creation of decent jobs; social protection; employment rights; fairness in energy access and use and social dialogue and democratic consultation with relevant stakeholders.

The concept has evolved, becoming prominent in the United States in 1980, related to environmental regulations that resulted in job losses from highly polluting industries. Traced from a purely labour movement, trade union space, the Just Transition framework emphasises that decent work and environmental protection are not incompatible. During COP 24, with the Just Transition Silesia Declaration, the concept gained in recognition and was signed by 56 Heads of State.

Implicit in a Just Transition is the notion of well-being, equity and justice – the realisation that transitions are inherently disruptive and deliberate effort may be required to ensure communities dependent on fossil-fuel based economies and industries do not suffer disproportionately {Chapter 4}. 'Just transitions' are integral to the European Union as mentioned in the EU Green Deal, the Scottish Government's development plans and other national low carbon transition strategies. The US Green New Deal Resolution puts structural inequality, poverty mitigation, and 'Just Transitions' at its centre. There is a growing awareness of the need for shifting finance towards Just Transition in the context of the COVID-19, in particular, public finance and governance have a major role in allowing Just Transition broadly {Chapter 15}.

In the immediate aftermath of the COVID-19 pandemic, low oil prices created additional financial problems for fossil fuel producer countries faced with loss of revenue and reduced fiscal latitude and space. Public spending and social safety nets associated with the proceeds from producer economies can be affected as assets become stranded and spending on strategic sustainable development goals such as free education and health care services are neglected. Fiscal challenges are intricately linked to 'Just Transitions' and the management associated with sustainable energy transition. There is no certainty on how energy systems will recover post-COVID-19. However, 'Just Transitions' will have equity implications if stimulus packages are implemented without due regard for the differentiated scales and speeds and national and regional contexts, especially in the context of developing countries.

A Just Transition entails targeted and proactive measures from governments, agencies, and other non-state authorities to ensure that any negative social, environmental, or economic impacts of economy-wide transitions are minimised, whilst benefits are maximised for those disproportionally affected. These proactive measures include eradication of poverty, regulating prosperity and creating jobs in "green" sectors. In addition, governments, polluting industries, corporations, and those more able to pay higher associated taxes, can pay for transition costs by providing a welfare safety net and adequate compensation to people, communities, and regions that have been impacted by pollution, or are marginalised, or are negatively impacted by a transition from a high- to low- carbon economy and society. There is, nonetheless, increased recognition that resources that can enable the transition, international development institutions, as well as other transitional drivers such as tools, strategies and finance, are scarce. A sample of global efforts are summarised in Box TS.4 Figure 1.



Box TS.4 Figure 1: Just Transitions around the world, 2020: Panel A shows commissions, task forces, dialogues behind a Just Transition in many countries; Panel B shows the funds related to the Just Transition within the European Union Green Deal, and Panel C shows the European Union's Platform for Coal Regions in Transition.{Figure 4.9}

END BOX TS.4 HERE

TS. 4.2 Long-term mitigation pathways

The characteristics of a wide range of long-term mitigation pathways, their common elements and differences are assessed in Chapter 3. Differences between pathways typically represent choices that can steer the system in alternative directions through the selection of different combinations of response options *(high confidence).* More than 2000 quantitative emissions pathways were submitted to the AR6 scenarios database, of which more than 1200 pathways included sufficient information for the associated warming to be assessed (consistent with AR6 WG I methods). (Box TS.5) {3.2, 3.3}

Many pathways in the literature show how to *likely* limit global warming to 2°C with no overshoot or to limit warming to 1.5°C with limited overshoot compared to 1850-1900. The likelihood of limiting warming to 1.5°C with no or limited overshoot has dropped in AR6 WG III compared to AR6 SR1.5 because global GHG emissions have risen since 2017, leading to higher near-term emissions (2030) and higher cumulative CO_2 emissions until the time of net zero *(medium confidence).* Only a small number of published pathways limit global warming to 1.5°C without overshoot over the course of the 21st century. {3.3, Annex III.II.3}

Mitigation pathways limiting warming to 1.5°C with no or limited overshoot reach 50% CO_2 reductions in the 2030s, relative to 2019, then reduce emissions further to reach net zero CO_2 emissions in the 2050s. Pathways *likely* limiting warming to 2°C reach 50% reductions in the 2040s and net zero CO_2 by 2070s (*medium confidence*). (Figure TS.10, Box TS.6) {3.3}

Cost-effective mitigation pathways assuming immediate action to *likely* limit warming to 2°C are associated with net global GHG emissions of 30-49 $GtCO_2$-eq yr^{-1} by 2030 and 13-26 $GtCO_2$-eq yr^{-1} by 2050 *(medium confidence)*. This corresponds to reductions, relative to 2019 levels, of 13-45% by 2030 and 52-76% by 2050. Pathways that limit global warming to below 1.5°C with no or limited overshoot require a further acceleration in the pace of transformation, with net GHG emissions typically around 21-36 $GtCO_2$-eq yr^{-1} by 2030 and 1-15 $GtCO_2$-eq yr^{-1} by 2050; this corresponds to reductions of 34–60% by 2030 and 73-98% by 2050 relative to 2019 levels. {3.3}

START BOX TS.5 HERE

Box TS.5: Illustrative Mitigation Pathways (IMPs), and Shared Socio-economic Pathways (SSPs)

The Illustrative Mitigation Pathways (IMPs)

The over 2500 model-based pathways submitted to the AR6 scenarios database pathways explore different possible evolutions of future energy and land use (with and without climate policy) and the consequences for greenhouse gas emissions.

From the full range of pathways, five archetype scenarios – referred to in this report as *Illustrative Mitigation Pathways* (IMPs) – were selected to illustrate key mitigation-strategy themes that flow through several chapters in this report. A further two *pathways illustrative of high emissions* assuming continuation of current policies or moderately increased action were selected to show the consequences of current policies and pledges. Together these pathways provide illustrations of potential future developments that can be shaped by human choices, including: Where are current policies and pledges leading us? What is needed to reach specific temperature goals? What are the consequences of using different strategies to meet these goals? What are the consequences of delay? How can we shift development from current practices to give higher priority to sustainability and the SDGs?

Each of the IMPs comprises: a *storyline* and a *quantitative illustration*. The *storyline* describes the key characteristics of the pathway qualitatively; the *quantitative illustration* is selected from the literature on long-term scenarios to effectively represent the IMP numerically. The five Illustrative Mitigation Pathways (IMPs) each emphasise a different scenario element as its defining feature, and are named accordingly: heavy reliance on renewables (IMP-Ren), strong emphasis on low demand for energy (IMP-LD), extensive use of Carbon Dioxide Removal (CDR) in the energy and the industry sectors to achieve net negative emissions (IMP-Neg), mitigation in the context of broader sustainable development and shifting development pathways (IMP-SP), and the implications of a less rapid and gradual strengthening of near-term mitigation actions (IMP-GS). In some cases, sectoral chapters may use different quantifications that follow the same storyline narrative but contain data that better exemplify the chapter's assessment. Some IMP variants are also used to explore the sensitivity around alternative temperature goals. {3.2, 3.3}

The two additional *pathways illustrative of higher emissions* are current policies (CurPol) and moderate action (ModAct).

This framework is summarised in Box TS.5 Table.1 below, which also shows where the IMPs are situated with respect to the classification of emissions scenarios into warming levels (C1-C8) introduced in Chapter 3, and the CMIP6 (Coupled Model Intercomparison Project 6) scenarios used in the AR6 WG I report.

Box TS.5 Table.1 *Illustrative Mitigation Pathways (IMPs)* and *pathways illustrative of higher emissions* in relation to scenarios' categories, and CMIP6 scenarios

Classification of emissions scenarios into warming levels: C1-C8	Pathways illustrative of higher emissions	Illustrative mitigation pathways (IMPs)	CMIP 6 scenarios
C8 (above 4°C)			SSP5-8.5
C7 (below 4°C)	CurPol		SSP3-7.0
C6 (below 3°C)	ModAct		SSP2-4.5
C5 (below 2.5°C)			SSP4-3.7
C4 (below 2°C)			
C3 (likely below 2°C)		IMP-GS (Sensitivities: Neg; Ren)	SSP2-2.6
C2 (below 1.5°C; large overshoot)		IMP-Neg	
C1 (below 1.5°C; no or limited overshoot)		IMP-LD IMP-Ren IMP-SP	SSP1-1.9

The Shared Socioeconomic Pathways (SSPs)

First published in 2017, the Shared Socioeconomic Pathways (SSPs) are alternative projections of socio-economic developments that may influence future GHG emissions.

The initial set of SSP narratives described worlds with different challenges to mitigation and adaptation: SSP1 (*sustainability*), SSP2 (*middle of the road*), SSP3 (*regional rivalry*), SSP4 (*inequality*) and SSP5 (*rapid growth*). The SSPs were subsequently quantified in terms of energy, land-use change, and emission pathways for both i) no-climate-policy reference scenarios and ii) mitigation scenarios that follow similar radiative forcing pathways as the Representative Concentration Pathways (RCPs) assessed in AR5 WG I. {3.2.3}

Most of the scenarios in the AR6 database are SSP-based. The majority of the assessed scenarios are consistent with SSP2. Using the SSPs permits a more systematic assessment of future GHG emissions and their uncertainties than was possible in AR5. The main emissions drivers across the SSPs include growth in population reaching 8.5-9.7 billion by 2050, and an increase in global GDP of 2.7-4.1% per year between 2015 and 2050. Final energy demand in the absence of any new climate policies is projected to grow to around 480 to 750 EJ yr^{-1} in 2050 (compared to around 390 EJ in 2015) *(medium confidence).* The highest emissions scenarios in the literature result in global warming of >5°C by 2100, based on assumptions of rapid economic growth and pervasive climate policy failures. (*high confidence*) {3.3}

END BOX TS.5 HERE

Table TS.3: GHG, CO_2 emissions and warming characteristics of different mitigation pathways submitted to the AR6 scenarios database, and as categorized in the climate assessment. {Table 3.2}

p50 (p5-p95) [0]	Global Mean Surface Air Temperature change		GHG emissions Gt CO_2-eq/yr			GHG emissions reductions from 2019 % [5]			Emissions milestones [6,7,8]				Cumulative CO_2 emissions Gt CO_2 [10]		Cumulative net-negative CO_2 emissions Gt CO_2	Temperature change 50% probability [11] °C		Likelihood of staying below (%) [12]			Time when specific temepraturе levels are reached (with a 50% probability)		
Category [1, 2, 3, 4] [# pathways]	Category description	WG1 SSP & IPs alignment	2030	2040	2050	2030	2040	2050	Peak CO_2 emissions	Peak GHG emissions	net-zero CO_2 [% net-zero pathways]	net-zero GHGs [9] [% net-zero pathways]	2020 to netzero CO_2	2020-2100	year of net-zero CO_2 to 2100	at peak warming	2100	<1.5°C	<2.0°C	<3.0°C	1.5°C	2.0°C	3.0°C
C1 [97]	Below 1.5°C with no or limited overshoot	SP, LD Ren, SSP1-1.9	31 (21-36)	17 (6-23)	9 (1-15)	43 (34-60)	69 (58-90)	84 (73-98)	2020-2025 [100%] (2020-2025)	2020-2025 [100%] (2020-2025)	2050-2055 [100%] (2035-2070)	2095-2100 [52%] (2050-...)	510 (330-710)	320 (-210-570)	-200 (-560-0)	1.6 (1.3-1.6)	1.3 (0.8-1.5)	38 (33-73)	90 (86-98)	100 (99-100)	2030-2035 [90%] (2030-...)	...-... [0%] (...-...)	...-... [0%] (...-...)
C2 [133]	Below 1.5°C with high overshoot	Neg	42 (31-55)	25 (16-34)	14 (5-21)	23 (0-44)	55 (40-71)	75 (62-91)	2020-2025 [100%] (2020-2030)	2020-2025 [100%] (2020-2030)	2055-2060 [100%] (2045-2070)	2070-2075 [87%] (2055-...)	720 (540-930)	400 (-90-620)	-330 (-620--30)	1.7 (1.4-1.8)	1.4 (0.8-1.5)	24 (15-58)	82 (71-95)	100 (99-100)	2030-2035 [100%] (2030-2035)	...-... [0%] (...-...)	...-... [0%] (...-...)
C3 [311]	Likely below 2°C	SSP2-2.6	44 (32-55)	29 (20-36)	20 (13-26)	21 (1-42)	46 (34-63)	64 (53-77)	2020-2025 [100%] (2020-2030)	2020-2025 [100%] (2020-2030)	2070-2075 [91%] (2060-...)	...-... [30%] (2075-...)	890 (640-1160)	800 (500-1140)	-40 (-280-0)	1.7 (1.4-1.8)	1.6 (1.1-1.8)	20 (13-66)	76 (68-97)	99 (98-100)	2030-2035 [100%] (2030-2040)	...-... [0%] (...-...)	...-... [0%] (...-...)
C3a [204]	Immediate action		40 (30-49)	29 (21-36)	20 (13-26)	27 (13-45)	47 (35-63)	63 (52-76)	2020-2025 [100%] (2020-2025)	2020-2025 [100%] (2020-2025)	2075-2080 [88%] (2060-...)	...-... [24%] (2080-..)	860 (640-1180)	790 (480-1150)	-10 (-280-0)	1.7 (1.4-1.8)	1.6 (1.1-1.8)	21 (14-70)	78 (69-97)	100 (98-100)	2030-2035 [100%] (2030-2040)	...-... [0%] (...-...)	...-... [0%] (...-...)
C3b [97]	NDCs	GS	52 (47-55)	29 (20-36)	18 (10-25)	5 (0-14)	46 (34-63)	68 (56-82)	2020-2025 [100%] (2020-2030)	2020-2025 [100%] (2020-2030)	2065-2070 [96%] (2060-2100)	...-... [42%] (2075-...)	910 (720-1150)	800 (560-1050)	-70 (-300-0)	1.8 (1.4-1.8)	1.6 (1.1-1.7)	17 (12-61)	73 (67-96)	99 (98-99)	2030-2035 [100%] (2030-2035)	...-... [0%] (...-...)	...-... [0%] (...-...)
C4 [159]	Below 2°C		50 (41-56)	38 (28-43)	28 (19-35)	10 (0-27)	31 (20-50)	49 (35-65)	2020-2025 [100%] (2020-2030)	2020-2025 [100%] (2020-2030)	2075-2080 [86%] (2065-...)	...-... [31%] (2075-...)	1210 (970-1500)	1160 (700-1490)	-30 (-390-0)	1.9 (1.5-2.0)	1.8 (1.2-2.0)	11 (7-50)	59 (50-93)	98 (95-99)	2030-2035 [100%] (2030-2035)	...-... [0%] (...-...)	...-... [0%] (...-...)
C5 [212]	Below 2.5°C		52 (46-56)	45 (36-52)	39 (30-49)	6 (-1-18)	18 (4-33)	29 (11-48)	2020-2025 [100%] (2020-2035)	2020-2025 [100%] (2020-2035)	...-... [40%] (2075-...)	...-... [11%] (2090-...)	1780 (1400-2360)	1780 (1260-2360)	0 (-140-0)	2.2 (1.6-2.5)	2.1 (1.5-2.5)	4 (0-28)	37 (18-84)	91 (83-99)	2030-2035 [100%] (2030-2035)	2060-2065 [99%] (2055-2095)	...-... [0%] (...-...)
C6 [97]	Below 3°C	SSP2-4.5 Mod-Act	54 (50-62)	53 (48-61)	52 (45-57)	2 (-10-11)	3 (-14-14)	5 (-2-18)	2030-2035 [96%] (2020-2085)	2030-2035 [96%] (2020-2085)	...-... [0%] (...-...)	...-... [0%] (...-...)	2790 (2440-3520)	2790 (2440-3520)	0 (0-0)	2.7 (2.0-2.9)	2.7 (2.0-2.9)	0 (0-2)	8 (2-45)	71 (53-96)	2030-2035 [100%] (2030-2035)	2050-2055 [100%] (2045-2060)	...-... [0%] (...-...)
C7 [164]	Below 4°C	SSP3-7.0 Cur-Pol	62 (53-69)	67 (56-76)	70 (58-83)	-11 (-18-3)	-19 (-31-0)	-24 (-41--2)	2070-2075 [56%] (2025-2095)	2070-2075 [56%] (2025-2095)	...-... [0%] (...-...)	...-... [0%] (...-...)	4220 (3160-5000)	4220 (3160-5000)	0 (0-0)	3.5 (2.5-3.9)	3.5 (2.5-3.9)	0 (0-0)	0 (0-5)	22 (7-80)	2030-2035 [100%] (2030-2035)	2045-2050 [100%] (2045-2055)	2080-2085 [100%] (2070-2100)
C8 [29]	Above 4°C	SSP5-8.5	71 (68-80)	79 (77-96)	87 (82-112)	-20 (-34--17)	-35 (-66--29)	-46 (-92--36)	2080-2085 [89%] (2060-2095)	2080-2085 [89%] (2060-2095)	...-... [0%] (...-...)	...-... [0%] (...-...)	5600 (4910-7450)	5600 (4910-7450)	0 (0-0)	4.2 (3.3-5.0)	4.2 (3.3-5.0)	0 (0-0)	0 (0-0)	4 (0-27)	2030-2035 [100%] (2025-2035)	2040-2045 [100%] (2040-2050)	2065-2070 [100%] (2060-2075)

Table TS.3 legend: 0 Values in the table refer to the 50th and (5th-95th) percentile values. For emissions-related columns this relates to the distribution of all the pathways in that category. For Temperature Change and Likelihood columns, single upper row values are the 50th percentile value across pathways in that Category for the MAGICC climate model emulator. For the bracketed ranges, the median warming for every pathway in that category is calculated for each of the three climate model emulators (MAGICC, FaIR and CICERO-SCM). Subsequently, the 5th and 95th percentile values across all pathways is calculated. The coolest and warmest outcomes (i.e. the lowest p5 of three emulators, and the highest p95, respectively) are shown in the brackets. Thus these ranges cover the extent of pathway and climate model emulator uncertainty.

1 Category definitions consider at-peak warming and warming at the end-of-century (2100).

C1: Below 1.5°C in 2100 with a greater than 50% probability and a peak warming higher than 1.5°C with less than 67% probability.

C2: Below 1.5°C in 2100 with a greater than 50% probability but peak warming higher than 1.5°C with a probability of 67% or greater.

C3: *Likely* below 2 °C throughout the century with a probability of 67% or greater.

C4, C5, C6, C7: Below 2 °C, 2.5 °C, 3 °C and 4 °C throughout the century, respectively, with greater than 50% probability.

C8: Peak warming above 4 °C with greater than 50% probability.

2 All warming levels are relative to 1850-1900.

3 The warming profile of the IMP-Neg peaks around 2060 and declines to below 1.5°C (50% likelihood) shortly after 2100. Whilst technically classified as a C3, it strongly exhibits the characteristics of C2 high overshoot pathways, hence it is placed under C2 category.

4 C3 pathways are sub-categorized according to policy ambition and consistent with Figure SPM 6. Two pathways derived from a cost-benefit analysis have been added to C3a, whilst 10 pathways with specifically designed near-term action until 2030 that fall below or above NDCs levels are not included in either of the two subclasses.

5 Percentage GHG reduction ranges shown here are calculated relative to the modelled 2019 emissions based on the harmonized and infilled projections from the models (Annex III, section II.2.5). Negative values (e.g. in C7, C8) represent an increase in emissions.

6 Percentage (%) reductions and emissions milestones are based on model data for CO_2 & GHG emissions, which has been harmonized to 2015 values. See also Footnote 9.

7 The first year range refers to the five year period within which the median peak emissions year or net zero year falls. The second year range refers to the full range (rounded to the nearest five years) within which the 5th and 95th percentiles fall.

8 Percentiles reported across all pathways in that category including pathways that do not reach net zero before 2100 (fraction of pathways reaching net zero is given in square brackets). If the fraction of pathways that reach net zero before 2100 is lower than the fraction of pathways covered by a percentile (e.g. 0.95 for the 95th percentile), the percentile is not defined and denoted with "…". Fraction of pathways reaching net zero is calculated based on the native model emissions profiles.

9 For cases where models do not report all GHGs, missing GHG species are infilled and calculated as Kyoto basket in CO2-eq using AR6 GWP100. For each pathway, a minimum of native reporting of CO_2, CH_4, and N_2O emissions was required for the assessment of the climate response and assignment to a climate category. Emissions pathways without climate assessment are not included in the ranges presented here. See Annex III for details.

10 For better comparability with the WG I assessment of the remaining carbon budget, the cumulative GHG emissions of the pathways are harmonized to the 2015 CO_2 emissions levels used in the WG I assessment and are calculated for the future starting in 1 January 2020.

11 Temperature change (Global Surface Air Temperature - GSAT) for category (at peak and in 2100), based on the median warming for each pathway assessed using the probabilistic climate model emulators.

12 Probability of staying below the temperature thresholds for the pathways in each category, taking into consideration the range of uncertainty from the climate model emulators consistent with the WG I AR6 assessment. The probabilities refer to the probability at peak temperature. Note that in the case of temperature overshoot (E.g., category C2 and some pathways in C1), the probabilities at the end of the century are higher than the probability at peak temperature.

Pathways following current NDCs until 2030 reach annual emissions of 47-57 $GtCO_2$-eq yr^{-1} by 2030, thereby making it impossible to limit warming to 1.5°C with no or limited overshoot and

strongly increasing the challenge of *likely* limiting warming to 2°C *(high confidence)*. A high overshoot of 1.5°C increases the risks from climate impacts and increases dependence on large scale carbon dioxide removal from the atmosphere. A future consistent with current NDCs implies higher fossil fuel deployment and lower reliance on low carbon alternatives until 2030, compared to mitigation pathways describing immediate action that limits warming to 1.5°C with no or limited overshoot, or *likely* limits warming to 2°C and below. After following the NDCs to 2030, to *likely* limit warming to 2°C the pace of global GHG emission reductions would need to abruptly increase from 2030 onward to an average of 1.3-2.1 $GtCO_2$-eq per year between 2030 and 2050. This is similar to the global CO_2 emission reductions in 2020 that occurred due to the COVID-19 pandemic lockdowns, and around 70% faster than in pathways where immediate action is taken to *likely* limit warming to 2°C. Accelerating emission reductions after following an NDC pathway to 2030 would also be particularly challenging because of the continued build-up of fossil fuel infrastructure that would take place between now and 2030. (TS 4.1, Table TS.3) {3.5, 4.2}

Pathways accelerating action compared to current NDCs – that reduce annual GHG emissions to 47 (38-51) $GtCO_2$-eq by 2030 (which is 3-9 $GtCO_2$-eq below projected emissions from fully implementing current NDCs) – make it less challenging to *likely* limit warming to 2°C after 2030 *(medium confidence)*. The accelerated action pathways are characterized by a global, but regionally differentiated, roll-out of regulatory and pricing policies. Compared to current NDCs, they describe less fossil fuel use and more low-carbon fuel use until 2030; they narrow, but do not close the gap to pathways that assume immediate global action using all available least-cost abatement options. All delayed or accelerated action pathways *likely* limiting warming to below 2°C converge to a global mitigation regime at some point after 2030 by putting a significant value on reducing carbon and other GHG emissions in all sectors and regions. {3.5}

In mitigation pathways, peak warming is determined by the cumulative net CO_2 emissions until the time of net zero CO_2 together with the warming contribution of other GHGs and climate forcers at that time *(high confidence)*. Cumulative net CO_2 emissions from 2020 to the time of net zero CO_2 are 510 (330-710) $GtCO_2$ in pathways that limit warming to 1.5°C with no or limited overshoot and 890 (640-1160) $GtCO_2$ in pathways *likely* limiting warming to 2.0°C. These estimates are consistent with the AR6 WG I assessment of remaining carbon budgets adjusting for methodological differences and non-CO_2 warming. {3.3, Box 3.4}

Rapid reductions in non-CO_2 GHGs, particularly CH_4, would lower the level of peak warming *(high confidence)*. Non-CO_2 emissions – at the time of reaching net zero CO_2 – range between 4-11 $GtCO_2$-eq yr-1 in pathways *likely* limiting warming to 2.0°C or below. CH_4 is reduced by around 20% (1-46%) in 2030 and almost 50% (26-64%) in 2050, relative to 2019. CH_4 emission reductions in pathways limiting warming to 1.5°C with no or limited overshoot are substantially higher by 2030, 33% (19-57%), but only moderately so by 2050, 50% (33-69%). CH_4 emissions reductions are thus attainable at comparatively low costs, but, at the same time, reductions are limited in scope in most 1.5-2°C pathways. Deeper CH_4 emissions reductions by 2050 could further constrain the peak warming. N_2O emissions are also reduced, but similar to CH_4, N_2O emission reductions saturate for more stringent climate goals. The emissions of cooling aerosols in mitigation pathways decrease as fossil fuels use is reduced. The overall impact on non-CO_2-related warming combines all these factors. {3.3}

Net zero GHG emissions imply net negative CO_2 emissions at a level that compensates for residual non-CO_2 emissions. Only 30% of the pathways *likely* limiting warming to 2°C or below reach net zero GHG emissions in the 21st century (*high confidence*). In those pathways reaching net zero GHGs, net zero GHGs is achieved around 10-20 years later than net zero CO_2 is achieved (*medium confidence*). The reported quantity of residual non-CO_2 emissions depends on accounting choices, and in particular the choice of GHG metric (Box TS.2). Reaching and sustaining global net zero GHG emissions – when emissions are measured and reported in terms of GWP100 – results in a gradual decline in temperature (*high confidence*). (Box TS.6) {3.3}

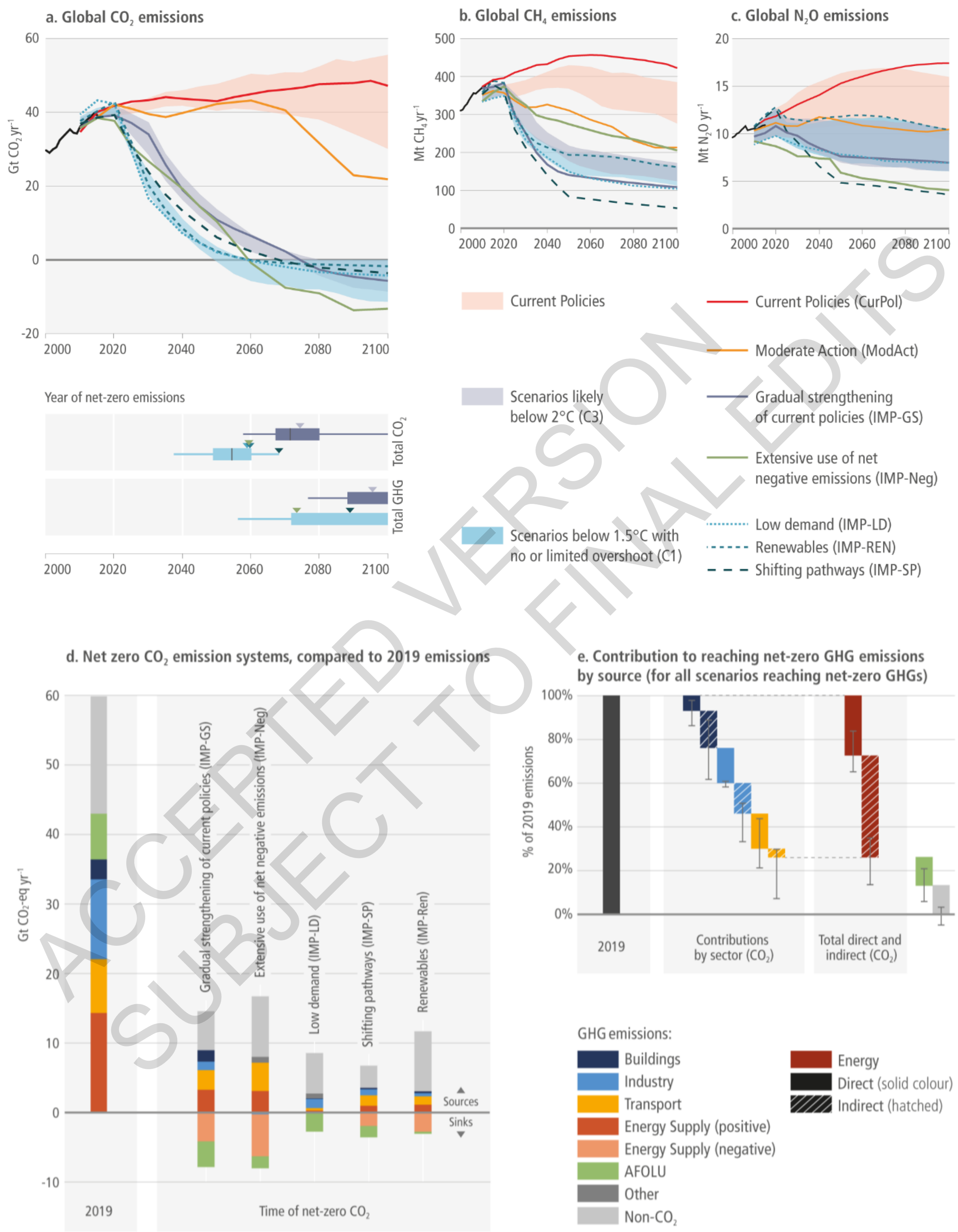


Figure TS.10: Mitigation pathways that limit warming to 1.5°C, or 2°C, involve deep, rapid and sustained emissions reductions. Net zero CO_2 and net zero GHG emissions are possible through different mitigation portfolios

Figure TS.10 legend: Panel a shows the development of global CO_2 emissions (upper sub-panel) and timing of when emissions from different sources reach net zero CO_2 and GHG emissions (lower sub-panel). Panels b and c show the development of global CH_4 and N_2O emissions, respectively. Ranges of baseline emissions pathways (red), <scenarios below 1.5ºC with no or limited overshoot pathways (light blue, category C1) and <scenarios likely below 2ºC pathways (grey, category C3) are compared to the emissions from two pathways illustrative of high emissions (CurPol and ModAct) and five Illustrative Mitigation Pathways (IMPs): IMP-LD (low demand), IMP-Ren (renewables), IMP-SP (shifting pathways), IMP-Neg (extensive use of CDR measures in the energy and the industry sectors to achieve net negative emissions) and IMP-GS (Gradual strengthening of current policies). The assessment of mitigation pathways explores a wide scenario space from the literature within which seven illustrative pathways (IPs) are explored, composed of two sets: (i) one set of five Illustrative Mitigation Pathways (IMPs) and (ii) one set of two reference pathways illustrative for of high emissions.

Panel d shows different net zero CO_2 emissions systems for the IMPs and the respective sectoral composition of CO_2 and non-CO_2 emissions sources and sinks. The net zero CO_2 emissions systems are compared to the emissions from the year 2019.

Panel e shows the contribution of different sectors and sources to the emissions reductions for reaching net-zero GHG emissions. Bars denote the median emissions reductions for all pathways reaching net zero GHG emissions. The full mitigation contributions of the service sectors (transport, buildings, industry) are split into direct as well as indirect (up-stream) CO_2 emissions reductions. In addition, the contributions from the AFOLU sector and reductions from non-CO_2 emissions sources (green and grey bars) are displayed.

Pathways *likely* limiting warming to 2°C or 1.5°C and below exhibit substantial reductions in emissions from all sectors (*high confidence*). 1.5°C pathways with no or limited overshoot entail CO_2 emissions reductions between 2019 and 2050 of around 77% (31-96%) for energy demand, around 115% (90 to 167%) for energy supply, and around 148% (94 to 387%) for AFOLU.[14] In pathways *likely* limiting warming to 2°C, projected CO_2 emissions are reduced between 2019 and 2050 by around 49% for energy demand, 97% for energy supply, and 136% for AFOLU. *(medium confidence)* {3.4}

If warming is to be limited, delaying or failing to achieve emissions reductions in one sector or region necessitates compensating reductions in other sectors or regions (*high confidence*). Mitigation pathways show differences in the timing of decarbonisation and when net zero CO_2 emissions are achieved across sectors and regions. At the time of *global net zero CO_2 emissions*, emissions in some sectors and regions are positive while others are negative; whether specific sectors and regions are positive or negative depends on the availability and cost of mitigation options in those regions, and the policies implemented. In cost-effective mitigation pathways, the energy supply sector typically reaches net zero CO_2 before the economy as a whole, while the demand sectors reach net zero CO_2 later, if ever (*high confidence*). (Figure TS.10) {3.4}

Pathways *likely* limiting warming to 2°C or 1.5°C involve substantial reductions in fossil fuel consumption and a near elimination of coal use without CCS (*high confidence*). These pathways show an increase in low carbon energy, with 88% (69-97%) of primary energy coming from low carbon sources by 2100. {3.4}

Stringent emissions reductions at the level required for 2°C or 1.5°C are achieved through the increased electrification of buildings, transport, and industry, consequently all pathways entail increased electricity generation (*high confidence*). Nearly all electricity in pathways *likely* limiting warming to 2°C or 1.5°C is also from low or no carbon technologies, with different shares across

FOOTNOTE [14] Reductions greater than 100% in energy supply and AFOLU indicate that these sectors would become carbon sinks.

pathways of: nuclear, biomass, non-biomass renewables, and fossil fuels in combination with CCS. {3.4}

Measures required to *likely* limit warming to 2°C or below can result in large scale transformation of the land surface (*high confidence*). These pathways are projected to reach net zero CO_2 emissions in the AFOLU sector between the 2020s and 2070.

Pathways limiting warming to 1.5°C with no or limited overshoot show an increase in forest cover of about 322 million ha (-67 to 890 million ha) in 2050 *(high confidence)*. In these pathways the cropland area to supply biomass for bioenergy (including bioenergy with carbon capture and storage (BECCS)) is around 199 (56-482) million ha in 2100. The use of bioenergy can lead to either increased or reduced emissions, depending on the scale of deployment, conversion technology, fuel displaced, and how, and where, the biomass is produced *(high confidence)*. {3.4}

Pathways *likely* to limit warming to 2°C or 1.5°C require some amount of CDR to compensate for residual GHG emissions, even after substantial direct emissions reductions are achieved in all sectors and regions (*high confidence*). CDR deployment in pathways serves multiple purposes: accelerating the pace of emissions reductions, offsetting residual emissions, and creating the option for net negative CO_2 emissions in case temperature reductions need to be achieved in the long term (*high confidence*). CDR options in pathways are mostly limited to BECCS, afforestation and direct air CO_2 capture and storage (DACCS). CDR through some measures in AFOLU can be maintained for decades but not over the very long term because these sinks will ultimately saturate (*high confidence*). {3.4}

Mitigation pathways show reductions in energy demand, relative to reference scenarios that assume continuation of current policies, through a diverse set of demand-side interventions (*high confidence*). Bottom-up and non-IAM studies show significant potential for demand-side mitigation. A stronger emphasis on demand-side mitigation implies less dependence on CDR and, consequently, reduced pressure on land and biodiversity. {3.4, 3.7}

Limiting warming requires shifting energy investments away from fossil-fuels and towards low-carbon technologies (*high confidence*). The bulk of investments are needed in medium- and low-income regions. Investment needs in the electricity sector are on average 2.3 trillion USD2015 yr^{-1} over 2023-2052 for pathways limiting temperature to 1.5°C with no or limited overshoot, and 1.7 trillion USD2015 yr^{-1} for pathways *likely* limiting warming to 2°C. {3.6.1}

Pathways *likely* to avoid overshoot of 2°C warming require more rapid near-term transformations and are associated with higher up-front transition costs, but at the same time bring long-term gains for the economy as well as earlier benefits in avoided climate change impacts *(high confidence)*. This conclusion is independent of the discount rate applied, though the modelled cost-optimal balance of mitigation action over time does depend on the discount rate. Lower discount rates favour earlier mitigation, reducing reliance on CDR and temperature overshoot. {3.6.1, 3.8}

Mitigation pathways *likely* to limit warming to 2°C entail losses in global GDP with respect to reference scenarios of between 1.3% and 2.7% in 2050. In pathways limiting warming to 1.5°C with no or limited overshoot, losses are between 2.6% and 4.2%. These estimates do not account for the economic benefits of avoided climate change impacts *(medium confidence)*. In mitigation pathways *likely* to limit warming to 2°C, marginal abatement costs of carbon are about 90 (60-120) USD2015/tCO_2 in 2030 and about 210 (140-340) USD2015/tCO_2 in 2050. This compares with about 220 (170-290) USD2015/tCO_2 in 2030 and about 630 (430-990) USD2015/tCO_2 in 2050[15] in pathways that limit warming to 1.5°C with no or limited overshoot. Reference scenarios, in the AR6 scenarios

FOOTNOTE [15] Numbers in parenthesis represent he interquartile range of the scenario samples.

database, describe possible emission trajectories in the absence of new stringent climate policies. Reference scenarios have a broad range depending on socioeconomic assumptions and model characteristics. {3.2.1, 3.6.1}

The global benefits of pathways *likely* to limit warming to 2°C outweigh global mitigation costs over the 21st century, if aggregated economic impacts of climate change are at the moderate to high end of the assessed range, and a weight consistent with economic theory is given to economic impacts over the long-term. This holds true even without accounting for benefits in other sustainable development dimensions or non-market damages from climate change (*medium confidence*). The aggregate global economic repercussions of mitigation pathways include: the macroeconomic impacts of investments in low-carbon solutions and structural changes away from emitting activities; co-benefits and adverse side effects of mitigation; avoided climate change impacts; and, reduced adaptation costs. Existing quantifications of the global aggregate economic impacts show a strong dependence on socioeconomic development conditions, as these shape exposure and vulnerability and adaptation opportunities and responses. Avoided impacts for poorer households and poorer countries represent a smaller share in aggregate economic quantifications expressed in GDP or monetary terms, whereas their well-being and welfare effects are comparatively larger. When aggregate economic benefits from avoided climate change impacts are accounted for, mitigation is a welfare-enhancing strategy *(high confidence).* {3.6.2}

The economic benefits on human health from air quality improvement arising from mitigation action can be of the same order of magnitude as mitigation costs, and potentially even larger *(medium confidence)*. {3.6.3}

Differences in aggregate employment between mitigation pathways and reference scenarios are relatively small, although there may be substantial reallocations across sectors, with job creation in some sectors and job losses in others (*medium confidence*). The net employment effect (and whether employment increases or decreases) depends on the scenario assumptions, modelling framework, and modelled policy design. Mitigation has implications for employment through multiple channels, each of which impacts geographies, sectors and skill-categories differently. {3.6.4}

The economic repercussions of mitigation vary widely across regions and households, depending on policy design and the level of international cooperation *(high confidence)*. Delayed global cooperation increases policy costs across regions, especially in those that are relatively carbon intensive at present (*high confidence*). Pathways with uniform carbon values show higher mitigation costs in more carbon-intensive regions, in fossil-fuels exporting regions, and in poorer regions (*high confidence*). Aggregate quantifications expressed in GDP or monetary terms undervalue the economic effects on households in poorer countries; the actual effects on welfare and well-being are comparatively larger (*high confidence*). Mitigation at the speed and scale required to *likely* limit warming to 2°C or below implies deep economic and structural changes, thereby raising multiple types of distributional concerns across regions, income classes, and sectors (*high confidence*). (Box TS.7) {3.6.1, 3.6.4}

START BOX TS.6 HERE

Box TS.6: Understanding net zero CO_2 and net zero GHG emissions

Reaching net zero CO_2 emissions* globally along with reductions in other GHG emissions is necessary to halt global warming at any level. At the point of net zero, the amount of CO_2 human activity is putting into the atmosphere equals the amount of CO_2 human activity is removing from the atmosphere. Reaching and sustaining net zero CO_2 emissions globally would stabilise CO_2-induced warming.

Moving to net negative CO_2 emissions globally would reduce peak cumulative net CO_2 emissions – which occurs at the time of reaching net zero CO_2 emissions – and lead to a peak and decline in CO_2-induced warming. {Cross-Chapter Box 3 in Chapter 3}

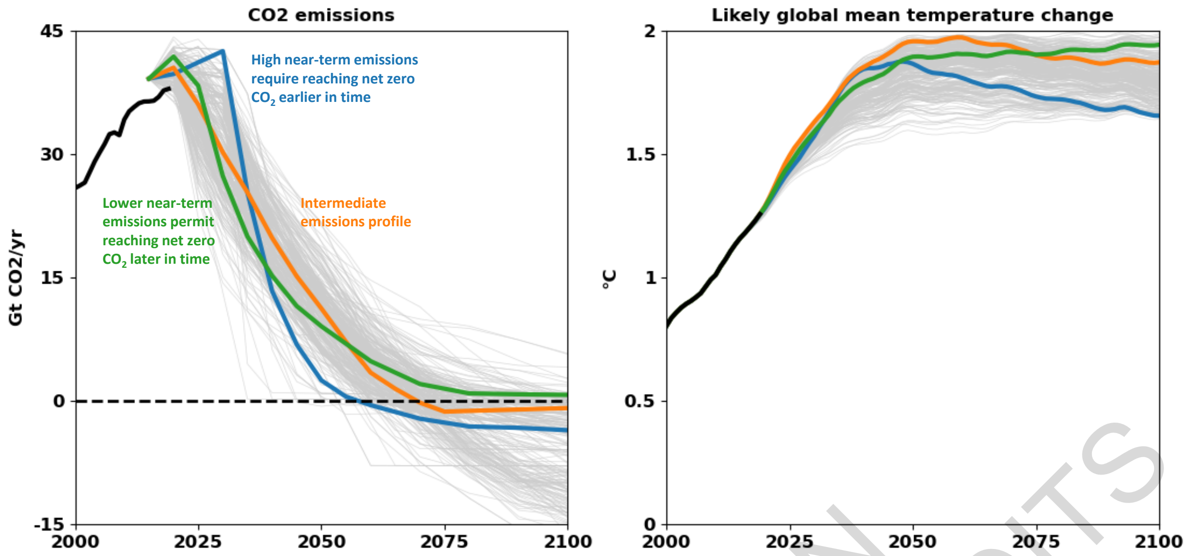
Reaching net zero CO_2 emissions sooner can reduce cumulative CO_2 emissions and result in less human-induced global warming. Overall human-induced warming depends not only on CO_2 emissions but also on the contribution from other anthropogenic climate forcers, including aerosols and other GHGs (e.g. CH_4 and F-gases). To halt total human-induced warming, emissions of other GHG, in particular CH_4, need to be strongly reduced.

In the AR6 scenario database, global emissions pathways limiting warming to 1.5°C with no or limited overshoot reach net zero CO_2 emissions between 2055-2060 (2035-2090) (median and 5-95th percentile ranges; 100% of pathways); pathways *likely* to limit warming to 2°C reach net zero CO_2 emissions between 2070-2075 (2055-2100) (median and 5-95th percentile ranges; 90% of pathways). This is later than assessed in the AR6 SR1.5 primarily due to more pathways in the literature that approach net-zero CO_2 emissions more gradually after a rapid decline of emissions until 2040. (Box TS.6 Figure 1)

It does not mean that the world has more time for emissions reductions while still limiting warming to 1.5°C than reported in the SR15. It only means that the exact timing of reaching net zero CO_2 after a steep decline of CO_2 emissions until 2040 can show some variation. The SR1.5 median value of 2050 is still close to the middle of the current range. If emissions are reduced less rapidly in the period up to 2030, an earlier net-zero year is needed.

Reaching net zero GHG emissions requires net negative CO_2 emissions to balance residual CH_4, N_2O and F-gas emissions. If achieved globally, net zero GHG emissions would reduce global warming from an earlier peak. Around half global emission pathways limiting warming to 1.5°C, and a third of pathways *likely* to limit warming to 2°C, reach net zero GHG emissions (based on GWP100) in the second half of the century, around 10-40 years later than net zero CO_2 emissions. They show warming being halted at some peak value followed by a gradual decline towards the end of the century. The remainder of the pathways do not reach net zero GHG emissions during the 21st century and show little decline of warming after it stabilised.

Global net zero CO_2 or GHG emissions can be achieved even while some sectors and regions continue to be net emitters, provided that others achieve net GHG removal. Sectors and regions have different potentials and costs to achieve net zero or even net GHG removal. The adoption and implementation of net zero emission targets by countries and regions depends on multiple factors, including equity and capacity criteria and international and cross-sectoral mechanisms to balance emissions and removals. The formulation of net zero pathways by countries will benefit from clarity on scope, plans-of-action, and fairness. Achieving net zero emission targets relies on policies, institutions and milestones against which to track progress.



Box TS.6 Figure 1*:* **CO_2 Emissions (panel a) and temperature change (panel b) of three alternative pathways *likely* limiting warming to 2°C and reaching net zero CO_2 emissions at different points in time.**

Box TS.6 Figure 1 legend: Limiting warming to a specific level can be consistent with a range of dates when net zero CO_2 emissions need to be achieved. This difference in the date of net zero CO_2 emissions reflects the different emissions profiles that are possible while staying within a specific carbon budget and the associated warming limit. Shifting the year of net zero to a later point in time (>2050), however, requires more rapid and deeper near-term emissions reductions (in 2030 and 2040) if warming is to be limited to the same level.

*Note: in this assessment the terms n*et zero CO_2 emissions* and *carbon neutrality* have different meanings and are only equivalent at the global scale. At the scale of regions, or sectors, each term applies different system boundaries. This is also the case for the related terms *net zero GHG* and *GHG neutrality*. {Cross-Chapter Box 3 in Chapter 3}

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Box TS.7 The Long-term Economic Benefits of Mitigation from Avoided Climate Change Impacts

Integrated studies use either a cost-effectiveness analysis (CEA) approach (minimising the total mitigation costs of achieving a given policy goal) or a cost-benefit analysis (CBA) approach (balancing the cost and benefits of climate action). In the majority of studies that have produced the body of work on the cost of mitigation assessed in this report, a CEA approach is adopted, and the feedbacks of climate change impacts on the economic development pathways are not accounted for. This omission of climate impacts leads to overly optimistic economic projections in the reference scenarios, in particular in reference scenarios with no or limited mitigation action where the extent of global warming is the greatest. Mitigation cost estimates computed against no or limited policy reference scenarios therefore omit economic benefits brought by avoided climate change impact along mitigation pathways. {1.7, 3.6.1}

The difference in aggregate economic impacts from climate change between two given temperature levels represents the aggregate economic benefits arising from avoided climate change impacts due to mitigation action. Estimates of these benefits vary widely, depending on the methodology used and impacts included, as well as on assumed socioeconomic development conditions, which shape exposure and vulnerability. The aggregate economic benefits of avoiding climate impacts increase with the stringency of the mitigation. Global economic impact studies with regional estimates find large differences across regions, with developing and transitional economies typically more vulnerable. Furthermore, avoided impacts for poorer households and poorer countries represent a smaller share in aggregate quantifications expressed in GDP terms or monetary terms, compared to their influence on well-being and welfare (*high confidence*). {3.6.2, Cross-Working Group Box 1 in Chapter 3}

CBA analysis and CBA integrated assessment models remain limited in their ability to represent all damages from climate change, including non-monetary damages, and capture the uncertain and heterogeneous nature of damages and the risk of catastrophic damages, such that other lines of evidence should be considered in decision-making. However, emerging evidence suggests that, even without accounting for co-benefits of mitigation on other sustainable development dimensions, the global benefits of pathways *likely* to limit warming to 2°C outweigh global mitigation costs over the 21st century (*medium confidence*). Depending on the study, the reason for this result lies in assumptions of economic damages from climate change in the higher end of available estimates, in the consideration of risks of tipping-points or damages to natural capital and non-market goods, or in the combination of updated representations of carbon cycle and climate modules, updated damage estimates and updated representations of economic and mitigation dynamics. In the studies that perform a sensitivity analysis, this result is found to be robust to a wide range of assumptions on social preferences (in particular on inequality aversion and pure rate of time preference), and holds except if assumptions of economic damages from climate change are in the lower end of available estimates and the pure rate of time preference is in the higher range of values usually considered (typically above 1.5%). However, although such pathways bring overall net benefits over time (in terms of aggregate discounted present value), they involve distributional consequences between and within generations. {3.6.2}

END BOX TS.7 HERE

TS. 5 Mitigation responses in sectors and systems

Chapters 5-12 assess recent advances in knowledge in individual sectors and systems. These chapters – *Energy* (Chapter 6), *Urban and other settlements* (Chapter 8), *Transport* (Chapter 10), *Buildings* Chapter 9), *Industry* (Chapter 11), and *Agriculture, forestry and other land use (AFOLU)* (Chapter 7) – correspond broadly to the IPCC National Greenhouse Gas Inventory reporting categories and build on similar chapters in previous WG III reports. Chapters 5 and 12 tie together the cross-sectoral aspects of this group of chapters including the assessment of costs and potentials, demand side aspects of mitigation, and carbon dioxide removal (CDR).

TS. 5.1 Energy

A broad-based approach to deploying energy sector mitigation options can reduce emissions over the next ten years and set the stage for still deeper reductions beyond 2030 (*high confidence*). There are substantial, cost-effective opportunities to reduce emissions rapidly, including in electricity generation, but near-term reductions will not be sufficient to *likely* limit warming to 2°C or limit warming to 1.5°C with no or limited overshoot. {6.4, 6.6, 6.7}

Warming cannot be limited to 2°C or 1.5°C without rapid and deep reductions in energy system CO_2 and GHG emissions (*high confidence*). In scenarios *likely* limiting warming to 1.5°C with no or limited overshoot (*likely* below 2°C), net energy system CO_2 emissions (interquartile range) fall by 87% to 97%% (60% to 79%) in 2050. In 2030, in scenarios limiting warming to 1.5°C with no or limited overshoot, net CO_2 and GHG emissions fall by 35-51% and 38-52% respectively. In scenarios limiting warming to 1.5°C with no or limited overshoot (*likely* below 2°C), net electricity sector CO_2 emissions reach zero globally between 2045 and 2055 (2050 and 2080) *(high confidence).* {6.7}

Limiting warming to 2°C or 1.5°C will require substantial energy system changes over the next 30 years. This includes reduced fossil fuel consumption, increased production from low- and zero-carbon energy sources, and increased use of electricity and alternative energy carriers (*high confidence*). Coal consumption without CCS falls by 67% to 82% (interquartile range) in 2030 in scenarios limiting warming to 1.5°C with no or limited overshoot. Oil and gas consumption fall more slowly. Low-carbon sources produce 93% to 97% of global electricity by 2050 in scenarios that *likely* limit warming to 2°C or below. In scenarios limiting warming to 1.5°C with no or limited overshoot (*likely* below 2°C), electricity supplies 48% to 58% (36% to 47%) of final energy in 2050, up from 20% in 2019. {6.7}

Net zero energy systems will share common characteristics, but the approach in every country will depend on national circumstances (*high confidence*). Common characteristics of net-zero energy systems will include: (1) electricity systems that produce no net CO_2 or remove CO_2 from the atmosphere; (2) widespread electrification of end uses, including light-duty transport, space heating, and cooking; (3) substantially lower use of fossil fuels than today; (4) use of alternative energy carriers such as hydrogen, bioenergy, and ammonia to substitute for fossil fuels in sectors less amenable to electrification; (5) more efficient use of energy than today; (6) greater energy system integration across regions and across components of the energy system; and (7) use of CO_2 removal including DACCS and BECCS to offset residual emissions. {6.6}

Energy demands and energy sector emissions have continued to rise (*high confidence*). From 2015 to 2019, global final energy consumption grew by 6.6%, CO_2 emissions from the global energy system grew by 4.6%, and total GHG emissions from energy supply rose by 2.7%. Fugitive CH_4 emissions from oil, gas, and coal, accounted for 5.8% of GHG emissions in 2019. Coal electricity capacity grew by 7.6% between 2015 and 2019, as new builds in some countries offset declines in others. Total consumption of oil and oil products increased by 5%, and natural gas consumption grew by 15%.

Declining energy intensity in almost all regions has been balanced by increased energy consumption. {6.3}

The unit costs for several key energy system mitigation options have dropped rapidly over the last five years, notably solar PV, wind power, and batteries (*high confidence*). From 2015 to 2020, the costs of electricity from PV and wind dropped 56% and 45%, respectively, and battery prices dropped by 64%. Electricity from PV and wind is now cheaper than electricity from fossil sources in many regions, electric vehicles are increasingly competitive with internal combustion engines, and large-scale battery storage on electricity grids is increasingly viable. (Figure TS.7) {6.3, 6.4}

Global wind and solar PV capacity and generation have increased rapidly driven by policy, societal pressure to limit fossil generation, low interest rates, and cost reductions (*high confidence*). Solar PV grew by 170% (to 680 TWh); wind grew by 70% (to 1420 TWh) from 2015 to 2019. Solar PV and wind together accounted for 21% of total low-carbon electricity generation and 8% of total electricity generation in 2019. Nuclear generation grew 9% between 2015 and 2019 and accounted for 10% of total generation in 2019 (2790 TWh); hydroelectric power grew by 10% and accounted for 16% (4290 TWh) of total generation. In total, low- and zero-carbon electricity generation technologies produced 37% of global electricity in 2019. {6.3, 6.4}

If investments in coal and other fossil infrastructure continue, energy systems will be locked-in to higher emissions, making it harder to limit warming to 2°C or 1.5°C (*high confidence*). Many aspects of the energy system – physical infrastructure; institutions, laws, and regulations; and behaviour – are resistant to change or take many years to change. New investments in coal-fired electricity without CCS are inconsistent with limiting warming to 2°C or 1.5°C. {6.3, 6.7}

Limiting warming to 2°C or 1.5°C will strand fossil-related assets, including fossil infrastructure and unburned fossil fuel resources (*high confidence*). The economic impacts of stranded assets could amount to trillions of dollars. Coal assets are most vulnerable over the coming decade; oil and gas assets are more vulnerable toward mid-century. CCS can allow fossil fuels to be used longer, reducing potential stranded assets. (Box TS.8) {6.7}

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Box TS. 8: Stranded Assets

Limiting warming to 2°C or 1.5°C is expected to result in the "stranding" of carbon-intensive assets. Stranded assets can be broadly defined as assets which "suffer from unanticipated or premature write-offs, downward revaluations or conversion to liabilities". Climate policies, other policies and regulations, innovation in competing technologies, and shifts in fuel prices could all lead to stranded assets. The loss of wealth from stranded assets would create risks for financial market stability, reduce fiscal revenue for hydrocarbon dependent economies, in turn affecting macro-economic stability and the prospects for a just transition. (Box TS.4) {6.7, 15.6, Chapter 17}

Two types of assets are at risk of being stranded: i) in-ground fossil resources and ii) human-made capital assets (e.g., power plants, cars). About 30% of oil, 50% of gas, and 80% of coal reserves will remain unburnable if warming is limited to 2°C. {6.7, Box 6.11}

Practically all long-lived technologies and investments that cannot be adapted to low-carbon and zero-emission modes could face stranding under climate policy – depending on their current age and expected lifetimes. Scenario evidence suggests that without carbon capture, the worldwide fleet of coal- and gas power plants would need to retire about 23 and 17 years earlier than expected lifetimes, respectively in order to limit global warming to 1.5°C and 2°C {2.7}. Blast furnaces and cement factories without CCS {11.4}, new fleets of airplanes and internal combustion engine vehicles {10.4, 10.5}, and new urban infrastructures adapted to sprawl and motorisation may also be stranded {Chapter 8; Box 10.1}.

Many countries, businesses, and individuals stand to lose wealth from stranded assets. Countries, businesses, and individuals may therefore desire to keep assets in operation even if financial, social, or environmental concerns call for retirement. This creates political economic risks, including actions by asset owners to hinder climate policy reform {6.7; Box 6.11}. It will be easier to retire these assets if the risks are communicated, if sustainability reporting is mandated and enforced, and if corporations are protected with arrangements that shield them from short-term shareholder value maximisation.

Without early retirements, or reductions in utilisation, the current fossil infrastructure will emit more GHGs than is compatible with limiting warming to 1.5°C {2.7}. Including the pipeline of planned investments would push these future emissions into the uncertainty range of 2°C carbon budgets {2.7}. Continuing to build new coal-fired power plants and other fossil infrastructure will increase future transition costs and may jeopardize efforts to *likely* limit warming to 2°C or 1.5°C with no or limited overshoot. One study has estimated that USD11.8 trillion in current assets will need to be stranded by 2050 for 2°C world; further delaying action for another 10 years would result in an additional USD7.7 trillion in stranded assets by 2050. {15.5.2}

Experience from past stranding indicates that compensation for the devaluation costs of private sector stakeholders by the public sector is common. Limiting new investments in fossil technologies hence also reduces public finance risks in the long term. {15.6.3}

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A low-carbon energy transition will shift investment patterns and create new economic opportunities (*high confidence*). Total energy investment needs will rise, relative to today, over the next decades, if it is to be likely that warming is limited to 2°C, or if warming is limited to 1.5°C with no or limited overshoot. These increases will be far less pronounced, however, than the reallocations of investment flows that are anticipated across sub-sectors, namely from fossil fuels (extraction, conversion, and electricity generation) without CCS and toward renewables, nuclear power, CCS, electricity networks and storage, and end-use energy efficiency. A significant and growing share of investments between now and 2050 will be made in emerging economies, particularly in Asia. {6.7}

Climate change will affect many future local and national low-carbon energy systems. The impacts, however, are uncertain, particularly at the regional scale (*high confidence*). Climate change will alter hydropower production, bioenergy and agricultural yields, thermal power plant efficiencies, and demands for heating and cooling, and it will directly impact power system infrastructure. Climate change will not affect wind and solar resources to the extent that it would compromise their ability to reduce emissions. {6.5}

Electricity systems powered predominantly by renewables will be increasingly viable over the coming decades, but it will be challenging to supply the entire energy system with renewable energy (*high confidence*). Large shares of variable solar PV and wind power can be incorporated in electricity grids through batteries, hydrogen, and other forms of storage; transmission; flexible non-renewable generation; advanced controls; and greater demand-side responses. Because some applications (e.g., aviation) are not currently amenable to electrification, it is anticipated that 100% renewable energy systems will need to include alternative fuels such as hydrogen or biofuels. Economic, regulatory, social, and operational challenges increase with higher shares of renewable electricity and energy. The ability to overcome these challenges in practice is not fully understood. (Box TS.9) {6.6}

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Box TS.9: The Transformation in Energy Carriers: Electrification and Hydrogen

To use energy, it must be "carried" from where it was produced – at a power plant, for example, or a refinery, or a coal mine – to where it is used. As countries reduce CO_2 emissions, they will need to switch from gasoline and other petroleum-based fuels, natural gas, coal, and electricity produced from these fossil fuels to energy carriers with little or no carbon footprint. An important question is which new energy carriers will emerge to support low-carbon transitions.

Low-carbon energy systems are expected to rely heavily on end-use electrification, where electricity produced with low GHG emissions is used for building and industrial heating, transport and other applications that rely heavily on fossil fuels at present. But not all end-uses are expected to be commercially electrifiable in the short to medium term {11.3.5}, and many will require low GHG liquid and gaseous fuels, i.e., hydrogen, ammonia, and biogenic and synthetic low GHG hydrocarbons made from low GHG hydrogen, oxygen and carbon sources (the latter from CCU[16], biomass, or direct air capture {11.3.6}). The future role of hydrogen and hydrogen derivatives will depend on how quickly and how far production technology improves, i.e. from electrolysis ("green"), biogasification, and fossil fuel reforming with CCS ("blue") sources. As a general rule, and across all sectors, it is more efficient to use electricity directly and avoid the progressively larger conversion losses from producing hydrogen, ammonia, or constructed low GHG hydrocarbons. What hydrogen does do, however, is add time and space option value to electricity produced using variable clean sources, for use as hydrogen, as stored future electricity via a fuel cell or turbine, or as an industrial feedstock. Furthermore, electrification and hydrogen involve a symbiotic range of general-purpose technologies, such as electric motors, power electronics, heat pumps, batteries, electrolysis, fuel cells etc., that have different applications across sectors but cumulative economies of innovation and production scale benefits. Finally, neither electrification nor hydrogen produce local air pollutants at point of end-use.

For almost 140 years we have primarily produced electricity by burning coal, oil, and gas to drive steam turbines connected to electricity generators. When switching to low-carbon energy sources – renewable sources, nuclear power, and fossil or bioenergy with CCS – electricity is expected to become a more pervasive energy carrier. Electricity is a versatile energy carrier, with much higher end-use efficiencies than fuels, and it can be used directly to avoid conversion losses.

An increasing reliance on electricity from variable renewable sources, notably wind and solar power, disrupts old concepts and makes many existing guidelines obsolete for power system planning, e.g., that specific generation types are needed for baseload, intermediate load, and peak load to follow and meet demand. In future power systems with high shares of variable electricity from renewable sources, system planning and markets will focus more on demand flexibility, grid infrastructure and interconnections, storage on various timelines (on the minute, hourly, overnight and seasonal scale), and increased coupling between the energy sector and the building, transport and industrial sectors. This shifts the focus to energy systems that can handle variable supply rather than always follow demand. Hydrogen may prove valuable to improve the resilience of electricity systems with high penetration of variable renewable electricity. Flexible hydrogen electrolysis, hydrogen power plants and long-duration hydrogen storage may all improve resilience. Electricity-to-hydrogen-to-electricity round-trip efficiencies are projected to reach up to 50% by 2030. {6.4.3}

FOOTNOTE[16] Carbon dioxide capture and utilisation (CCU) refers to a process in which CO_2 is captured and the carbon is then used in a product. The climate effect of CCU depends on the product lifetime, the product it displaces, and the CO_2 source (fossil, biomass or atmosphere). CCU is sometimes referred to as Carbon Dioxide Capture and Use, or Carbon Capture and Utilisation.

Electrification is expected to be the dominant strategy in buildings as electricity is increasingly used for heating and for cooking. Electricity will help to integrate renewable energy into buildings and will also lead to more flexible demand for heating, cooling, and electricity. District heating and cooling offers potential for demand flexibility through energy storage and supply flexibility through cogeneration. Heat pumps are increasingly used in buildings and industry for heating and cooling {9.3.3, Box 9.3}. The ease of switching to electricity means that hydrogen is not expected to be a dominant pathway for buildings {Box 9.6}. Using electricity directly for heating, cooling and other building energy demand is more efficient than using hydrogen as a fuel, for example, in boilers or fuel cells. In addition, electricity distribution is already well developed in many regions compared to essentially non-existent hydrogen infrastructure, except for a few chemicals industry pipelines. At the same time, hydrogen could potentially be used for on-site storage should technology advance sufficiently.

Electrification is already occurring in several modes of personal and light freight transport, and vehicle-to-grid solutions for flexibility have been extensively explored in the literature and small-scale pilots. The role of hydrogen in transport depends on how far technology develops. Batteries are currently a more attractive option than hydrogen and fuel-cells for light-duty vehicles. Hydrogen and hydrogen-derived synthetic fuels, such as ammonia and methanol, may have a more important role in heavy vehicles, shipping, and aviation {10.3}. Current transport of fossil fuels may be replaced by future transport of hydrogen and hydrogen carriers such as ammonia and methanol, or energy intensive basic materials processed with hydrogen (e.g. reduced iron) in regions with bountiful renewable resources. {Box 11.1}

Both light and heavy industry are potentially large and flexible users of electricity for both final energy use (e.g., directly and using heat pumps in light industry) and for feedstocks (e.g., hydrogen for steel making and chemicals). For example, industrial process heat demand, ranging from below 100°C to above 1000 °C, can be met through a wide range of electrically powered technologies instead of using fuels. Future demand for hydrogen (e.g., for nitrogen fertiliser or as reduction agent in steel production) also offers electricity demand flexibility for electrolysis through hydrogen storage and flexible production cycles {11.3.5}. The main use of hydrogen and hydrogen carriers in industry is expected to be as feedstock (e.g., for ammonia and organic chemicals) rather than for energy as industrial electrification increases.

END BOX TS.9 HERE

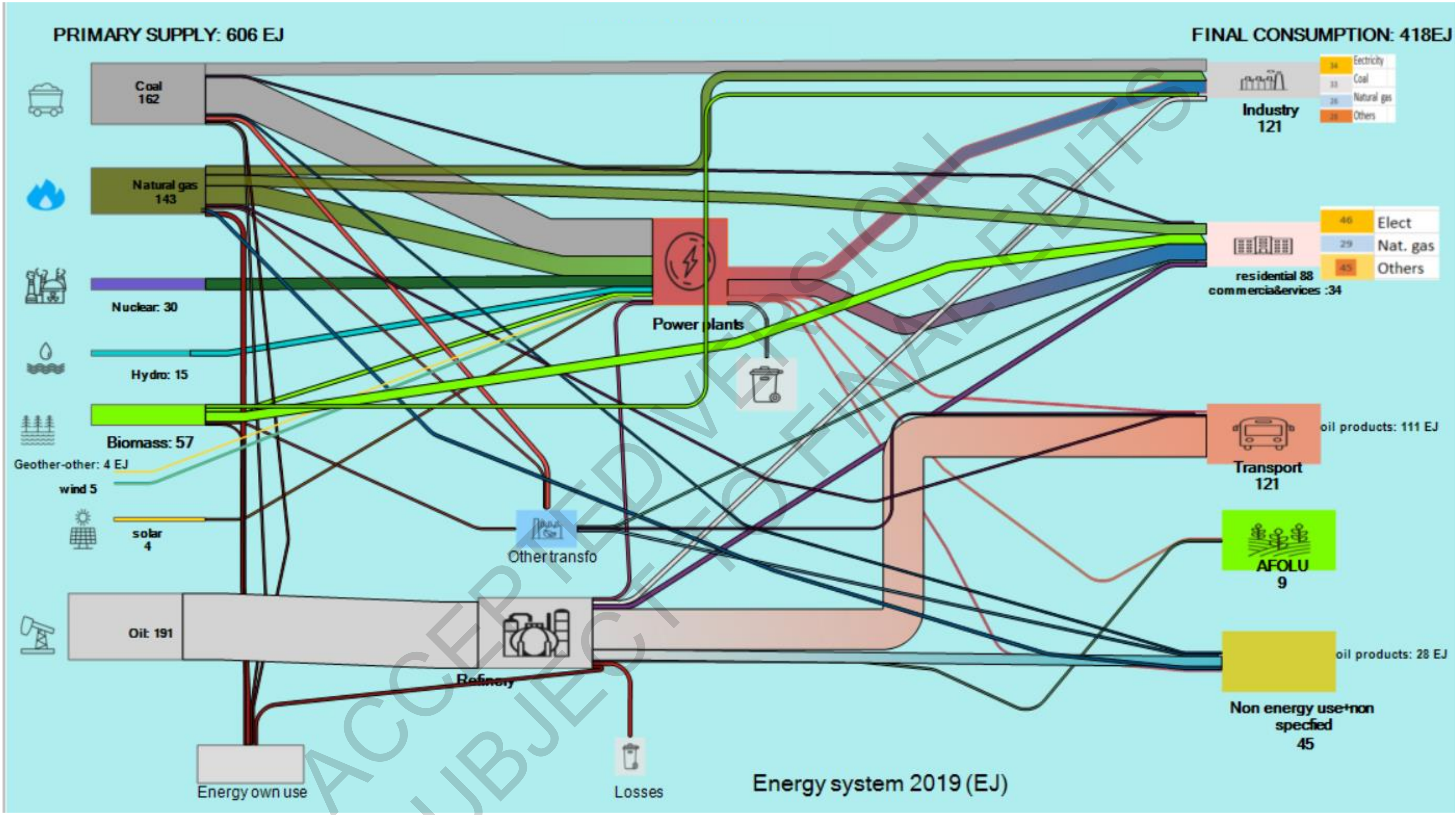
Multiple energy supply options are available to reduce emissions over the next decade (*high confidence*). Nuclear power and hydropower are already established technologies. Solar PV and wind are now cheaper than fossil-generated electricity in many locations. Bioenergy accounts for about a tenth of global primary energy. Carbon capture is widely used in the oil and gas industry, with early applications in electricity production and biofuels. It will not be possible to widely deploy all of these and other options without efforts to address the geophysical, environmental-ecological, economic, technological, socio-cultural, and institutional factors that can facilitate or hinder their implementation. (*high confidence*). (Figure TS.11, Figure TS.31) {6.4}

Enhanced integration across energy system sectors and across scales will lower costs and facilitate low-carbon energy system transitions (*high confidence*). Greater integration between the electricity sector and end use sectors can facilitate integration of variable renewable energy options. Energy systems can be integrated across district, regional, national, and international scales *(high confidence).* {6.4, 6.6}

The viable speed and scope of a low-carbon energy system transition will depend on how well it can support SDGs and other societal objectives (*high confidence*). Energy systems are linked to a range of societal objectives, including energy access, air and water pollution, health, energy security, water security, food security, economic prosperity, international competitiveness, and employment. These linkages and their importance vary among regions. Energy sector mitigation and efforts to achieve SDGs generally support one another, though there are important region-specific exceptions. *(high confidence)*. (Figure TS.29) {6.1, 6.7}

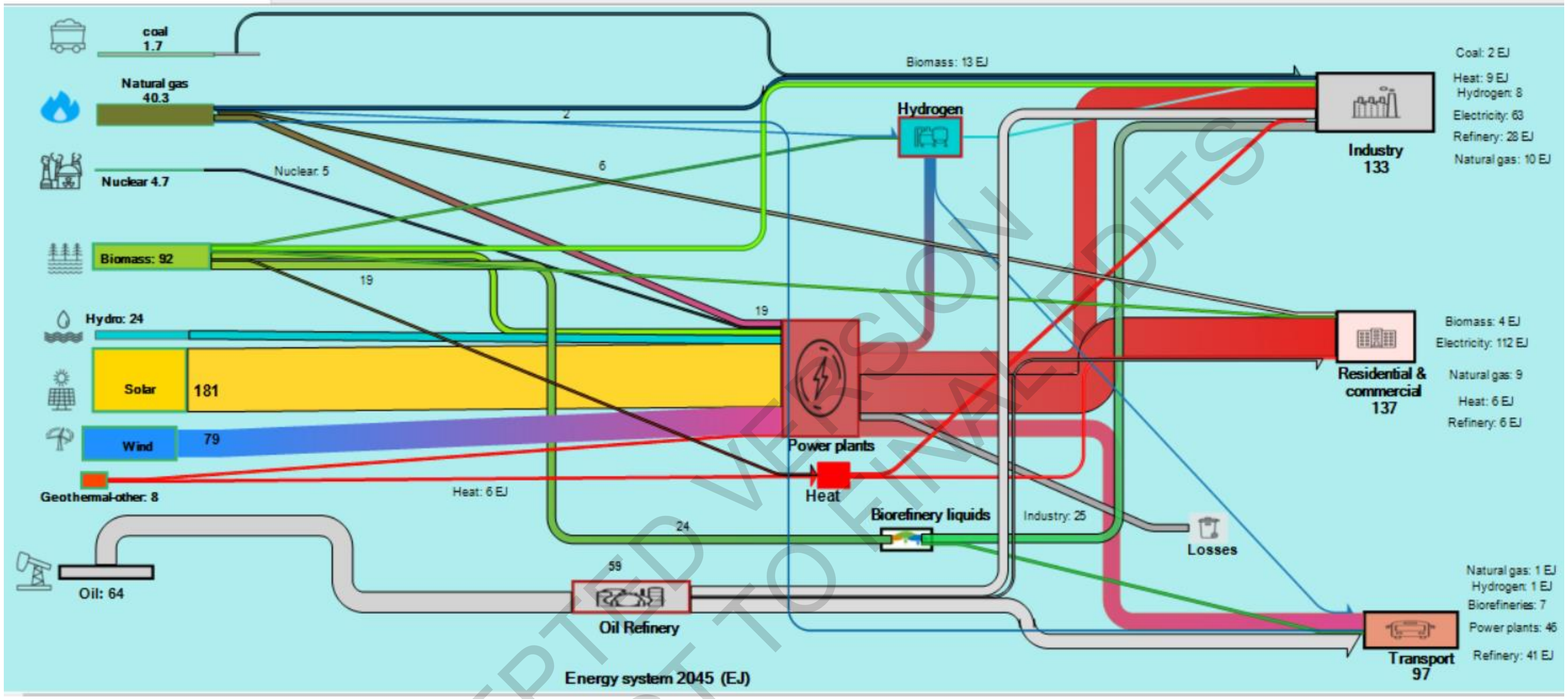
The economic outcomes of low-carbon transitions in some sectors and regions may be on par with, or superior to those of an emissions-intensive future (*high confidence*). Cost reductions in key technologies, particularly in electricity and light-duty transport, have increased the economic attractiveness of near-term low-carbon transitions. Long-term mitigation costs are not well understood and depend on policy design and implementation, and the future costs and availability of technologies. Advances in low-carbon energy resources and carriers such as next-generation biofuels, hydrogen produced from electrolysis, synthetic fuels, and carbon-neutral ammonia would substantially improve the economics of net zero energy systems (*medium confidence*). {6.4, 6.7}

1

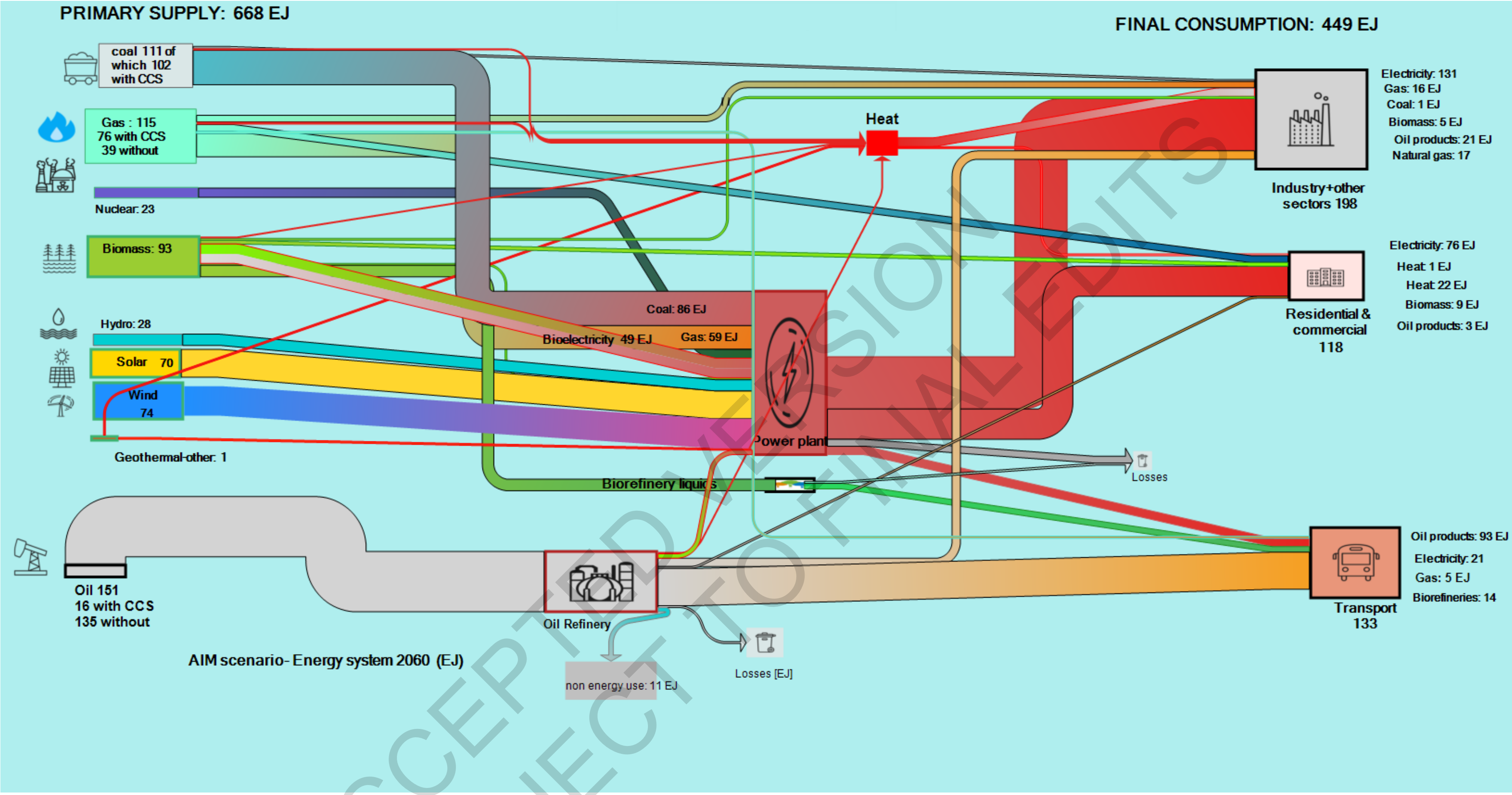


2

Panel a: flows within the 2019 global energy system



Panel b: flows withing an illustrative future net zero CO_2 emissions global energy system



Panel c: flows within an illustrative future net zero CO_2 emissions global energy system

Figure TS.11 Global energy flows within the 2019 global energy system (panel a) and within two illustrative futures, net zero CO_2 emissions global energy systems (panels b and c)

Figure TS.11 legend: Flows below 1 EJ are not represented, rounded figures. The illustrative net zero scenarios correspond to the year in which net energy system CO_2 emissions reach zero {Figure 6.1}

TS. 5.2 Urban and other settlements

Although urbanisation is a global trend often associated with increased incomes and higher consumption, the growing concentration of people and activities is an opportunity to increase resource efficiency and decarbonise at scale *(very high confidence)*. The same urbanisation level can have large variations in per capita urban carbon emissions. For most regions, per capita urban emissions are lower than per capita national emissions *(very high confidence*). {8.1.4, 8.3.3, 8.4, Box 8.1}

Most future urban population growth will occur in developing countries, where per capita emissions are currently low but are expected to increase with the construction and use of new infrastructure and the built environment, and changes in incomes and lifestyles *(very high confidence)*. The drivers of urban GHG emissions are complex and include an interplay of population size, income, state of urbanisation, and how cities are laid out. How new cities and towns are designed, constructed, managed, and powered will lock-in behaviour, lifestyles, and future urban GHG emissions. Urban strategies can improve well-being while minimising impact on GHG emissions. However, urbanisation can result in increased global GHG emissions through emissions outside the city's boundaries *(very high confidence).* {8.1.4, 8.3, Box 8.1, 8.4, 8.6}

The urban share of combined global (CO_2 and CH_4 emissions is substantial and continues to increase *(high confidence)*. Urban areas generated between 67–72% (~28 $GtCO_2$-eq) of combined global CO_2 and CH_4 emissions in 2020 through the production and consumption of goods and services. These emissions are projected to rise to 34–65 $GtCO_2$-eq by 2050 with moderate to no mitigation efforts, driven by a growing population, infrastructure, and service demands in urban areas. About 100 of the highest emitting urban areas account for approximately 18% of the global carbon footprint *(high confidence).* {8.1.6, 8.3.3}

The urban share of regional GHG emissions increased between 2000 and 2015, with much inter-regional variation in the magnitude of the increase *(high confidence).* Globally, the urban share of national emissions increased six percentage points, from 56% in 2000 to 62% in 2015. For 2000 to 2015, the urban emissions share increased from 28% to 38% in Africa, from 46% to 54% in Asia and Developing Pacific, from 62% to 72% in Developed Countries, from 57% to 62% in Eastern Europe and West-Central Asia, from 55% to 66% in Latin America and Caribbean, and from 68% to 69% in the Middle East *(high confidence).* {8.1.6, 8.3.3}

Per capita urban GHG emissions increased between 2000 and 2015, with cities in developed countries accounting for nearly seven times more per capita than the lowest emitting region *(medium confidence)*. From 2000 to 2015, global urban GHG emissions per capita increased from 5.5 to 6.2 tCO_2-eq per person (an increase of 11.8%). Emissions in Africa increased from 1.3 to 1.5 tCO_2-eq per person (22.6%); in Asia and Developing Pacific from 3.0 to 5.1 tCO_2-eq per person (71.7%); in Eastern Europe and West-Central Asia from 6.9 to 9.8 tCO_2-eq per person (40.9%); in Latin America and the Caribbean from 2.7 to 3.7 tCO_2-eq per person (40.4%); and in the Middle East from 7.4 to 9.6 tCO_2-eq per person (30.1%). Albeit starting from the highest level, developed countries showed a modest decline of 11.4 to 10.7 tCO_2-eq per person (-6.5%). (Figure TS.12) {8.3.3}

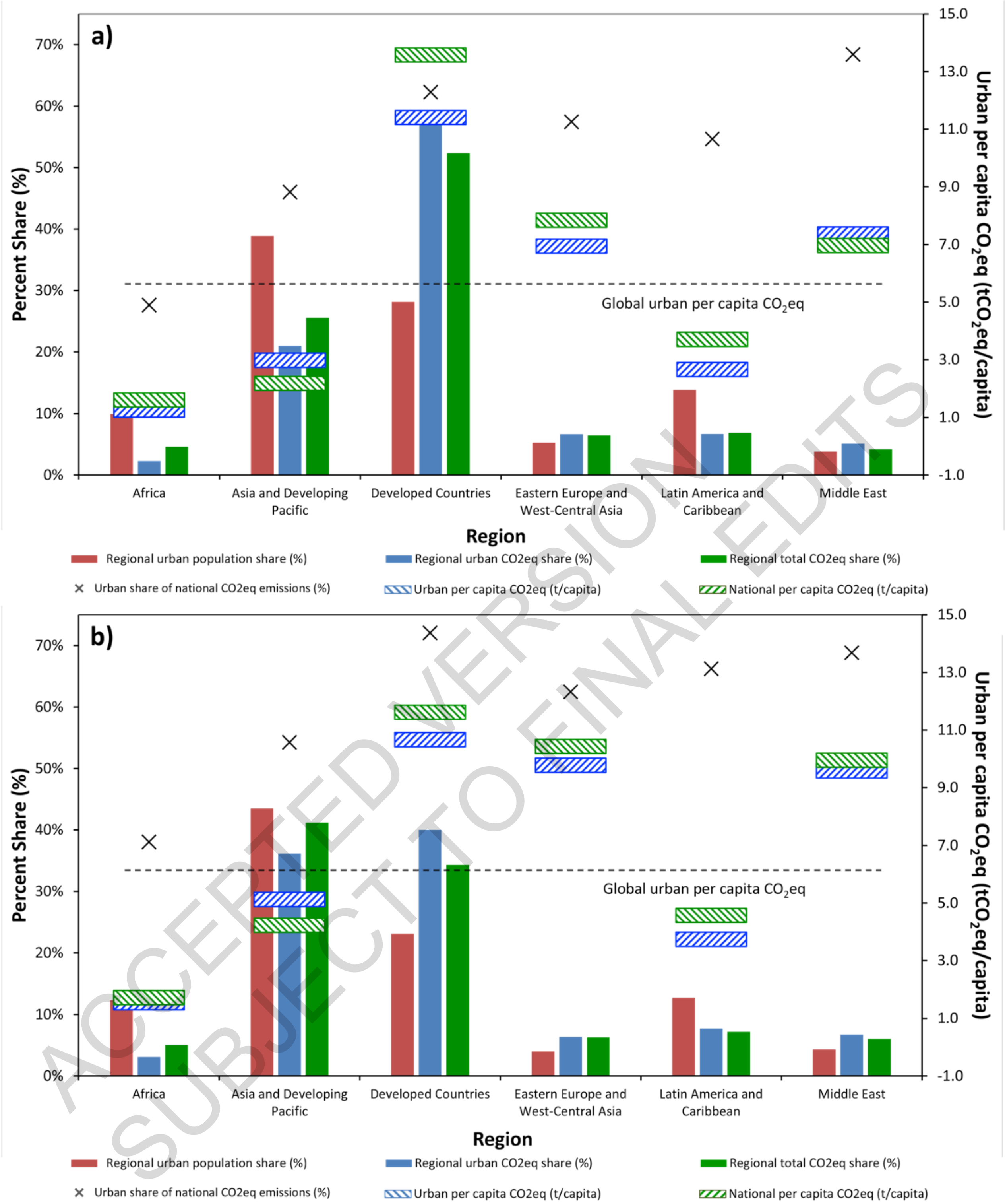


Figure TS.12 Changes in six metrics associated with urban and national-scale combined CO_2 and CH_4 emissions represented in the WG III AR6 6-region aggregation, with (a) 2000 and (b) 2015

Figure TS.12 legend: The total values exclude aviation, shipping, and biogenic sources. The dashed grey line represents the global average urban per capita CO_2-eq emissions. The regional urban population share, regional CO_2-eq share in total emissions, and national per capita CO_2-eq emissions by region are given for comparison. {Figure 8.9}

The global share of future urban GHG emissions is expected to increase through 2050 with moderate to no mitigation efforts due to growth trends in population, urban land expansion and infrastructure and service demands, but the extent of the increase depends on the scenario and the scale and timing of urban mitigation action (*medium confidence*). With aggressive and immediate mitigation policies to limit global warming to 1.5°C by the end of the century, including high levels of electrification, energy and material efficiency, renewable energy preferences, and socio-behavioural responses, urban GHG emissions could approach net zero and reach a maximum of 3 $GtCO_2$-eq in 2050. Under a scenario with aggressive but not immediate urban mitigation policies to limit global warming to 2°C, urban emissions could reach 17 $GtCO_2$-eq in 2050. With no urban mitigation efforts, urban emissions could more than double from 2020 levels and reach 65 $GtCO_2$-eq in 2050, while being limited to 34 $GtCO_2$-eq in 2050 with only moderate mitigation efforts. (Figure TS.13) {8.3.4}

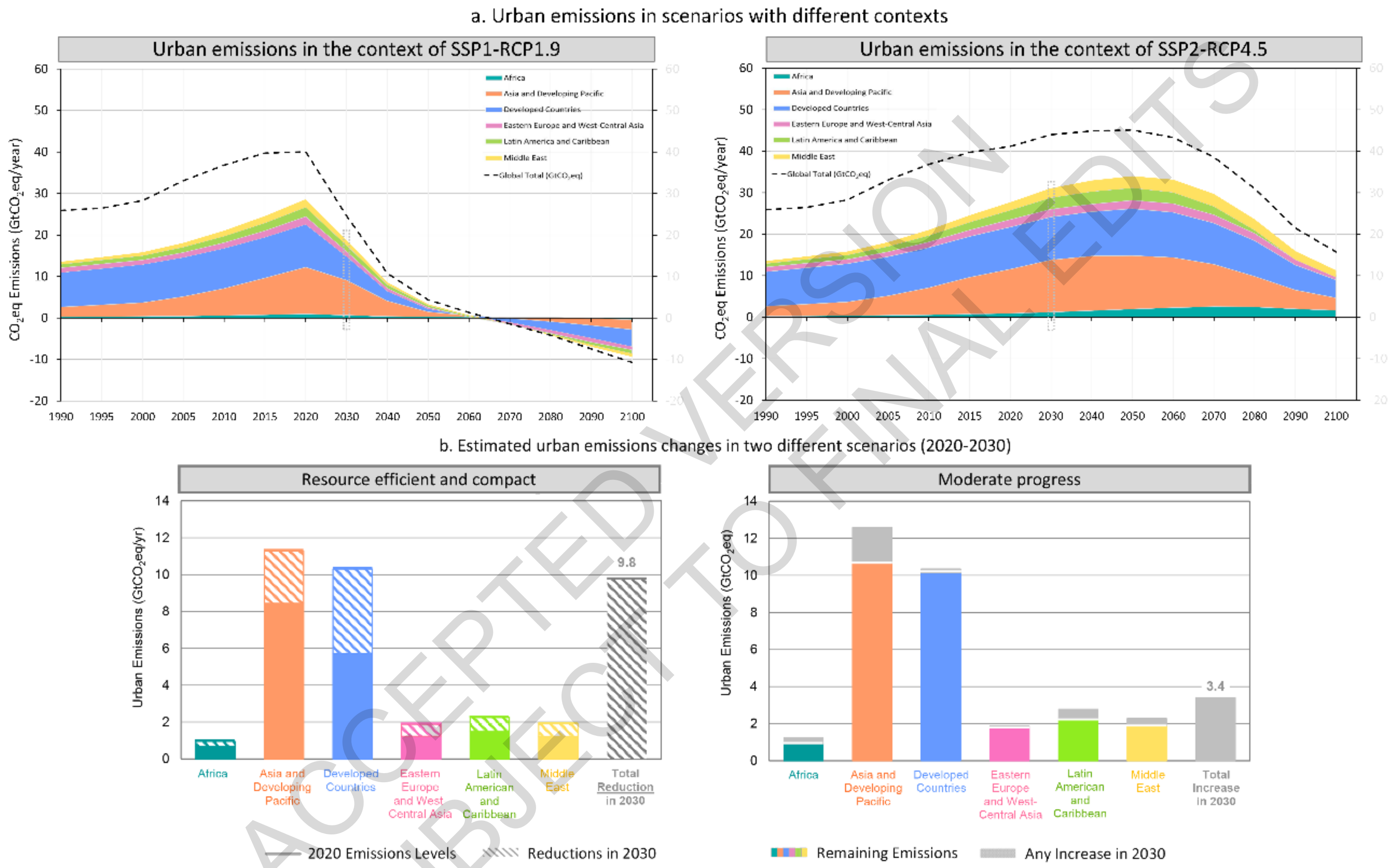


Figure TS.13 Panel a: Carbon dioxide equivalent emissions from global urban areas from 1990 to 2100. Urban areas are aggregated to five regional domains; Panel b: Comparison of urban emissions under different urbanisation scenarios (GtCO$_2$-eq yr^{-1}) for different regions {Figure 8.13, Figure 8.14}

Urban land areas could triple between 2015 and 2050, with significant implications for future carbon lock-in (*medium confidence*). There is a large range in the forecasts of urban land expansion across scenarios and models, which highlights an opportunity to shape future urban development towards low- or net zero GHG emissions. By 2050, urban areas could increase up to 211% over the 2015 global urban extent, with the median projected increase ranging from 43% to 106%. While the largest absolute amount of new urban land is forecasted to occur in Asia and Developing Pacific, and in Developed Countries, the highest rate of urban land growth is projected to occur in Africa, Eastern Europe and West-Central Asia, and in the Middle East. Given past trends, the expansion of urban areas is expected to take place on agricultural lands and forests, with implications for the loss of carbon stocks. The infrastructure that will be constructed concomitant with urban land expansion will lock-in patterns of energy consumption that will persist for decades. {8.3.1, 8.3.4, 8.4.1, 8.6}

The construction of new, and upgrading of existing, urban infrastructure through 2030 will add to emissions (*medium evidence, high agreement)*. The construction of new and upgrading of existing urban infrastructure using conventional practices and technologies can result in significant increase in CO_2 emissions, ranging from 8.5 $GtCO_2$ to 14 $GtCO_2$ annually up to 2030 and more than double annual resource requirements for raw materials to about 90 billion tonnes per year by 2050, up from 40 billion tonnes in 2010. {8.4.1, 8.6}

Given the dual challenges of rising urban GHG emissions and future projections of more frequent extreme climate events, there is an urgent need to integrate urban mitigation and adaptation strategies for cities to address climate change *(very high confidence).* Mitigation strategies can enhance resilience against climate change impacts while contributing to social equity, public health, and human well-being. Urban mitigation actions that facilitate economic decoupling can have positive impacts on employment and local economic competitiveness. {8.2, Cross-Working Group Box 2 in Chapter 8, 8.4}

Cities can achieve net zero or near net zero GHG emissions only through deep decarbonisation and systemic transformation *(very high confidence).* Effective emission reductions in cities entail implementing three broad strategies concurrently: (1) reducing urban energy consumption across all sectors, including through compact and efficient urban forms and supporting infrastructure; (2) electrification and switching to low carbon energy sources; and (3) enhancing carbon uptake and stocks (*medium evidence, high agreement*). Given the regional and global reach of urban supply chains, a city cannot achieve net zero GHG emissions by only focusing on reducing emissions within its administrative boundaries. {8.1.6, 8.3.4, 8.4, 8.6}

Packages of mitigation policies that implement multiple urban-scale interventions can have cascading effects across sectors, reduce GHG emissions outside a city's administrative boundaries, and reduce emissions more than the net sum of individual interventions, particularly if multiple scales of governance are included *(high confidence).* Cities have the ability to implement policy packages across sectors using an urban systems approach, especially those that affect key infrastructure based on spatial planning, electrification of the urban energy system, and urban green and blue infrastructure. The institutional capacity of cities to develop, coordinate, and integrate sectoral mitigation strategies within their jurisdiction varies by context, particularly those related to governance, the regulatory system, and budgetary control. {8.4, 8.5, 8.6}

Integrated spatial planning to achieve compact and resource-efficient urban growth through co-location of higher residential and job densities, mixed land use, and transit-oriented development could reduce urban energy use between 23-26% by 2050 compared to the business-as-usual scenario (*high confidence*). Compact cities with shortened distances between housing and jobs, and interventions that support a modal shift away from private motor vehicles towards walking, cycling, and low-emissions shared, or public, transportation, passive energy comfort in buildings, and urban green infrastructure can deliver significant public health benefits and lower GHG emissions. {8.2, 8.3.4, 8.4, 8.6}

Urban green and blue infrastructure can mitigate climate change through carbon sinks, avoided emissions, and reduced energy use while offering multiple co-benefits (*high confidence*). Urban green and blue infrastructure, including urban forests and street trees, permeable surfaces, and green roofs offer potentials to mitigate climate change directly through storing carbon, and indirectly by inducing a cooling effect that reduces energy demand and reducing energy use for water treatment. Globally, urban trees store approximately 7.4 billion tonnes of carbon, and sequester approximately 217 million tonnes of carbon annually, although carbon storage is highly dependent on biome. Among the multiple co-benefits of green and blue infrastructure are reducing the urban heat island (UHI) effect and heat stress, reducing stormwater runoff, improving air quality, and improving the mental and physical health of urban dwellers. Many of these options also provide benefits to climate adaptation. {8.2, 8.4.4}

The potentials and sequencing of mitigation strategies to reduce GHG emissions will vary depending on a city's land use and spatial form and its state of urbanisation, whether it is an established city with existing infrastructure, a rapidly growing city with new infrastructure, or an emerging city with infrastructure build-up *(medium confidence)*. The long lifespan of urban infrastructures locks in behaviour and emissions. Urban infrastructures and urban form can enable socio-cultural and lifestyle changes that can significantly reduce carbon footprints. Rapidly growing cities can avoid higher future emissions through urban planning to co-locate jobs and housing to achieve compact urban form, and by leapfrogging to low-carbon technologies. Established cities will achieve the largest GHG emissions savings by replacing, repurposing, or retrofitting the building stock, strategic infilling and densifying, as well as through modal shift and the electrification of the urban energy system. New and emerging cities have unparalleled potential to significantly reduce GHG emissions while achieving high quality of life by creating compact, co-located, and walkable urban areas with mixed land use and transit-oriented design, that also preserve existing green and blue assets. {8.2, 8.4, 8.6}

With over 880 million people living in informal settlements, there are opportunities to harness and enable informal practices and institutions in cities related to housing, waste, energy, water, and sanitation to reduce resource use and mitigate climate change *(low evidence, medium agreement)*. The upgrading of informal settlements and inadequate housing to improve resilience and well-being offers a chance to create a low-carbon transition. However, there is limited quantifiable data on these practices and their cumulative impacts on GHG emissions. {8.1.4, 8.2.2, Cross-Working Group Box 2 in Chapter 8, 8.3.2, 8.4, 8.6, 8.7}

Achieving transformational changes in cities for climate change mitigation and adaptation will require engaging multiple scales of governance, including governments and non-state actors, and in connection with substantial financing beyond sectoral approaches *(very high confidence)*. Large and complex infrastructure projects for urban mitigation are often beyond the capacity of local municipality budgets, jurisdictions, and institutions. Partnerships between cities and international institutions, national and region governments, transnational networks, and local stakeholders play a pivotal role in mobilizing global climate finance resources for a range of infrastructure projects with low-carbon emissions and related spatial planning programs across key sectors. {8.4, 8.5}

TS. 5.3 Transport

Meeting climate mitigation goals would require transformative changes in the transport sector. In 2019, direct GHG emissions from the transport sector were 8.7 $GtCO_2$-eq (up from 5.0 $GtCO_2$-eq in 1990) and accounted for 23% of global energy-related CO_2 emissions. 70% of direct transport emissions came from road vehicles, while 1%, 11%, and 12% came from rail, shipping, and aviation, respectively. Emissions from shipping and aviation continue to grow rapidly. Transport-related emissions in developing regions of the world have increased more rapidly than in Europe or North America, a trend that is expected to continue in coming decades. (*high confidence*) {10.1, 10.5, 10.6}

Since AR5 there has been a growing awareness of the need for demand management solutions combined with new technologies, such as the rapidly growing use of electromobility for land transport and the emerging options in advanced biofuels and hydrogen-based fuels for shipping and aviation and in other specific land-based contexts (*high confidence*). There is a growing need for systemic infrastructure changes that enable behavioural modifications and reductions in demand for transport services that can in turn reduce energy demand. The response to the COVID-19 pandemic has also shown that behavioural interventions can reduce transport-related GHG emissions. For example, COVID-19-based lockdowns have confirmed the transformative value of telecommuting replacing significant numbers of work and personal journeys as well as promoting local active transport. There are growing opportunities to implement strategies that drive behavioural change and support the adoption of new transport technology options. {Chapter 5, 10.2, 10.3, 10.4, 10.8}

Changes in urban form, behaviour programs, the circular economy, the shared economy, and digitalisation trends can support systemic changes that lead to reductions in demand for transport services or expands the use of more efficient transport modes (*high confidence*). Cities can reduce their transport-related fuel consumption by around 25% through combinations of more compact land use and the provision of less car-dependent transport infrastructure. Appropriate infrastructure, including protected pedestrian and bike pathways, can also support much greater localised active travel.[17] Transport demand management incentives are expected to be necessary to support these systemic changes. There is mixed evidence of the effect of circular economy initiatives, shared economy initiatives, and digitalisation on demand for transport services (Box TS.14). For example, while dematerialisation can reduce the amount of material that needs to be transported to manufacturing facilities, an increase in online shopping with priority delivery can increase demand for freight transport. Similarly, while teleworking could reduce travel demand, increased ridesharing could increase vehicle-km travelled. {Chapter 1, Chapter 5, 10.2, 10.8}

Battery-electric vehicles (BEVs) have lower life cycle greenhouse gas emissions than internal combustion engine vehicles (ICEVs) when BEVs are charged with low carbon electricity (*high confidence*). Electromobility is being rapidly implemented in micro-mobility (e-autorickshaws, e-scooters, e-bikes), in transit systems, especially buses, and to a lesser degree, in personal vehicles. BEVs could also have the added benefit of supporting grid operations. The commercial availability of mature lithium-ion batteries (LIBs) has underpinned this growth in electromobility. As global battery production increases, unit costs are declining. Further efforts to reduce the GHG footprint of battery production, however, are essential for maximising the mitigation potential of BEVs. The continued growth of electromobility for land transport would entail investments in electric charging and related grid infrastructure. Electromobility powered by low-carbon electricity has the potential to rapidly reduce transport GHG and can be applied with multiple co-benefits, especially in the developing countries. {10.3, 10.4, 10.8}

FOOTNOTE [17] 'Active travel' is travel that requires physical effort, for example journeys made by walking or cycling.

Land-based, long-range, heavy-duty trucks can be decarbonised through battery-electric haulage (including the use of electric road systems), complemented by hydrogen- and biofuel-based fuels in some contexts. These same technologies and expanded use of available electric rail systems can support rail decarbonisation *(medium confidence*). Initial deployments of battery-electric, hydrogen- and bio-based haulage are underway, and commercial operations of some of these technologies are considered feasible by 2030 *(medium confidence)*. These technologies nevertheless face challenges regarding driving range, capital and operating costs, and infrastructure availability. In particular, fuel cell durability, high energy consumption, and costs continue to challenge the commercialisation of hydrogen-based fuel cell vehicles. Increased capacity for low-carbon hydrogen production would also be essential for hydrogen-based fuels to serve as an emissions reduction strategy *(high confidence)*. (Box TS.15) {10.3, 10.4, 10.8}

Decarbonisation options for shipping and aviation still require R&D, though advanced biofuels, ammonia, and synthetic fuels are emerging as viable options *(medium confidence*). Increased efficiency has been insufficient to limit the emissions from shipping and aviation, and natural gas-based fuels are expected to be inadequate to meet stringent decarbonisation goals for these segments (*high confidence*). High energy density, low carbon fuels are required, but they have not yet reached commercial scale. Advanced biofuels could provide low carbon jet fuel (*medium confidence*). The production of synthetic fuels using low-carbon hydrogen with CO_2 captured through DACCS/BECCS could provide jet and marine fuels but these options still require demonstration at scale (*low confidence*). Ammonia produced with low-carbon hydrogen could also serve as a marine fuel (*medium confidence*). Deployment of these fuels requires reductions in production costs. (Figure TS.14) {10.2, 10.3, 10.4, 10.5, 10.6, 10.8}

Scenarios from bottom-up and top-down models indicate that, without intervention, CO_2 emissions from transport could grow in the range of 16% and 50% by 2050 (*medium confidence*). The scenarios literature projects continued growth in demand for freight and passenger services, particularly in developing countries in Africa and Asia (*high confidence*). This growth is projected to take place across all transport modes. Increases in demand notwithstanding, scenarios that limit warming to 1.5°C degree with no or limited overshoot suggest that a 59% reduction (42-68% interquartile range) in transport-related CO_2 emissions by 2050, compared to modelled 2020 levels is required. While many global scenarios place greater reliance on emissions reduction in sectors other than transport, a quarter of the 1.5°C scenarios describe transport-related CO_2 emissions reductions in excess of 68% (relative to modelled 2020 levels) (*medium confidence)*. Illustrative Mitigation Pathways IMP-ren and IMP-LD (TS 4.2) describe emission reductions of 80% and 90% in the transport sector, respectively, by 2050. Transport-related emission reductions, however, may not happen uniformly across regions. For example, transport emissions from the Developed Countries, and Eastern Europe and West-Central Asia countries decrease from 2020 levels by 2050 across all scenarios limiting global warming to 1.5°C by 2100, but could increase in Africa, Asia and developing Pacific (APC), Latin America and Caribbean, and the Middle East in some of these scenarios. {10.7}

The scenarios literature indicates that fuel and technology shifts are crucial in reducing carbon emissions to meet temperature goals (*high confidence*). In general terms, electrification tends to play the key role in land-based transport, but biofuels and hydrogen (and derivatives) could play a role in decarbonisation of freight in some contexts. Biofuels and hydrogen (and derivatives) are expected to be more prominent in shipping and aviation. The shifts towards these alternative fuels must occur alongside shifts towards clean technologies in other sectors. {10.7}

There is a growing awareness of the need to plan for the significant expansion of low-carbon energy infrastructure, including low-carbon power generation and hydrogen production, to support emissions reductions in the transport sector (*high confidence*). Integrated energy planning and operations that take into account energy demand and system constraints across all sectors (transport, buildings, and industry) offer the opportunity to leverage sectoral synergies and avoid inefficient allocation of energy resources. Integrated planning of transport and power infrastructure would be particularly useful in developing countries where 'greenfield' development doesn't suffer from constraints imposed by legacy systems. {10.3, 10.4, 10.8}

The deployment of low-carbon aviation and shipping fuels that support decarbonisation of the transport sector could require changes to national and international governance structures (*medium confidence*). The UNFCCC does not specifically cover emissions from international shipping and aviation. Reporting emissions from international transport is at the discretion of each country. While the International Civil Aviation Organisation (ICAO) and International Maritime Organisation (IMO) have established emissions reductions targets, only strategies to improve fuel efficiency and demand reductions have been pursued, and there has been minimal commitment to new technologies. {10.5, 10.6, 10.7}

There are growing concerns about resource availability, labour rights, non-climate environmental impacts, and costs of critical minerals needed for lithium-ion batteries (*medium confidence*). Emerging national strategies on critical minerals and the requirements from major vehicle manufacturers are leading to new, more geographically diverse mines. The standardisation of battery modules and packaging within and across vehicle platforms, as well as increased focus on design for recyclability are important. Given the high degree of potential recyclability of lithium-ion batteries, a nearly closed-loop system in the future could mitigate concerns about critical mineral issues (*medium confidence*). {10.3, 10.8}

Legislated climate strategies are emerging at all levels of government, and together with pledges for personal choices, could spur the deployment of demand and supply-side transport mitigation strategies (*medium confidence*). At the local level**,** legislation can support local transport plans that include commitments or pledges from local institutions to encourage behaviour change by adopting an organisational culture that motivates sustainable behaviour with inputs from the creative arts. Such institution-led mechanisms could include bike-to-work campaigns, free transport passes, parking charges, or eliminating car benefits. Community-based solutions like *solar sharing*, *community charging*, and *mobility as a service* can generate new opportunities to facilitate low-carbon transport futures. At the regional and national levels, legislation can include vehicle and fuel efficiency standards, R&D support, and large-scale investments in low-carbon transport infrastructure. (Figure TS.14) {10.8, Chapter 15}

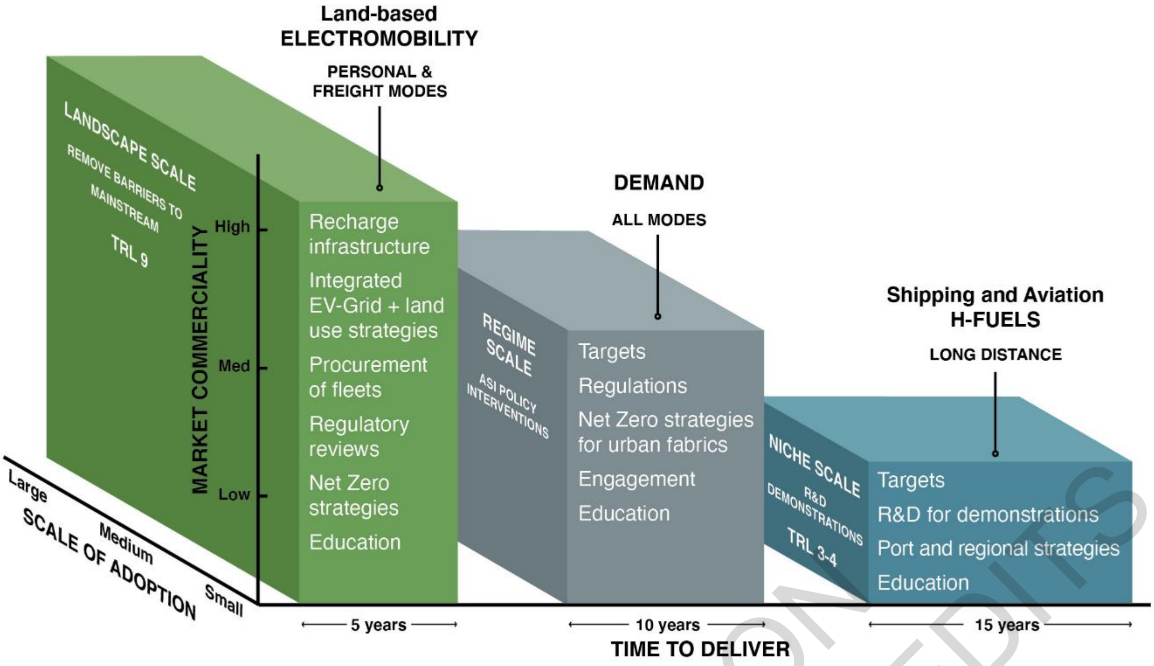


Figure TS.14: Mitigation Options and Enabling Conditions for Transport. 'Niche' scale includes strategies that still require innovation. {Figure 10.22}

ASI: Avoid Shift, Improve; TRL: Technology readiness level

TS. 5.4 Buildings

Global GHG emissions from buildings were 12 $GtCO_2$-eq in 2019, equivalent to 21% of global GHG emissions. Of this, 57% (6.8 $GtCO_2$-eq) were indirect emissions from offsite generation of electricity and heat, 24% (2.9 $GtCO_2$-eq) direct emissions produced onsite and 18% (2.2 $GtCO_2$-eq) were embodied emissions from the production of cement and steel used in buildings (*high confidence*). Most building sector emissions are CO_2. Final energy demand from buildings reached 128 EJ globally in 2019 (around 31% of global final energy demand), and electricity demand from buildings was slightly above 43 EJ globally (around 18% of global electricity demand). Residential buildings consumed 70% (90 EJ) of the global final energy demand from buildings. Over the period 1990-2019, global CO_2 emissions from buildings increased by 50%, global final energy demand from buildings grew by 38% and global final electricity demand increased by 161%. {9.3}

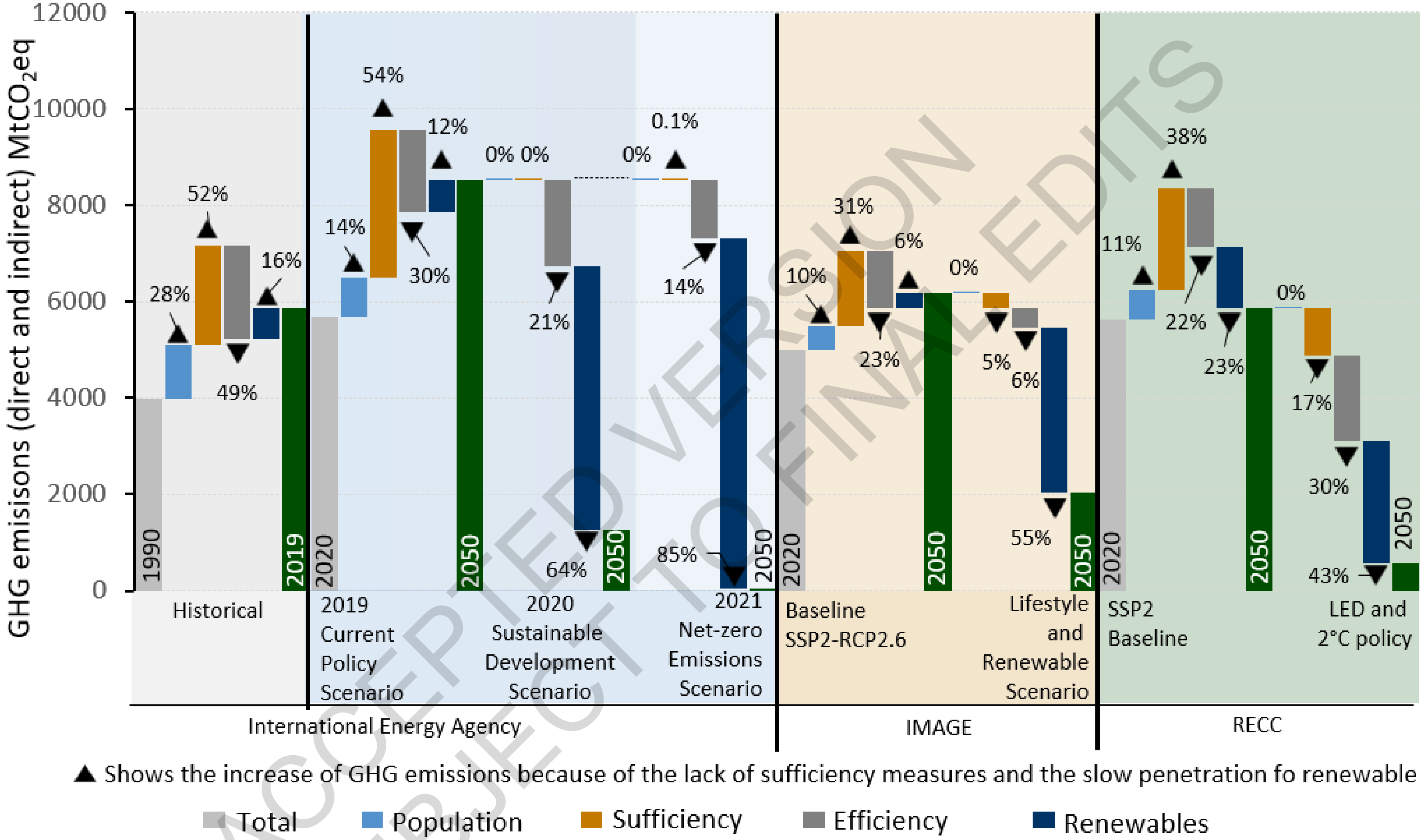
In most regions, historical improvements in efficiency have been approximately matched by growth in floor area per capita (*high confidence*). At the global level, building specific drivers of GHG emissions include: (i) population growth, especially in developing countries; (ii) increasing floor area per capita, driven by the increasing size of dwellings while the size of households kept decreasing, especially in developed countries; (iii) the inefficiency of newly constructed buildings, especially in developing countries, and the low renovation rates and low ambition level in developed countries when existing buildings are renovated; iv) the increase in use, number and size of appliances and equipment, especially Information and Communication Technologies (ICT) and cooling, driven by income; and, (v) the continued reliance on carbon intensive electricity and heat. These factors taken together are projected to continue driving increased GHG emissions in the building sector in the future. {9.3, 9.6, 9.9}

Building sector GHG emissions were assessed using the Sufficiency, Efficiency, Renewable (SER) framework. Sufficiency measures tackle the causes of GHG emissions by limiting the demand for energy and materials over the lifecycle of buildings and appliances (*high confidence*). In Chapter 9 of this report, *sufficiency* differs from *efficiency*. *Sufficiency* is about long-term actions driven by non-technological solutions, which consume less energy in absolute terms. *Efficiency*, in contrast is about continuous short-term marginal technological improvements. Use of the SER framework reduces the cost of constructing and using buildings without reducing occupant's well-being and comfort. {9.1, 9.4, 9.5, 9.9}

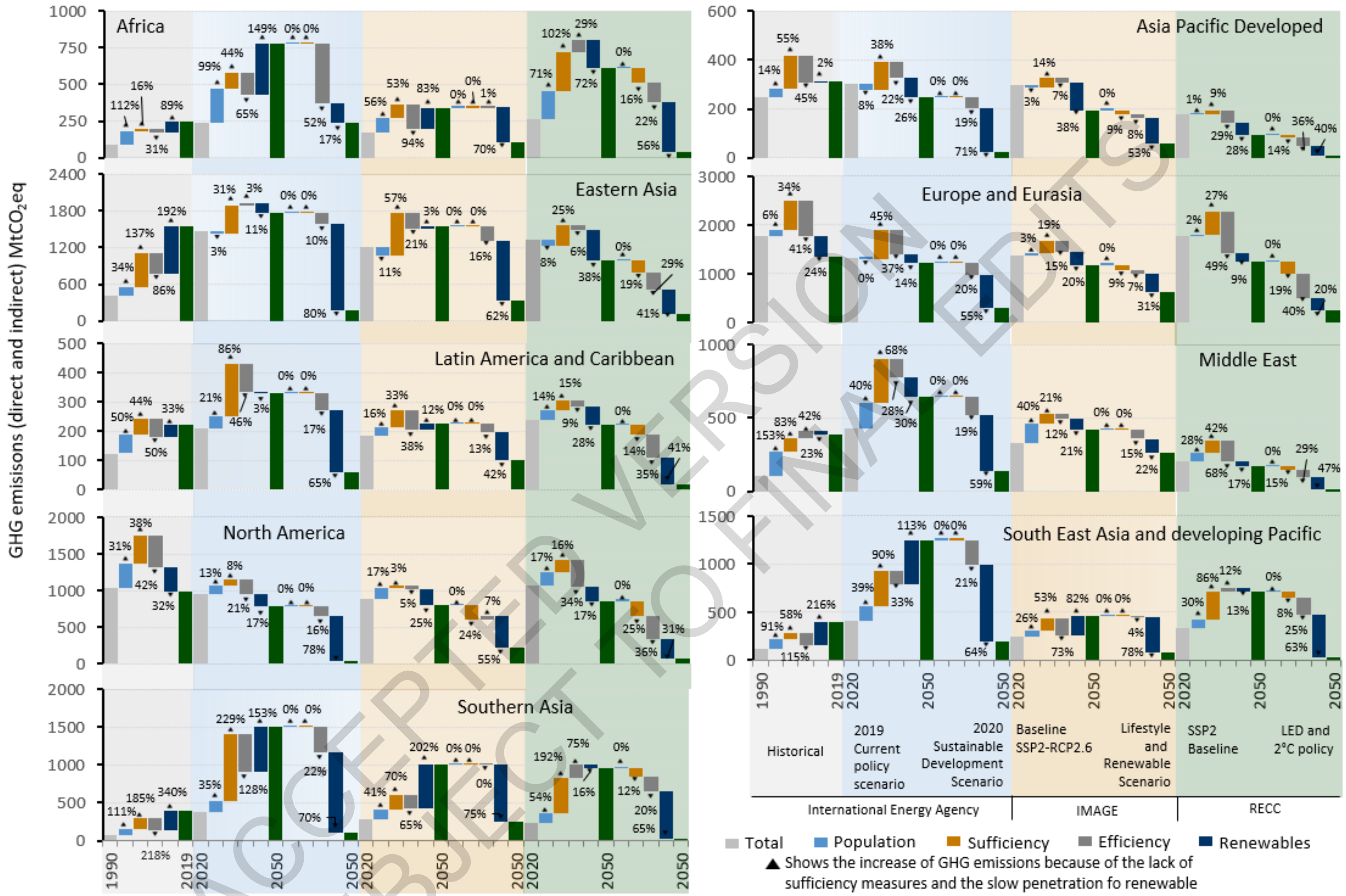
Sufficiency interventions do not consume energy during the use phase of buildings and do not require maintenance nor replacement over the lifetime of buildings. Density, compacity, bioclimatic design to optimise the use of nature-based solutions, multi-functionality of space through shared space and to allow for adjusting the size of buildings to the evolving needs of households, circular use of materials and repurposing unused existing buildings to avoid using virgin materials, optimisation of the use of buildings through lifestyle changes, use of the thermal mass of buildings to reduce thermal needs, moving from ownership to usership of appliances are among the sufficiency interventions implemented in leading municipalities (*high confidence*). At a global level, up to 17% of the mitigation potential in the buildings sector could be captured by 2050 through sufficiency interventions (*medium confidence*). (Figure TS. 15) {9.2, 9.3, 9.4, 9.5, 9.9}.

The potential associated with sufficiency measures, as well as the replacement of appliances, equipment and lights by efficient ones, is below zero cost (*high confidence*). The construction of high-performance buildings is expected to become a business-as-usual technology by 2050 with costs below USD20 tCO_2^{-1} in developed countries and below USD100 tCO_2^{-1} in developing countries (*medium confidence*). For existing buildings, there have been many examples of deep retrofits where additional costs per CO_2 abated are not significantly higher than those of shallow retrofits. However, for the whole building stock they tend to be in cost intervals of USD-200 tCO_2^{-1} and >USD200 tCO_2^{-1}

(*medium confidence*). Literature emphasizes the critical role of the 2020-2030 decade in accelerating the learning of know-how and skills to reduce the costs and remove feasibility constraints for achieving high efficiency buildings at scale and set the sector in the pathway to realize its full potential (*high confidence*). {9.3, 9.6, 9.9}.



Panel a: global



Panel b: regional

Figure TS.15: Decompositions of changes in historical residential energy emissions 1990-2019, changes in emissions projected by baseline scenarios for 2020-2050, and differences between scenarios in 2050 using scenarios from three models: IEA, IMAGE, and RECC.

Figure TS.15 legend: RECC-LED data include only space heating and cooling and water heating in residential buildings (a) Global resolution, and (b) for nine world regions. Emissions are decomposed using the equation $\mathrm{CO_2}\ \mathrm{Pop} \times \frac{\mathrm{m^2}}{\mathrm{Pop}} \times \frac{\mathrm{EJ}}{\mathrm{m^2}} \times \frac{\mathrm{Mt_{CO2}}}{\mathrm{EJ}} = \mathrm{Pop} \times \mathrm{Sufficiency} \times \mathrm{Efficiency} \times \mathrm{Renenewable}$, which shows changes in driver variables of population, sufficiency (floor area per capita), efficiency (final energy per floor area), and renewables (GHG emissions per final energy). 'Renewables' is a summary term describing changes in GHG intensity of energy supply. Emission projections to 2050, and differences between scenarios in 2050, demonstrate mitigation potentials from the dimensions of the SER framework realised in each model scenario. In most regions, historical improvements in efficiency have been approximately matched by growth in floor area per capita. Implementing sufficiency measures that limit growth in floor area per capita, particularly in developed regions, reduces the dependence of climate mitigation on technological solutions. {Figure 9.5, Box 9.2}

The development, since AR5, of integrated approaches to the construction and retrofit of buildings has led to increasing the number of zero energy or zero carbon buildings in almost all climate zones. The complementarity and interdependency of measures leads to cost reductions, while optimising the mitigation potential achieved and avoiding the lock-in-effect (*medium confidence*). {9.6, 9.9}

The decarbonisation of buildings is constrained by multiple barriers and obstacles as well as limited finance flows (*high confidence*). The lack of institutional capacity, especially in developing countries, and appropriate governance structures slow down the decarbonisation of the global building stock (*medium confidence*). The building sector is highly heterogenous with many different building types, sizes, and operational uses. The sub-segment representing rented property faces principal/agent problems where the tenant benefits from the decarbonisation's investment made by the landlord. The organisational context and the governance structure could trigger or hinder the decarbonisation of buildings. Global investment in the decarbonisation of buildings was estimated at USD164 billion in 2020. However, this is not enough by far to close the investment gap (*high confidence*). {9.9}

Policy packages could grasp the full mitigation potential of the global building stock. Building energy codes represent the main regulatory instrument to reduce emissions from both new and existing buildings (*high confidence*). The most advanced building energy codes include requirements on each of the three pillars of the SER framework in the *use* and *construction* phase of buildings. Building energy codes have proven to be effective if compulsory and combined with other regulatory instruments such as minimum energy performance standard for appliances and equipment, if the performance level is set at the level of the best available technologies in the market (*high confidence*). Market-based instruments such as carbon taxes with recycling of the revenues and personal or building carbon allowances could also contribute to fostering the decarbonisation of the building sector (*medium confidence*). {9.9}

Adapting buildings to future climate while ensuring well-being for all requires action. Expected heatwaves will inevitably increase cooling needs to limit the health impacts of climate change (*medium confidence*). Global warming will impact cooling and heating needs but also the performance, durability and safety of buildings, especially historical and coastal ones, through changes in temperature, humidity, atmospheric concentrations of CO_2 and chloride, and sea level rise. Adaptation measures to cope with climate change may increase the demand for energy and materials leading to an increase in GHG emissions if not mitigated. Sufficiency measures which anticipate climate change, and include natural ventilation, white walls, and nature-based solutions (e.g. green roofs) will decrease the demand for cooling. Shared cooled spaces with highly efficient cooling solutions are among the mitigation strategies which can limit the effect of the expected heatwaves on people's health. {9.7, 9.8}

Well-designed and effectively implemented mitigation actions in the buildings sector have significant potential to help achieve the SDGs (*high confidence*). As shown in Figure TS.16, the impacts of mitigation actions in the building sector go far beyond the goal of climate action (SDG13) and contribute to meeting fifteen other SDGs. Mitigation actions in the building sector bring health gains through improved indoor air quality and thermal comfort, and have positive significant macro- and micro-economic effects, such as increased productivity of labour, job creation, reduced poverty, especially energy poverty, and improved energy security (*high confidence*). (Figure TS.29) {9.8}

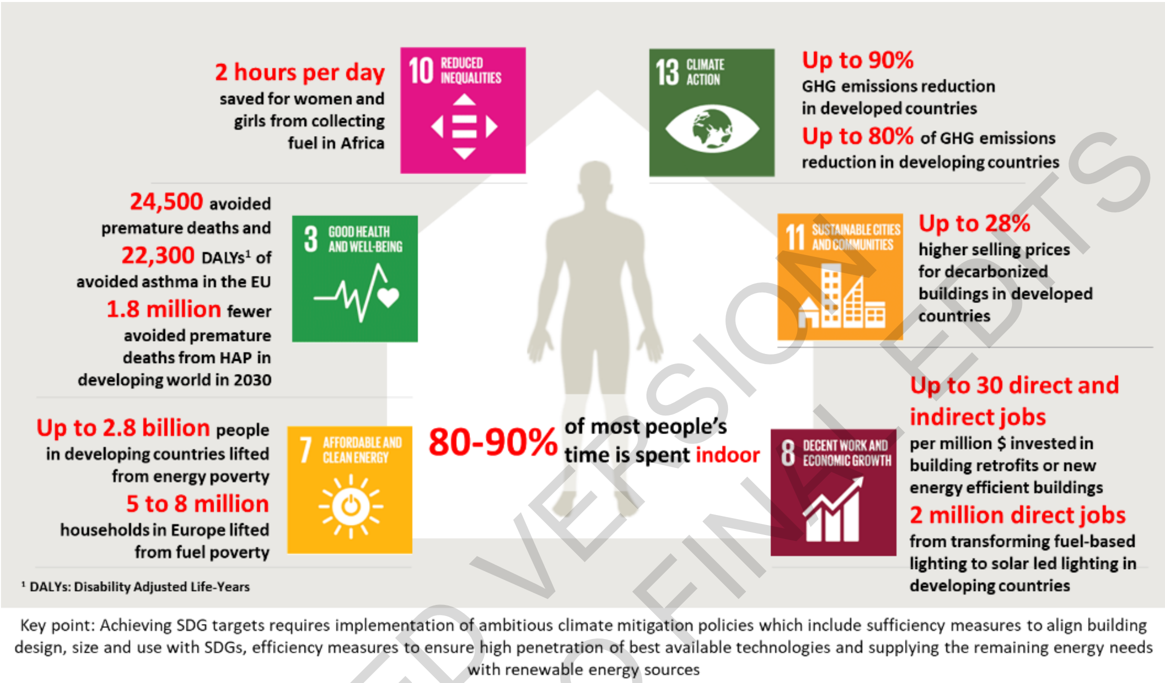


Figure TS.16. Contribution of building sector mitigation policies to meeting sustainable development goals. {Figure 9.18}

The COVID-19 pandemic emphasised the importance of buildings for human well-being and highlighted the inequalities in access for all to suitable, healthy buildings, which provide natural daylight and clean air to their occupants (*medium confidence*). The new WHO health recommendations emphasised indoor air quality, preventive maintenance of centralised mechanical heating, ventilation, and cooling systems. There are opportunities for repurposing existing non-residential buildings, no longer in use due to the expected spread of teleworking triggered by the health crisis and enabled by digitalisation. (TS BOX.14) {9.1}

TS. 5.5 Industry

The industry chapter focuses on new developments since AR5 and emphasises the role of the energy-intensive and emissions-intensive basic materials industries in strategies for reaching net zero emissions. The Paris Agreement, the SDGs and the COVID-19 pandemic provide a new context for the evolution of industry and mitigation of industry greenhouse gas (GHG) emissions *(high confidence)*. {11.1.1}

Net zero CO_2 industrial sector emissions are possible but challenging *(high confidence)*. Energy efficiency will continue to be important. Reduced materials demand, material efficiency, and circular economy solutions can reduce the need for primary production. Primary production options include switching to new processes that use low to zero GHG energy carriers and feedstocks (e.g., electricity, hydrogen, biofuels, and carbon dioxide capture and utilisation (CCU) to provide carbon feedstocks). Carbon capture and storage (CCS) will be required to mitigate remaining CO_2 emissions {11.3}. These options require substantial scaling up of electricity, hydrogen, recycling, CO_2, and other infrastructure, as well as phase-out or conversion of existing industrial plants. While improvements in the GHG intensities of major basic materials have nearly stagnated over the last 30 years, analysis of historical technology shifts and newly available technologies indicate these intensities can be significantly reduced by mid-century. {11.2, 11.3, 11.4}

Industry sector emissions have been growing faster since 2000 than emissions in any other sector, driven by increased basic materials extraction and production *(high confidence)*. GHG emissions attributed to the industrial sector originate from fuel combustion, process emissions, product use and waste, which jointly accounted for 14.1 $GtCO_2$-eq or 24% of all direct anthropogenic emissions in 2019, second behind the energy supply sector. Industry is a leading GHG emitter - 20 $GtCO_2$-eq or 34% of global emissions in 2019 - if indirect emissions from power and heat generation are included. The share of emissions originating from direct fuel combustion is decreasing and was 7 $GtCO_2$-eq, 50% of direct industrial emissions in 2019. {11.2.2}

Global material intensity – the in-use stock of manufactured capital in tonnes per unit of GDP– is increasing *(high confidence)*. In-use stock of manufactured capital per capita has been growing faster than GDP per capita since 2000. Total global in-use stock of manufactured capital grew by 3.4% yr^{-1} in 2000–2019. At the same time, per capita material stocks in several developed countries have stopped growing, showing a decoupling from GDP per capita. {11.2.1, 11.3.1}

The demand for plastic has been growing most strongly since 1970 *(high confidence)*. The current >99% reliance on fossil feedstock, very low recycling, and high emissions from petrochemical processes is a challenge for reaching net zero emissions. At the same time, plastics are important for reducing emissions elsewhere, for example, light-weighting vehicles. There are as yet no shared visions for fossil-free plastics, but several possibilities. {11.4.1.3}

Scenario analyses show that significant reductions in global GHG emissions and even close to net zero emissions from GHG intensive industry (e.g., steel, plastics, ammonia, and cement) can be achieved by 2050 by deploying multiple available and emerging options *(medium confidence)*. Significant reductions in industry emissions require a reorientation from the historic focus on important but incremental improvements (e.g., energy efficiency) to transformational changes in energy and feedstock sourcing, materials efficiency, and more circular material flows. {11.3, 11.4}

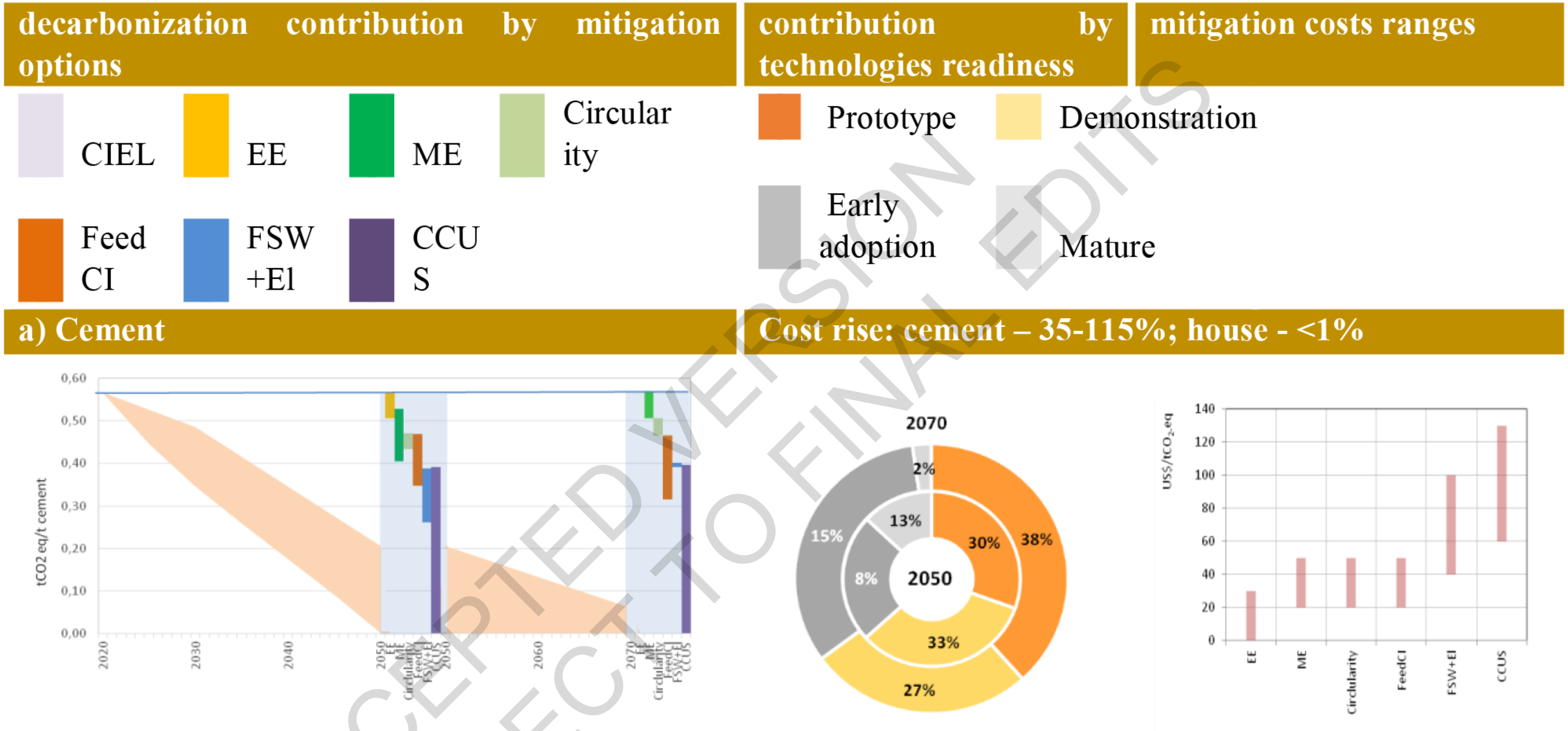
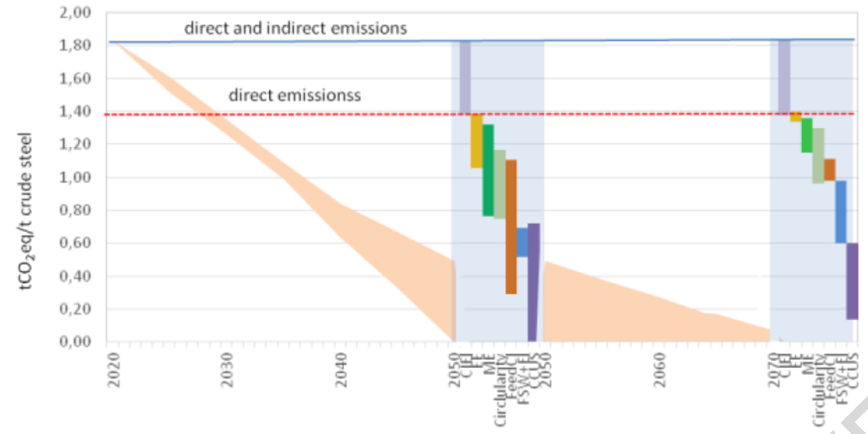
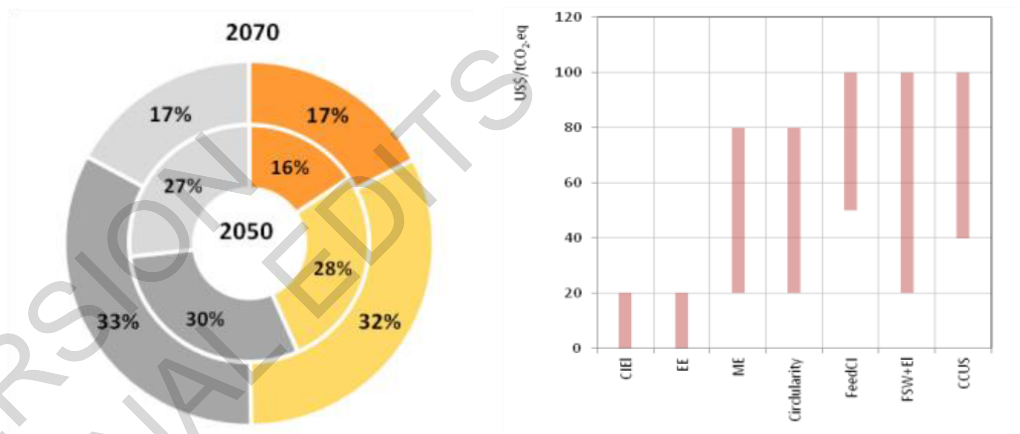


Figure TS.17 Page-i: Potentials and costs for zero-carbon mitigation options for industry and basic materials

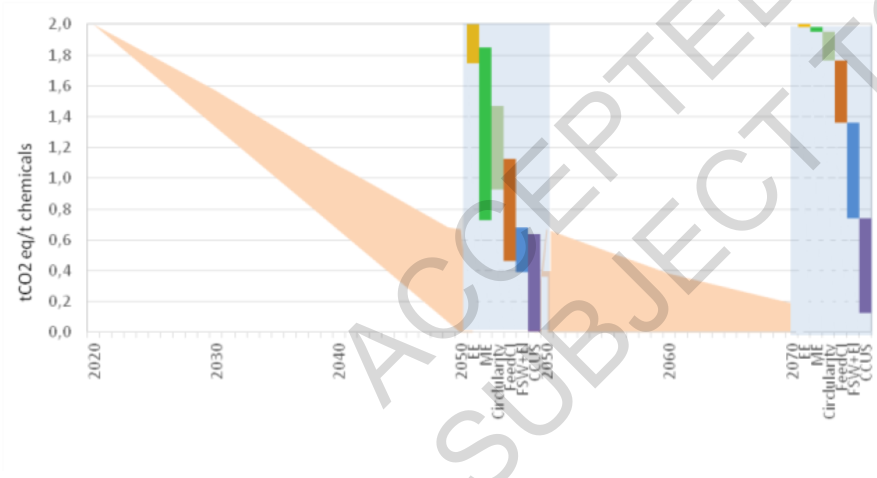
b) Steel



Cost rise: steel – 10-50%; house or car - <1%



c) Primary chemicals



Cost rise: primary chemicals – 15-115%; plastic bottle - <1%

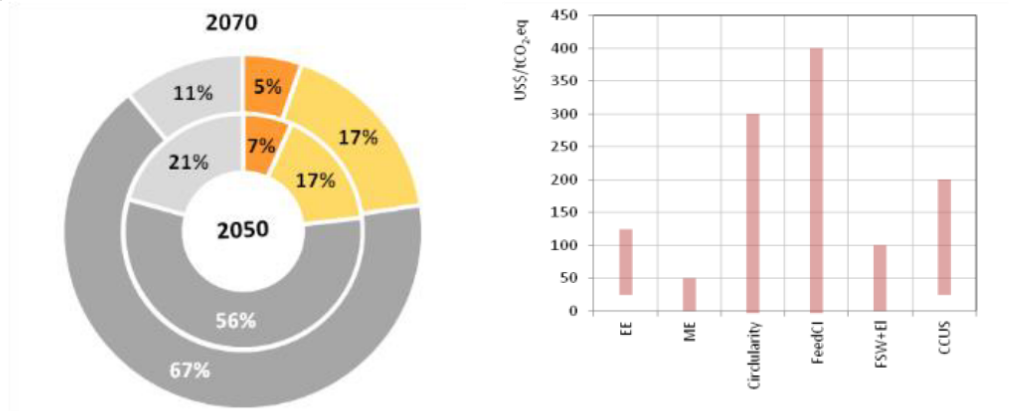


Figure TS.17 Page-ii: Potentials and costs for zero-carbon mitigation options for industry and basic materials

d) Industry (waste excluded)

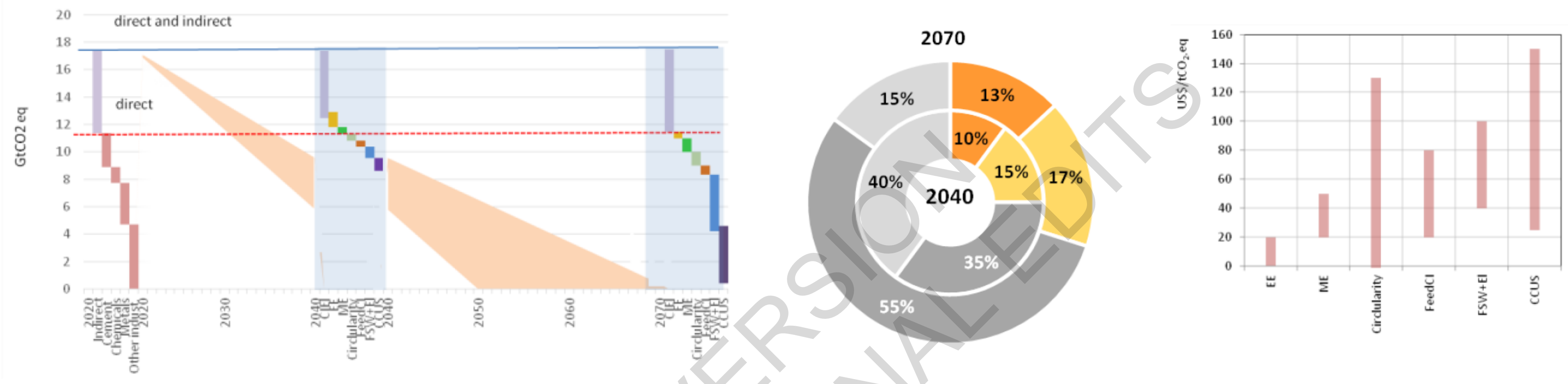


Figure TS.17 page-iii : Potentials and costs for zero-carbon mitigation options for industry and basic materials

Figure TS.17 legend: Key shown on Figure TS.17 page-i also applies to TS.17 pages ii & iii. CIEl –carbon intensity of electricity for indirect emissions; EE – energy efficiency; ME – material efficiency; Circularity - material flows (clinker substituted by coal fly ash, blast furnace slag or other by-products and waste, steel scrap, plastic recycling, etc.); FeedCI – feedstock carbon intensity (hydrogen, biomass, novel cement, natural clinker substitutes); FSW+El – fuel switch and processes electrification with low carbon electricity. Ranges for mitigation options are shown based on bottom-up studies for grouped technologies packages, not for single technologies. In circles contribution to mitigation from technologies based on their readiness are shown for 2050 (2040) and 2070. Direct emissions include fuel combustion and process emissions. Indirect emissions include emissions attributed to consumed electricity and purchased heat. For basic chemicals only methanol, ammonia and high-value chemicals are considered. Total for industry does not include emissions from waste. Negative mitigation costs for some options like Circularity are not reflected. {Figure 11.13}

Key mitigation options such as materials efficiency, circular material flows and emerging primary processes, are not well represented in climate change scenario modelling and integrated assessment models, albeit with some progress in recent years *(high confidence)*. The character of these interventions (e.g., appearing in many forms across complex value chains, making cost estimates difficult) combined with the limited data on new fossil free primary processes help explain why they are less represented in models than, for example, CCS. As a result, overall mitigation costs and the need for CCS may be overestimated. {11.4.2.1}

Electrification is emerging as a key mitigation option for industry *(high confidence)*. Using electricity directly, or indirectly via hydrogen from electrolysis for high temperature and chemical feedstock requirements, offers many options to reduce emissions. It also can provide substantial grid balancing services, for example through electrolysis and storage of hydrogen for chemical process use or demand response. (Box TS.9) {11.3.5}

Carbon is a key building block in organic chemicals, fuels and materials and will remain important *(high confidence)*. In order to reach net zero CO_2 emissions for the carbon needed in society (e.g., plastics, wood, aviation fuels, solvents, etc.), it is important to close the use loops for carbon and carbon dioxide through increased circularity with mechanical and chemical recycling, more efficient use of biomass feedstock with addition of low GHG hydrogen to increase product yields (e.g., for biomethane and methanol), and potentially direct air capture of CO_2 as a new carbon source. {11.3, 11.4.1}

Production costs for very low to zero emissions basic materials may be high but the cost for final consumers and the general economy will be low *(medium confidence)*. Costs and emissions reductions potential in industry, and especially heavy industry, are highly contingent on innovation, commercialisation, and market uptake policies. Technologies exist to take all industry sectors to very low or zero emissions, but require 5–15 years of intensive innovation, commercialisation, and policy to ensure uptake. Mitigation costs are in the rough range of USD50–150 $tCO_2\text{-eq}^{-1}$, with wide variation within and outside this band. This affects competitiveness and requires supporting policy. Although production cost increases can be significant, they translate to very small increases in the costs for final products, typically less than a few percent depending on product, assumptions, and system boundaries. (Figure TS.17) {11.4.1.5}

Several technological options exist for very low to zero emissions steel, but their uptake will require integrated material efficiency, recycling, and production decarbonisation policies *(high confidence)*. Material efficiency can potentially reduce steel demand by up to 40% based on design for less steel use, long life, reuse, constructability, and low contamination recycling. Secondary production through high quality recycling must be maximised. Production decarbonisation will also be required, starting with the retrofitting of existing facilities for partial fuel switching (e.g., to biomass or hydrogen), CCU and CCS, followed by very low and zero emissions production based on high-capture CCS or direct hydrogen, or electrolytic iron ore reduction followed by an electric arc furnace. {11.3.2, 11.4.1.1}

Several current and emerging options can significantly reduce cement and concrete emissions. Producer, user, and regulator education, as well as innovation and commercialisation policy are needed *(medium confidence)*. Cement and concrete are currently overused because they are inexpensive, durable, and ubiquitous, and consumption decisions typically do not give weight to their production emissions. Basic material efficiency efforts to use only well-made concrete thoughtfully and only where needed (e.g., using right-sized, prefabricated components) could reduce emissions by 24–50% through lower demand for clinker. Cementitious material substitution with various materials (e.g., ground limestone and calcined clays) can reduce process calcination emissions by up to 50% and occasionally much more. Until a very low GHG emissions alternative binder to Portland cement is commercialised – which is not anticipated in the near to medium term – CCS will be essential for eliminating the limestone calcination process emissions for making clinker, which currently represent 60% of GHG emissions in best available technology plants. {11.3.2, 11.3.6, 11.4.1.2}

While several technological options exist for decarbonizing the main industrial feedstock chemicals and their derivatives, the costs vary widely *(high confidence).* Fossil fuel-based feedstocks are inexpensive and still without carbon pricing, and their biomass- and electricity-based replacements are expected to be more expensive. The chemical industry consumes large amounts of hydrogen, ammonia, methanol, carbon monoxide, ethylene, propylene, benzene, toluene, and mixed xylenes & aromatics from fossil feedstock, and from these basic chemicals produces tens of thousands of derivative end-use chemicals. Hydrogen, biogenic or air-capture carbon, and collected plastic waste for the primary feedstocks can greatly reduce total emissions. Biogenic carbon feedstock is expected to be limited due to competing land-uses. {11.4.1}

Light industry and manufacturing can be largely decarbonized through switching to low GHG fuels (e.g., biofuels and hydrogen) and electricity (e.g., for electrothermal heating and heat pumps) *(high confidence).* Most of these technologies are already mature, for example for low temperature heat, but a major challenge is the current low cost of fossil CH_4 and coal relative to low and zero GHG electricity, hydrogen, and biofuels. {11.4.1}

The pulp and paper industry has significant biogenic carbon emissions but relatively small fossil carbon emissions. Pulp mills have access to biomass residues and by-products and in paper mills the use of process heat at low to medium temperatures allows for electrification *(high confidence)*. Competition for feedstock will increase if wood substitutes for building materials and petrochemicals feedstock. The pulp and paper industry can also be a source of biogenic carbon dioxide, carbon for organic chemicals feedstock, and for CDR using CCS. {11.4.1}

The geographical distribution of renewable resources has implications for industry *(medium confidence)*. The potential for zero emission electricity and low-cost hydrogen from electrolysis powered by solar and wind, or hydrogen from other very low emission sources, may reshape where currently energy and emissions intensive basic materials production is located, how value chains are organized, trade patterns, and what gets transported in international shipping. Regions with bountiful solar and wind resources, or low fugitive CH_4 co-located with CCS geology, may become exporters of hydrogen or hydrogen carriers such as methanol and ammonia, or home to the production of iron and steel, organic platform chemicals, and other energy intensive basic materials. {11.2, 11.4, Box 11.1}

The level of policy maturity and experience varies widely across the mitigation options *(high confidence)*. Energy efficiency is a well-established policy field with decades of experience from voluntary and negotiated agreements, regulations, energy auditing and demand side-management (DSM) programs. In contrast, materials demand management and efficiency are not well understood and addressed from a policy perspective. Barriers to recycling that policy could address are often specific to the different material loops (e.g., copper contamination for steel and lack of technologies or poor economics for plastics) or waste management systems. For electrification and fuel switching the focus has so far been mainly on innovation and developing technical supply-side solutions rather than creating market demand. {11.5.2, 11.6}

Industry has so far largely been sheltered from the impacts of climate policy and carbon pricing due to concerns about carbon leakage[18] and reducing competitiveness *(high confidence)*. New approaches to industrial development policy are emerging for a transition to net zero GHG emissions. The transition requires a clear direction towards net zero, technology development, market demand for low-carbon materials and products, governance capacity and learning, socially inclusive phase-out plans, as well as international coordination of climate and trade policies (see also TS 6.5). It requires

FOOTNOTE [18] See section TS 5.9

comprehensive and sequential industrial policy strategies leading to immediate action as well as preparedness for future decarbonisation, governance at different levels (from international to local) and integration with other policy domains. {11.6}

TS. 5.6 Agriculture, forestry and other land uses, and food systems

TS. 5.6.1 AFOLU

The Agriculture, Forestry and Other Land Uses (AFOLU)[19] sector encompasses managed ecosystems and offers significant mitigation opportunities while providing food, wood and other renewable resources as well as biodiversity conservation, provided the sector adapts to climate change. Land-based mitigation measures can reduce GHG emissions within the AFOLU sector, deliver CDR and provide biomass thereby enabling emission reductions in other sectors.[20] The rapid deployment of AFOLU measures features in all pathways that l limit global warming to 1.5°C. Where carefully and appropriately implemented, AFOLU mitigation measures are positioned to deliver substantial co-benefits and help address many of the wider challenges associated with land management. If AFOLU measures are deployed badly then, when taken together with the increasing need to produce sufficient food, feed, fuel and wood, they may exacerbate trade-offs with the conservation of habitats, adaptation, biodiversity and other services. At the same time the capacity of the land to support these functions may be threatened by climate change. (*high confidence*) {WG I Figure SPM7; WG II, 7.1, 7.6}

The AFOLU sector, on average, accounted for 13-21% of global total anthropogenic GHG emissions in the period 2010-2019. At the same time managed and natural terrestrial ecosystems were a carbon sink, absorbing around one third of anthropogenic CO_2 emissions (*medium confidence*). Estimated anthropogenic net CO_2 emissions from AFOLU (based on bookkeeping models) result in a net source of +5.9 ± 4.1 $GtCO_2$ yr^{-1} between 2010 and 2019 with an unclear trend. Based on FAOSTAT or national GHG inventories, the net CO_2 emissions from AFOLU were 0.0 to +0.8 $GtCO_2$ yr^{-1} over the same period. There is a discrepancy in the reported CO_2 AFOLU emissions magnitude because alternative methodological approaches that incorporate different assumptions are used {7.2.2}. If the responses of all managed and natural land to both anthropogenic environmental change and natural climate variability, estimated to be a gross sink of -12.5 ± 3.2 $GtCO_2$ yr^{-1} for the period 2010–2019, are added to land-use emissions, then land overall constituted a net sink of -6.6 ± 5.2 $GtCO_2$ yr^{-1} in terms of CO_2 emissions (*medium confidence*). (Table TS.4) {7.2, Table 7.1}

Land use change drives net AFOLU CO_2 emission fluxes. The rate of deforestation, which accounts for 45% of total AFOLU emissions, has generally declined, while global tree cover and global forest growing stock levels are *likely* increasing (*medium confidence*). There are substantial regional differences, with losses of carbon generally observed in tropical regions and gains in temperate and boreal regions. Agricultural CH_4 and N_2O emissions are estimated to average 157 ± 47.1 $MtCH_4$ yr^{-1} and 6.6 ± 4.0 MtN_2O yr^{-1} or 4.2 ± 1.3 and 1.8 ± 1.1 $GtCO_2$-eq yr^{-1} (using IPCC AR6 GWP100 values for CH_4 and N_2O) respectively between 2010 and 2019 {7.2.1, 7.2.3}. AFOLU CH_4 emissions continue to increase, the main source of which is enteric fermentation from ruminant animals. Similarly, AFOLU N_2O emissions are increasing, dominated by agriculture, notably from manure application,

FOOTNOTE [19] AFOLU is a sector in the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. AFOLU anthropogenic greenhouse gas emissions and removals by sinks reported by governments under the UNFCCC are defined as all those occurring on 'managed land'. Managed land is land where human interventions and practices have been applied to perform production, ecological or social functions.

FOOTNOTE [20] For example: in the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, CO_2 emissions from biomass used for energy are reported in the AFOLU sector, calculated as an implicit component of carbon stock changes. In the energy sector, CO_2 emissions from biomass combustion for energy are recorded as an information item that is not included in the sectoral total emissions for the that sector.

nitrogen deposition, and nitrogen fertiliser use (*high confidence*). In addition to being a net carbon sink and source of GHG emissions, land plays an important role in climate through albedo effects, evapotranspiration, and aerosol loading through emissions of volatile organic compounds (VOCs). The combined role of CH_4, N_2O and aerosols in total climate forcing, however, is unclear and varies strongly with bioclimatic region and management practice. {2.4.2.5, 7.2, 7.3}

Table TS.4 Net anthropogenic emissions (annual averages for 2010–2019[a]) from Agriculture, Forestry and Other Land Use (AFOLU)

For context, the net flux due to the natural response of land to climate and environmental change is also shown for CO_2 in column E. Positive values represent emissions, negative values represent removals. Due to different approaches to estimate anthropogenic fluxes, AFOLU CO_2 estimates in the table below are not directly comparable to LULUCF in National Greenhouse Gas Inventories (NGHGIs).

Anthropogenic						Natural Response	Natural + Anthropogenic
Gas	**Units**	**AFOLU Net anthropogenic emissions**	**Non-AFOLU anthropogenic GHG emissions**	**Total net anthropogenic emissions (AFOLU + non-AFOLU) by gas**	**AFOLU as a % of total net anthropogenic emissions by gas**	**Natural land sinks including natural response of land to anthropogenic environmental change and climate variability**	**Net-land atmosphere CO_2 flux (i.e. anthropogenic AFOLU + natural fluxes across entire land surface**
		A	**B**	**C = A+B**	**D = (A/C) *100**	**E**	**F=A+E**
CO_2	$GtCO_2$-eq yr^{-1}	5.9 ± 4.1 (bookkeeping models only) 0 to 0.8 (NGHGI/ FAOSTAT data)	36.2 ± 2.9	42.0 ± 29.0	14%	**-12.5 ± 3.2**	**-6.6 ± 4.6**
CH_4	$MtCH_4$ yr^{-1}	157.0 ± 47.1	207.5 ± 62.2	364.4 ± 109.3			
	$GtCO_2$-eq yr^{-1}	4.2 ± 1.3	5.9 ± 1.8	10.2 ± 3.0	41%		
N_2O	MtN_2O yr^{-1}	6.6 ± 4.0	2.8 ± 1.7	9.4 ± 5.6			
	$GtCO_2$-eq yr^{-1}	1.8 ± 1.1	0.8 ± 0.5	2.6 ± 1.5	69%		
Total	$GtCO_2$-eq yr^{-1}	11.9 ± 4.4 (CO_2 component considers bookkeeping models only)	44 ± 3.4	55.9 ± 6.1	21%		

[a] Estimates are given for 2019 as this is the latest date when data are available for all gases, consistent with Chapter 2, this report. Positive fluxes are emission from land to the atmosphere. Negative fluxes are removals. {Table 7.1}

The AFOLU sector offers significant near-term mitigation potential at relatively low cost and can provide 20-30% of the 2050 emissions reduction described in scenarios that *likely* limit warming to 2°C or lower (*high evidence, medium agreement*). The AFOLU sector can provide 20–30% (interquartile range) of the global mitigation needed for a 1.5 °C or 2°C pathway towards 2050, though there are highly variable mitigation strategies for how AFOLU potential can be deployed for achieving climate targets {Illustrative Mitigation Pathways in 7.5}. The estimated economic (< USD100 tCO_2-eq^{-1}) AFOLU sector mitigation potential is 8 to 14 $GtCO_2$-eq yr^{-1} between 2020-2050, with the bottom end of this range representing the mean from IAMs and the upper end representing the mean estimate from global sectoral studies. The economic potential is about half of the technical potential from AFOLU, and about 30-50% could be achieved under USD20 tCO_2-eq^{-1} {7.4}. The implementation of robust measurement, reporting and verification processes is paramount to improving the transparency of changes in land carbon stocks and this can help prevent misleading assumptions or claims on mitigation. {7.1, 7.4, 7.5}

Between 2020 and 2050, mitigation measures in forests and other natural ecosystems provide the largest share of the AFOLU mitigation potential (up to USD100 tCO_2-eq^{-1}), followed by agriculture and demand-side measures (*high confidence*). In the global sectoral studies, the protection, improved management, and restoration of forests, peatlands, coastal wetlands, savannas and grasslands have the potential to reduce emissions and/or sequester 7.3 mean (3.9–13.1 range) $GtCO_2$-eq yr^{-1}. Agriculture provides the second largest share of the mitigation potential, with 4.1 (1.7–6.7) $GtCO_2$-eq yr^{-1} (up to USD100 tCO_2-eq^{-1}) from cropland and grassland soil carbon management, agroforestry, use of biochar, improved rice cultivation, and livestock and nutrient management. Demand-side measures including shifting to sustainable healthy diets, reducing food waste, building with wood, biochemicals, and bio-textiles, have a mitigation potential of 2.2 (1.1–3.6) $GtCO_2$-eq yr^{-1}. Most mitigation options are available and ready to deploy. Emissions reductions can be achieved relatively quickly, whereas CDR needs upfront investment. Sustainable intensification in agriculture, shifting diets, and reducing food waste could enhance efficiencies and reduce agricultural land needs, and are therefore critical for enabling supply-side measures such as reforestation, restoration, as well as decreasing CH_4 and N_2O emissions from agricultural production. In addition, emerging technologies (e.g., vaccines or CH_4 inhibitors) have the potential to substantially increase the CH_4 mitigation potential beyond current estimates. AFOLU mitigation is not only relevant in countries with large land areas. Many smaller countries and regions, particularly with wetlands, have disproportionately high levels of AFOLU mitigation potential density. {7.4, 7.5}

The economic and political feasibility of implementing AFOLU mitigation measures is hampered by persistent barriers. Assisting countries to overcome barriers will help to achieve significant short-term mitigation (*medium confidence*). Finance forms a critical barrier to achieving these gains as currently mitigation efforts rely principally on government sources and funding mechanisms which do not provide sufficient resources to enable the economic potential to be realised. Differences in cultural values, governance, accountability and institutional capacity are also important barriers. Climate change itself could reduce the mitigation potential from the AFOLU sector, although an increase in the capacity of natural sinks could occur despite changes in climate (*medium confidence*) {WG I Figure SPM7 and Sections 7.4 and 7.6}. The continued loss of biodiversity makes ecosystems less resilient to climate change extremes and this may further jeopardise the achievement of the AFOLU mitigation potentials indicated in this chapter (*high confidence*). (Box TS.15) {7.6}

The provision of biomass for bioenergy (with/without BECCS) and other biobased products represents an important share of the total mitigation potential associated with the AFOLU sector, though these mitigation effects accrue to other sectors (*high confidence*). Recent estimates of the technical bioenergy potential, when constrained by food security and environmental considerations, are within the ranges 5–50 and 50–250 EJ yr^{-1} by 2050 for residues and dedicated biomass production systems, respectively.[21] (TS 5.7) {7.4, 12.3}

FOOTNOTE [21] These potentials do not include avoided emissions resulting from bioenergy use associated with BECCS, which depends on energy substitution patterns, conversion efficiencies, and supply chain emissions for both the BECCS and substituted energy systems. Estimates of substitution effects of bioenergy indicate that this additional mitigation would be of the same magnitude as provided through CDR using BECCS. Biobased products with long service life, e.g., construction timber, can also provide mitigation through substitution of steel, concrete, and other products, and through carbon storage in the biobased product pool. See section TS 5.7 for the CDR potential of BECCS. {7.4, 12.3}

Bioenergy is the most land-intensive energy option, but total land occupation of other renewable energy options can also become significant in high deployment scenarios. While not as closely connected to the AFOLU sector as bioenergy, other renewable energy options can influence AFOLU activities in both synergistic and detrimental ways *(high confidence)*. The character of land occupation, and associated impacts, vary considerably among mitigation options and also for the same option depending on geographic location, scale, system design and deployment strategy. Land occupation can be large uniform areas, e.g., reservoir hydropower dams and tree plantations, and more distributed occupation that is integrated with other land uses, e.g., wind turbines and agroforestry in agriculture landscapes. Deployment can be partly decoupled from additional land use, e.g., use of organic waste and residues and integration of solar PV into buildings and other infrastructure (*high confidence*). Wind and solar power can coexist with agriculture in beneficial ways (*medium confidence*). Indirect land occupation includes new agriculture areas following displacement of food production with bioenergy plantations and expansion of mining activities providing minerals required for manufacture of EV batteries, PV, and wind power. {7.4, 12.5}

The deployment of land-based mitigation measures can provide co-benefits, but there are also risks and trade-offs from inappropriate land management (*high confidence*). Such risks can best be managed if AFOLU mitigation is pursued in response to the needs and perspectives of multiple stakeholders to achieve outcomes that maximise synergies while limiting trade-offs (*medium confidence*). The results of implementing AFOLU measures are often variable and highly context specific. Depending on local conditions (e.g., ecosystem, climate, food system, land ownership) and management strategies (e.g., scale, method), mitigation measures can positively or negatively affect biodiversity, ecosystem functioning, air quality, water availability and quality, soil productivity, rights infringements, food security, and human well-being. The agriculture and forestry sectors can devise management approaches that enable biomass production and use for energy in conjunction with the production of food and timber, thereby reducing the conversion pressure on natural ecosystems (*medium confidence*). Mitigation measures addressing GHGs may also affect other climate forcers such as albedo and evapotranspiration. Integrated responses that contribute to mitigation, adaptation, and other land challenges will have greater likelihood of being successful (*high confidence*); measures which provide additional benefits to biodiversity and human well-being are sometimes described as 'Nature-based Solutions'. {7.1, 7.4, 7.6, 12.4, 12.5}

AFOLU mitigation measures have been well understood for decades but deployment remains slow, and emissions trends indicate unsatisfactory progress despite beneficial contributions to global emissions reduction from forest-related options (*high confidence*). Globally, the AFOLU sector has so far contributed modestly to net mitigation, as past policies have delivered about 0.65 $GtCO_2 yr^{-1}$ of mitigation during 2010–2019 or 1.4% of global gross emissions. The majority (>80%) of emission reduction resulted from forestry measures. Although the mitigation potential of AFOLU measures is large from a biophysical and ecological perspective, its feasibility is hampered by lack of institutional support, uncertainty over long-term additionality and trade-offs, weak governance, fragmented land ownership, and uncertain permanence effects. Despite these impediments to change, AFOLU mitigation options are demonstrably effective and with appropriate support can enable rapid emission reductions in most countries. {7.4, 7.6}

Concerted, rapid and sustained effort by all stakeholders, from policy makers and investors to land-owners and managers is a pre-requisite for achieving high levels of mitigation in the AFOLU sector (*high confidence*). To date USD0.7 billion yr^{-1} is estimated to have been spent on AFOLU mitigation. This is well short of the more than USD400 billion yr^{-1} that is estimated to be necessary to deliver the up to 30% of global mitigation effort envisaged in deep mitigation scenarios (*medium confidence)*. This estimate of the global funding requirement is smaller than current subsidies provided to agriculture and forestry. A gradual redirection of existing agriculture and forestry subsidies would greatly advance mitigation. Effective policy interventions and national (investment) plans as part of NDCs, specific to local circumstances and needs, are urgently needed to accelerate the deployment of AFOLU mitigation options. These interventions are effective when they include funding schemes and long-term consistent support for implementation with governments taking the initiative together with private funders and non-state actors. {7.6}

Realising the mitigation potential of the AFOLU sector depends strongly on policies that directly address emissions and drive the deployment of land-based mitigation options, consistent with carbon prices in deep mitigation scenarios (*high confidence*). Examples of successful policies and measures include establishing and respecting tenure rights and community forestry, improved agricultural management and sustainable intensification, biodiversity conservation, payments for ecosystem services, improved forest management and wood chain usage, bioenergy, voluntary supply chain management efforts, consumer behaviour campaigns, private funding and joint regulatory efforts to avoid e.g., leakage. The efficacy of different policies, however, will depend on numerous region-specific factors. In addition to funding, these factors include governance, institutions, long-term consistent execution of measures, and the specific policy setting. While the governance of land-based mitigation can draw on lessons from previous experience with regulating biofuels and forest carbon integrating these insights requires governance that goes beyond project-level approaches emphasising integrated land use planning and management within the frame of the sustainable development goals. {7.4, Box 7.2, 7.6}

Addressing the many knowledge gaps in the development and testing of AFOLU mitigation options can rapidly advance the likelihood of achieving sustained mitigation (*high confidence*). Research priorities include improved quantification of anthropogenic and natural GHG fluxes and emissions modelling, better understanding of the impacts of climate change on the mitigation potential, permanence and additionality of estimated mitigation actions, and improved (real time and cheap) measurement, reporting and verification. There is a need to include a greater suite of mitigation measures in IAMs, informed by more realistic assessments that take into account local circumstances and socio-economic factors and cross-sector synergies and trade-offs. Finally, there is a critical need for more targeted research to develop appropriate country-level, locally specific, policy and land management response options. These options could support more specific NDCs with AFOLU measures that enable mitigation while also contributing to biodiversity conservation, ecosystem functioning, livelihoods for millions of farmers and foresters, and many other SDGs. {7.7, Figure 17.1}

TS. 5.6.2 Food systems

Realising the full mitigation potential from the food system requires change at all stages from producer to consumer and waste management, which can be facilitated through integrated policy packages *(high confidence)*. 23-42% of global GHG emissions are associated with food systems, while there is still wide-spread food insecurity and malnutrition. Absolute GHG emissions from food systems increased from 14 to 17 $GtCO_2$-eq yr^{-1} in the period 1990-2018. Both supply and demand side measures are important to reduce the GHG intensity of food systems. Integrated food policy packages based on a combination of market-based, administrative, informative, and behavioural policies can reduce cost compared to uncoordinated interventions, address multiple sustainability goals, and increase acceptance across stakeholders and civil society *(limited evidence, medium agreement)*. Food systems governance may be pioneered through local food policy initiatives complemented by national and international initiatives, but governance on the national level tends to be fragmented, and thus have limited capacity to address structural issues like inequities in access. (Figure TS.18, Table TS.5, Table TS.6) {7.2, 7.4, 12.4}

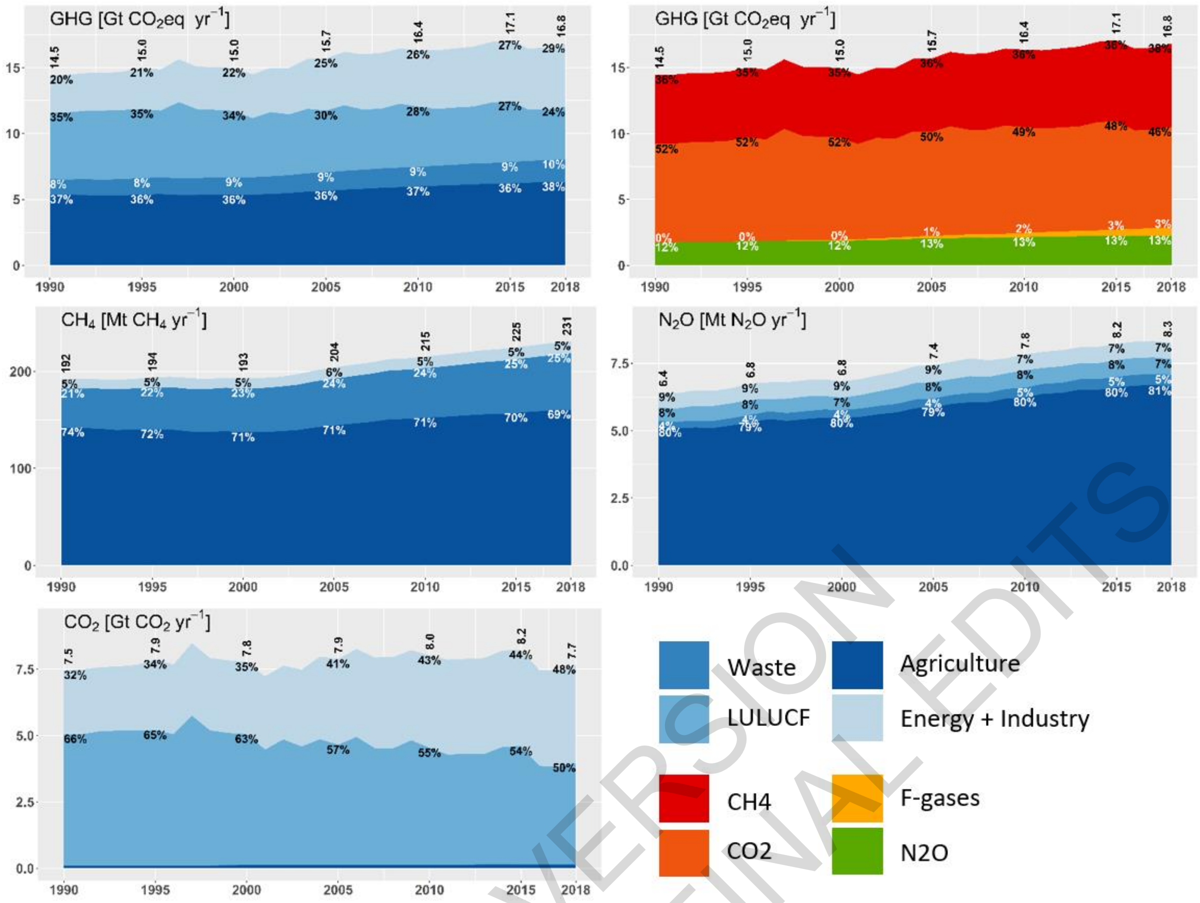


Figure TS.18: Food system GHG emissions from the agriculture, Land Use, Land-Use Change & Forestry (LULUCF), Waste, and energy & industry sectors. {Figure 12.5}

Diets high in plant protein and low in meat and dairy are associated with lower GHG emissions (*high confidence*). Ruminant meat shows the highest GHG intensity. Beef from dairy systems has lower emissions intensity than beef from beef herds (8-23 and 17-94 $kgCO_2$-eq (100g protein)$^{-1}$, respectively) when some emissions are allocated to dairy products. The wide variation in emissions reflects differences in production systems, which range from intensive feedlots with stock raised largely on grains through to rangeland and transhumance production systems. Where appropriate, a shift to diets with a higher share of plant protein, moderate intake of animal-source foods and reduced intake of saturated fats could lead to substantial decreases in GHG emissions. Benefits would also include reduced land occupation and nutrient losses to the surrounding environment, while at the same time providing health benefits and reducing mortality from diet-related non-communicable diseases. (Figure TS.19) {7.4.5, 12.4}

Emerging food technologies such as cellular fermentation, cultured meat, plant-based alternatives to animal-based food products, and controlled environment agriculture, can bring substantial reduction in direct GHG emissions from food production *(limited evidence, high agreement)*. These technologies have lower land, water, and nutrient footprints, and address concerns over animal welfare. Realising the full mitigation potential depends on access to low-carbon energy as some emerging technologies are relatively more energy intensive. This also holds for deployment of cold chain and packaging technologies, which can help reduce food loss and waste, but increase energy and materials use in the food system. (Table TS.5) {11.4.1.3, 12.4}

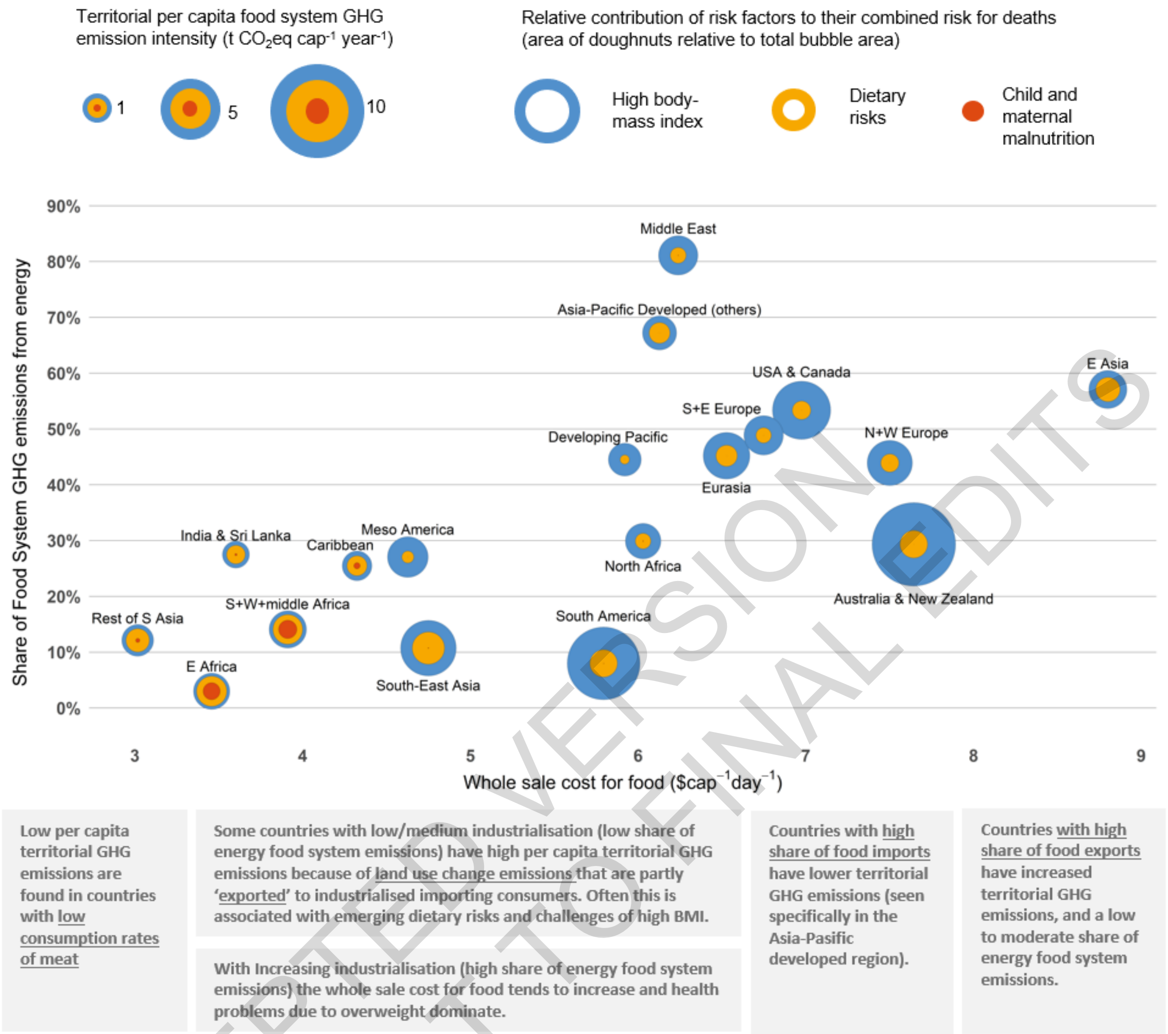


Figure TS.19: Regional differences in health outcome, territorial per capita GHG emissions from national food systems, and share of food system GHG emission from energy use

Figure TS.19 legend: GHG emissions are calculated according to the IPCC Tier 1 approach and are assigned to the country where they occur, not necessarily where the food is consumed. Health outcome is expressed as relative contribution of each of the following risk factors to their combined risk for deaths: Child and maternal malnutrition (red), Dietary risks (yellow) or High body-mass index (blue). {Figure 12.7}

Table TS.5 Food system mitigation opportunities

Food system mitigation options (I: incremental; T: transformative)		**Direct and indirect effect on GHG mitigation (+/0/-) [a]**	**Co-benefits / Adverse effects [b]**
Food from agricultural, aquaculture and fisheries	(I) Dietary shift, in particular increased share of plant-based protein sources	D+ ↓ GHG footprint	A+ Animal welfare L+ Land sparing H+ Good nutritional properties, potentially ↓ risk from zoonotic diseases, pesticides and antibiotics
	(I/T) Digital agriculture	D+ ↑ logistics	L+ Land sparing R+ ↑ resource use efficiencies
	(T) Gene technology	D+ ↑ productivity or efficiency	H+ ↑ nutritional quality E0 ↓ use of agrochemicals; ↑ probability of off-target impacts
	(I) Sustainable intensific. land use optimisation	D+ ↓ GHG footprint E0 Mixed effects	L+ Land sparing R- Might ↑ pollution/biodiversity loss
	(I) Agroecology	D+ ↓ GHG/area, positive micro-climatic effects E+ ↓ energy, possibly ↓ transport FL+ Circular approaches	E+ Focus on co-benefits/ecosystem services R+ Circular, ↑ nutrient and water use efficiencies
Controlled environment agriculture	(T) Soilless agriculture	D+ ↑ productivity, weather independent FL+ Harvest on demand E- Currently ↑ energy demand, but ↓ transport, building spaces can be used for renewable energy	R+ Controlled loops ↑ nutrient and water use efficiency L+ Land sparing H+ Crop breeding can be optimised for taste and/or nutritional quality
Emerging Food Production technologies	(T) Insects	D0 Good feed conversion efficiency FW+ Can be fed on food waste	H0 Good nutritional qualities but attention to allergies and food safety issues required
	(I/T) Algae and bivalves	D+ ↓ GHG footprints	A+ Animal welfare L+ Land sparing H+ Good nutritional qualities; risk of heavy metal and pathogen contamination R+ Biofiltration of nutrient-polluted waters
	(I/T) Plant-based alternatives to animal-based food products	D+ No emissions from animals, ↓ inputs for feed	A+ Animal welfare L+ Land sparing H+ Potentially ↓ risk from zoonotic diseases, pesticides and antibiotics; but ↑ processing demand

Food system mitigation options (I: incremental; T: transformative)		**Direct and indirect effect on GHG mitigation (+/0/-) [a]**	**Co-benefits / Adverse effects [b]**
	(T) Cellular agriculture (including cultured meat, microbial protein)	D+ No emissions from animals, high protein conversion efficiency E- ↑ energy need FLW+ ↓ food loss & waste	A+ Animal welfare R+ ↓ emissions of reactive nitrogen or other pollutants H0 Potentially ↓ risk from zoonotic diseases, pesticides and antibiotics; ↑ research on safety aspects needed
Food processing and packaging	(I) Valorisation of by-products, FLW logistics and management	M+ Substitution of bio-based materials FL+ ↓ of food losses	
	(I) Food conservation	FW+ ↓ of food waste E0 ↑ energy demand but also energy savings possible (e.g., refrigeration, transport)	
	(I) Smart packaging and other technologies	FW+ ↓ of food waste M0 ↑ material demand and ↑ material-efficiency E0 ↑ energy demand; energy savings possible	H+ Possibly ↑ freshness/reduced food safety risks
	(I) Energy efficiency	E+ ↓ energy	
Storage and distribution	(I) Improved logistics	D+ ↓ transport emissions FL+ ↓ losses in transport FW- Easier access to food could ↑ food waste	
	(I) Specific measures to reduce food waste in retail and food catering	FW+↓ of food waste E+ ↓ downstream energy demand M+ ↓ downstream material demand	
	(I) Alternative fuels/transport modes	D+ ↓ emissions from transport	
	(I) Energy efficiency	E+ ↓ energy in refrigeration, lightening, climatisation	
	(I) Replacing refrigerants	D+ ↓ emissions from the cold chain	

a. Direct and indirect GHG effects: D – direct emissions except emissions from energy use, E – energy demand, M – material demand, FL – food losses, FW – food waste; direction of effect on GHG mitigation: (+) increased mitigation, (0) neutral, (-) decreased mitigation.

b. Co-benefits/Adverse effects: H - health aspects, A - animal welfare, R - resource use, L - land demand, E – ecosystem services; (+) co-benefits, (-) adverse effects. {Table 12.8}

Table TS.6 Assessment of food system policies targeting (post-farm gate) food chain actors and consumers

	Level	Transformative potential	Environ. effective.	Feasibility	Distributional effects	Cost	Co-benefits[a] and adverse side-effect	Implications for coordination, coherence and consistency in policy package[b]
Integrated food policy packages	**NL**				**can be controlled**	**Cost efficient**	**+ balanced, addresses multiple sustainability goals**	Reduces cost of uncoordinated interventions; increases acceptance across stakeholders and civil society *(high confidence).*
Taxes on food products	GN				regressive	low[#1]	- unintended substitution effects	High enforcing effect on other food policies; higher acceptance if compensation or hypothecated taxes *(medium evidence, high agreement).*
GHG taxes on food	GN				regressive	low[#2]	-unintended substitution effects +high spillover effect	Supportive, enabling effect on other food policies, agricultural/fishery policies; requires changes in power distribution and trade agreements *(medium confidence).*
Trade policies	G				impacts global distribution	complex effects	+ counters leakage effects +/- effects on market structure and jobs	Requires changes in existing trade agreements *(medium evidence, high agreement).*
Investment into research & innovation	GN				none	medium	+ high spillover effect + converging with digital society	Can fill targeted gaps for coordinated policy packages (e.g. monitoring methods) *(high confidence).*
Food and marketing regulations	N					low		Can be supportive; might be supportive to realise innovation; voluntary standards might be less effective *(medium confidence).*
Organisational level procurement policies	NL					low	+ can address multiple sustainability goals	Enabling effect on other food policies; reaches large share of population *(medium evidence, high agreement).*
Sustainable food-based dietary guidelines	GNL				none	low	+ can address multiple sustainability goals	Little attention so far on environmental aspects; can serve as benchmark for other policies (labels, food formulation standards, etc.) *(medium confidence).*
Food labels/ information	GNL				education level relevant	low	+ empowers citizens + increases awareness + multiple objectives	Effective mainly as part of a policy package; incorporation of other objectives (e.g., animal welfare, fair trade...); higher effect if mandatory *(medium confidence).*
Nudges	NL				none	low	+ possibly counteracting information deficits in population subgroups	High enabling effect on other food policies *(medium evidence, high agreement).*

Color code: **Effect of measures:** negative , none/unclear , slightly positive , positive ; **Level:** G: global/multinational, N: national, L: local; **#1** Minimum level to be effective 20% price increase; **#2** Minimum level to be effective 50-80 USD tCO_2-eq^{-1}.

a. In addition, all interventions are assumed to address health and climate change mitigation.

b. Requires coordination between policy areas, participation of stakeholders, transparent methods and indicators to manage trade-offs and prioritisation between possibly conflicting objectives; and suitable indicators for monitoring and evaluation against objectives. {Table 12.9}

TS. 5.7 Carbon dioxide removal (CDR)

CDR is a key element in scenarios that *likely* limit warming to 2°C or 1.5°C by 2100 (*high confidence*). Implementation strategies need to reflect that CDR methods differ in terms of removal process, timescale of carbon storage, technological maturity, mitigation potential, cost, co-benefits, adverse side-effects, and governance requirements. (Box TS.10)

All the illustrative mitigation pathways (IMPs) assessed in this report use land-based biological CDR (primarily afforestation/reforestation (A/R)) and/or bioenergy with carbon capture and storage (BECCS). Some also include direct air CO_2 capture and storage (DACCS) *(high confidence)*. Across the scenarios *likely* limiting warming to 2°C or below, cumulative volumes[22] of BECCS reach 328 (168–763) $GtCO_2$, net CO_2 removal on managed land (including A/R) reaches 252 (20–418) $GtCO_2$, and DACCS reaches 29 (0–339) $GtCO_2$, for the 2020-2100 period. Annual volumes in 2050 are 2.75 (0.52–9.45) $GtCO_2$ yr^{-1} for BECCS, 2.98 (0.23–6.38) $GtCO_2$ yr^{-1} for the net CO_2 removal on managed land (including A/R), and 0.02 (0 -1.74) $GtCO_2$ yr^{-1} for DACCS. (Box TS.10) {12.3, Cross-Chapter Box 8 in Chapter 12}

Despite limited current deployment, estimated mitigation potentials for DACCS, enhanced weathering (EW) and ocean-based CDR methods (including ocean alkalinity enhancement and ocean fertilisation) are moderate to large *(medium confidence)*. The potential for DACCS (5–40 $GtCO_2$ yr^{-1}) is limited mainly by requirements for low-carbon energy and by cost (100-300 (full range: 84–386) USD tCO_2^{-1}). DACCS is currently at a medium technology readiness level. EW has the potential to remove 2–4 (full range: <1 to ~100) $GtCO_2$ yr^{-1}, at costs ranging from 50 to 200 (full range: 24–578) USD tCO_2^{-1}. Ocean-based methods have a combined potential to remove 1–100 $GtCO_2$ yr^{-1} at costs of USD40–500 tCO_2^{-1}, but their feasibility is uncertain due to possible side-effects on the marine environment. EW and ocean-based methods are currently at a low technology readiness level. {12.3}

CDR governance and policymaking can draw on widespread experience with emissions reduction measures (*high confidence*). Additionally, to accelerate research, development, and demonstration, and to incentivise CDR deployment, a political commitment to formal integration into existing climate policy frameworks is required, including reliable measurement, reporting and verification MRV of carbon flows. {12.3.3, 12.4, 12.5}

START BOX TS.10 HERE

Box TS.10: Carbon Dioxide Removal

Carbon Dioxide Removal (CDR) is necessary to achieve net zero CO_2 and GHG emissions both globally and nationally, counterbalancing 'hard-to-abate' residual emissions. CDR is also an essential element of scenarios that limit warming to 1.5°C or *likely* below 2°C by 2100, regardless of whether global emissions reach near zero, net zero or net negative levels. While national mitigation portfolios aiming at net zero emissions or lower will need to include some level of CDR, the choice of methods and the scale and timing of their deployment will depend on the achievement of gross emission reductions, and managing multiple sustainability and feasibility constraints, including political preferences and social acceptability.

CDR refers to anthropogenic activities removing *CO_2* from the atmosphere and durably storing it in *geological*, *terrestrial*, or *ocean* reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological, geochemical or chemical CO_2 sinks, but excludes natural CO_2 uptake not directly caused by human activities (Annex I). Carbon Capture and Storage (CCS) and

FOOTNOTE [22] As a median value (5 to 95% range).

Carbon Capture and Utilisation (CCU) applied to fossil CO_2 do not count as removal technologies. CCS and CCU can only be part of CDR methods if the CO_2 is biogenic or directly captured from ambient air, and stored durably in geological reservoirs or products. {12.3}

There is a great variety of CDR methods and respective implementation options {Cross-Chapter Box 8 Figure 1 in Chapter 12}. Some of these methods (like afforestation and soil-carbon sequestration) have been practiced for decades to millennia, although not necessarily with the intention to remove carbon from the atmosphere. Conversely, for methods such as DACCS and BECCS, experience is growing but still limited in scales. A categorisation of CDR methods can be based on several criteria, depending on the highlighted characteristics. In this report, the categorisation is focused on the role of CDR methods in the carbon cycle, i.e. on the removal process (*land-based biological*; *ocean-based biological*; *geochemical*; *chemical*) and on the timescale of storage (*decades to centuries*; *centuries to millennia*; *10 thousand years or longer*), the latter being closely linked to different carbon storage media. Within one category (e.g., ocean-based biological CDR) options often differ with respect to other dynamic or context-specific dimensions such as mitigation potential, cost, potential for co-benefits and adverse side-effects, and technology readiness level. (Table TS.7; TS 5.6, 5.7) {12.3}

It is useful to distinguish between CO_2 removal from the atmosphere as the outcome of deliberate activities implementing CDR options, and the net emissions outcome achieved with the help of CDR deployment (i.e., gross emissions minus gross removals). As part of ambitious mitigation strategies at global or national levels, gross CDR can fulfil three different roles in complementing emissions abatement: (1) lowering net CO_2 or GHG emissions in the near-term; (2) counterbalancing 'hard-to-abate' residual emissions like CO_2 from industrial activities and long-distance transport, or CH_4 and nitrous oxide from agriculture, in order to help reach net zero CO_2 or GHG emissions in the mid-term; (3) achieving net negative CO_2 or GHG emissions in the long-term if deployed at levels exceeding annual residual emissions {2.7, 3.3, 3.4, 3.5}. These roles of CDR are not mutually exclusive: for example, achieving net zero CO_2 or GHG emissions globally might involve individual developed countries attaining net negative CO_2 emissions at the time of global net zero, thereby allowing developing countries a smoother transition. {Cross-Chapter Box 8 Figure 2 in Chapter 12}

END BOX TS.10 HERE

Table TS.7: Summary of status, costs, potentials, risk and impacts, co-benefits, trade-offs and spill over effects and the role in mitigation pathways for CDR methods {12.3.2, 7.4} TRL = Technology Readiness Level

CDR option	Status (TRL)	Cost (USD tCO_2^{-1})	Mitigation Potential ($GtCO_2$ yr^{-1})	Risk and Impacts	Co-benefits	Trade-offs and spill over effects	Role in mitigation pathways	Section
Afforestation/Reforestation	(8-9)	0-240	0.5-10	Reversal of carbon removal through wildfire, disease, pests may occur. Reduced catchment water yield and lower groundwater level if species and biome are inappropriate.	Enhanced employment and local livelihoods, improved biodiversity, improved renewable wood products provision, soil carbon and nutrient cycling. Possibly less pressure on primary forest.	Inappropriate deployment at large scale can lead to competition for land with biodiversity conservation and food production.	Substantial contribution in IAMs and also in bottom-up sectoral studies.	{7.4}
Soil Carbon Sequestration in croplands and grasslands	(8-9)	45-100	0.6-9.3	Risk of increased nitrous oxide emissions due to higher levels of organic nitrogen in the soil; risk of reversal of carbon sequestration.	Improved soil quality, resilience and agricultural productivity.	Attempts to increase carbon sequestration potential at the expense of production. Net addition per hectare is very small; hard to monitor.	In development – not yet in global mitigation pathways simulated by IAMs in bottom-up studies: with medium contribution.	{7.4}
Peatland and coastal wetland restoration	(8-9)	Insufficient data	0.5-2.1	Reversal of carbon removal in drought or future disturbance. Risk of increased CH_4 emissions.	Enhanced employment and local livelihoods, increased productivity of fisheries, improved biodiversity, soil carbon and nutrient cycling.	Competition for land for food production on some peatlands used for food production.	Not in IAMs but some bottom-up studies with medium contribution.	{7.4}
Agroforestry	(8-9)	Insufficient data	0.3-9.4	Risk that some land area lost from food production; requires very high skills.	Enhanced employment and local livelihoods, variety of products improved soil quality, more resilient systems.	Some trade off with agricultural crop production, but enhanced biodiversity, and resilience of system.	No data from IAMs, but in bottom-up sectoral studies with medium contribution.	{7.4}
Improved Forest management	(8-9)	Insufficient data	0.1-2.1	If improved management is understood as merely intensification involving increased fertiliser use and introduced species, then it could reduce biodiversity and increase eutrophication.	In case of sustainable forest management, it leads to enhanced employment and local livelihoods, enhanced biodiversity, improved productivity.	If it involves increased fertiliser use and introduced species it could reduce biodiversity and increase eutrophication and upstream GHG emissions.	No data from IAMs, but in bottom-up sectoral studies with medium contribution.	{7.4}
Biochar	(6-7)	10-345	0.3-6.6	Particulate and GHG emissions from production; biodiversity and carbon stock loss from unsustainable biomass harvest.	Increased crop yields and reduced non-CO_2 emissions from soil; and resilience to drought.	Environmental impacts associated particulate matter; competition for biomass resource.	In development – not yet in global mitigation pathways simulated by IAMs.	{7.4}
DACCS	6	100-300 (84–386)	5-40	Increased energy and water use.	Water produced (solid sorbent DAC designs only).	Potentially increased emissions from water supply and energy generation.	In a few IAMs; DACCS complements other CDR methods.	{12.3}
BECCS	(5-6)	15-400	0.5-11	Inappropriate deployment at very large- scale leads to additional land and water use to grow biomass feedstock. Biodiversity and carbon stock loss if from unsustainable biomass harvest.	Reduction of air pollutants; fuel security, optimal use of residues, additional income, health benefits and if implemented well can enhance biodiversity.	Competition for land with biodiversity conservation and food production.	Substantial contribution in IAMs and bottom -up sectoral studies. Note-mitigation through avoided GHG emissions resulting from the bioenergy use is of the same magnitude as	{7.4}

CDR option	Status (TRL)	Cost (USD tCO_2^{-1})	Mitigation Potential ($GtCO_2$ yr^{-1})	Risk and Impacts	Co-benefits	Trade-offs and spill over effects	Role in mitigation pathways	Section
							the mitigation from CDR (TS.5.6).	
Enhanced weathering	3-4	50-200 (24-578)	2-4 (<1-95)	Mining impacts; air quality impacts of rock dust when spreading on soil.	Enhanced plant growth, reduced erosion, enhanced soil carbon, reduced pH, soil water retention.	Potentially increased emissions from water supply and energy generation.	In a few IAMs; EW complements other CDR methods.	{12.3}
"Blue carbon" in coastal wetlands	2-3	Insufficient data	<1	If degraded or lost, coastal blue carbon ecosystems are expected to release most of their carbon back to the atmosphere; potential for sediment contaminants, toxicity, bioaccumulation and biomagnification in organisms; issues related to altering degradability of coastal plants; use of subtidal areas for tidal wetland carbon removal; effect of shoreline modifications on sediment redeposition and natural marsh accretion; abusive use of coastal blue carbon as means to reclaim land for purposes that degrade capacity for carbon removal.	Provide many non-climatic benefits and can contribute to ecosystem-based adaptation, coastal protection, increased biodiversity, reduced upper ocean acidification; could potentially benefit human nutrition or produce fertiliser for terrestrial agriculture, anti-methanogenic feed additive, or as an industrial or materials feedstock.		Not incorporated in IAMs, but in some bottom-up studies: small contribution.	{7.4, 12.3.1}
Ocean fertilisation	1-2	50-500	1-3	Nutrient redistribution, restructuring of the ecosystem, enhanced oxygen consumption and acidification in deeper waters, potential for decadal-to-millennial-scale return to the atmosphere of nearly all the extra carbon removed, risks of unintended side effects.	Increased productivity and fisheries, reduced upper ocean acidification.	Subsurface ocean acidification, deoxygenation; altered meridional supply of macro-nutrients as they are utilised in the iron-fertilised region and become unavailable for transport to, and utilisation in other regions, fundamental alteration of food webs, biodiversity.	No data.	{12.3.1}
Ocean alkalinity enhancement	1-2	40–260	1–100	Increased seawater pH and saturation states and may impact marine biota. Possible release of nutritive or toxic elements and compounds. Mining impacts.	Limiting ocean acidification.	Potentially increased emissions of CO_2 and dust from mining, transport and deployment operations.	No data.	{12.3.1}

Range based on authors' estimates (as assessed from literature) are shown, with full literature ranges shown in brackets

TS. 5.8 Demand-side aspects of mitigation

The assessment of the social science literature and regional case studies reveals how social norms, culture, and individual choices interact with infrastructure and other structural changes over time. This provides new insight into climate change mitigation strategies, and how economic and social activity might be organised across sectors to support emission reductions. To enhance well-being, people demand services and not primary energy and physical resources per se. Focusing on demand for services and the different social and political roles people play broadens the participation in climate action. (Box TS.11)

Demand-side mitigation and new ways of providing services can help *Avoid* and *Shift* final service demands and *Improve* service delivery. Rapid and deep changes in demand make it easier for every sector to reduce GHG emissions in the short and medium term (*high confidence*). {5.2, 5.3}

The indicative potential of demand-side strategies across all sectors to reduce emissions is 40-70% by 2050 (*high confidence*). Technical mitigation potentials compared to the International Energy Agency's 2020 World Energy Outlook STEPS (Stated Policy Scenarios) baseline are up to 5.7 $GtCO_2$-eq for building use and construction, 8 $GtCO_2$-eq for food demand, 6.5 $GtCO_2$-eq for land transport, and 5.2 $GtCO_2$-eq for industry. Mitigation strategies can be classified as *Avoid-Shift-Improve* (ASI) options, that reflect opportunities for socio-cultural, infrastructural, and technological change. The greatest *Avoid* potential comes from reducing long-haul aviation and providing short-distance low-carbon urban infrastructures. The greatest *Shift* potential would come from switching to plant-based diets. The greatest *Improve* potential comes from within the building sector, and in particular increased use of energy efficient end-use technologies and passive housing. (Figure TS.20, Figure TS.21) {5.3.1, 5.3.2, Figure 5.7, Figure 5.8, Table 5.1, Table SM 5.2}

Socio-cultural and lifestyle changes can accelerate climate change mitigation (*medium confidence*). Among 60 identified actions that could change individual consumption, individual mobility choices have the largest potential to reduce carbon footprints. Prioritising car-free mobility by walking and cycling and adoption of electric mobility could save 2 tCO_2-eq cap^{-1} yr^{-1}. Other options with high mitigation potential include reducing air travel, cooling setpoint adjustments, reduced appliance use, shifts to public transit, and shifting consumption towards plant-based diets. {5.3.1, 5.3.1.2, Figure 5.8}

START BOX TS.11 HERE

Box TS.11: A New Chapter in WG III AR6 Focusing on the Social Science of Demand, and Social Aspects of Mitigation

The WG III contribution to the Sixth Assessment Report of the IPCC (AR6) features a distinct chapter on demand, services and social aspects of mitigation {5}. The scope, theories, and evidence for such an assessment are addressed in Sections 5.1 and 5.4 within Chapter 5 and a Social Science Primer as an Appendix to Chapter 5.

The literature on social science – from sociology, psychology, gender studies and political science for example – and climate change mitigation is growing rapidly. A bibliometric search of the literature identified 99,065 peer-reviewed academic papers, based on 34 search queries with content relevant to Chapter 5. This literature is expanding by 15% per year, with twice as many publications in the AR6 period (2014-2020) as in all previous years.

The models of stakeholders' decisions assessed by IPCC have continuously evolved. From AR1 to AR4, rational choice was the implicit assumption: agents with perfect information and unlimited processing capacity maximising self-focused expected utility and differing only in wealth, risk attitude, and time discount rate. AR5 introduced a broader range of goals (material, social, and psychological) and decision processes (calculation-based, affect-based, and rule-based processes). However, its perspective was still individual- and agency-focused, neglecting structural, cultural, and institutional constraints and the influence of physical and social context.

A social science perspective is important in two ways. By adding new actors and perspectives, it (i) provides more options for climate mitigation; and (ii) helps to identify and address important social and cultural barriers and opportunities to socioeconomic, technological, and institutional change. Demand-side mitigation involves five sets of social actors: individuals (e.g., consumption choices, habits), groups and collectives (e.g., social movements, values), corporate actors (e.g., investments, advertising), institutions (e.g., political agency, regulations), and infrastructure actors (e.g., very long-term investments and financing). Actors either contribute to the status-quo of a global high-carbon, consumption, and GDP growth-oriented economy, or help generate the desired change to a low-carbon energy-services, well-being, and equity-oriented economy. Each set of actors has novel implications for the design and implementation of both demand- and supply-side mitigation policies. They show important synergies, making energy demand mitigation a dynamic problem where the packaging and/or sequencing of different policies play a role in their effectiveness {5.5, 5.6}. Incremental interventions change social practices, simultaneously affecting emissions and well-being. The transformative change requires coordinated action across all five sets of actors (Table 5.4), using social science insights about intersection of behaviour, culture, institutional and infrastructural changes for policy design and implementation. *Avoid*, *Shift*, and *Improve* choices by individuals, households and communities support mitigation {5.3.1.1, Table 5.1}. They are instigated by role models, changing social norms driven by policies and social movements. They also require appropriate infrastructures designed by urban planners and building and transport professionals, corresponding investments, and a political culture supportive of demand side mitigation action.

END BOX TS.11 HERE

Leveraging improvements in end-use service delivery through behavioural and technological innovations, and innovations in market organisation, leads to large reductions in upstream resource use (*high confidence*). Analysis of indicative potentials range from a factor 10- to 20-fold improvement in the case of available energy (exergy) analysis, with the highest improvement potentials at the end-user and service-provisioning levels. Realisable service level efficiency improvements could reduce upstream energy demand by 45% in 2050. (Figure TS.20) {5.3.2, Figure 5.10}

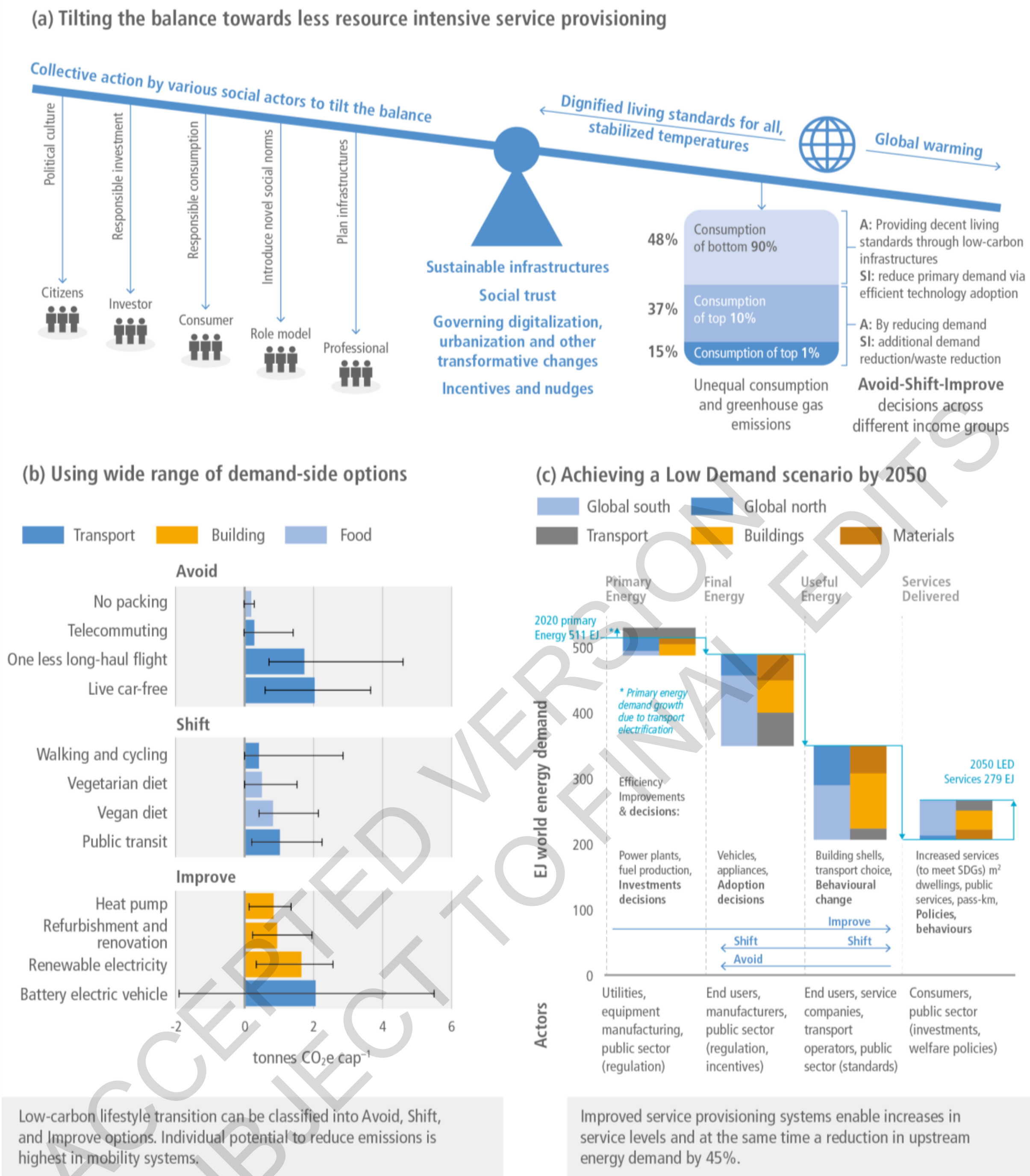
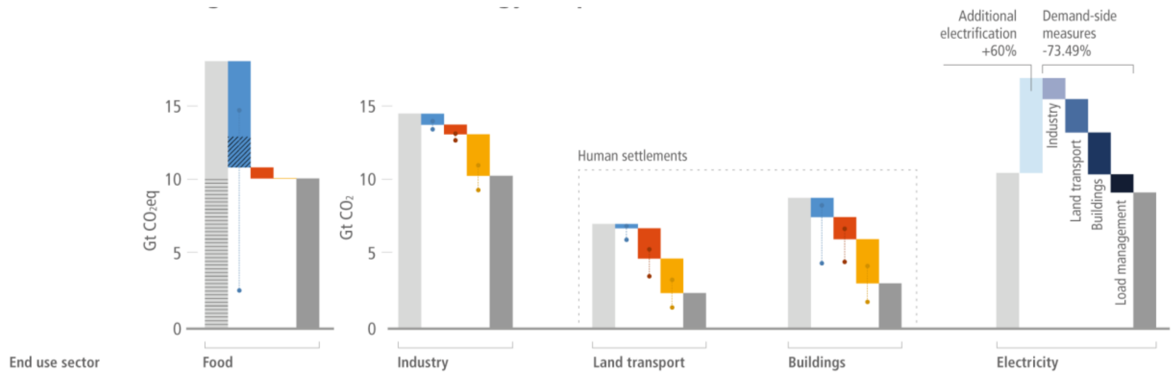


Figure TS.20: Demand-side strategies for mitigation. Demand-side mitigation is about more than behavioural change and transformation happens through societal, technological and institutional changes {Figure 5.10, Figure 5.14}



Demand for service	Nutrition	Manufactured products	Mobility	Shelter
Socio-cultural factors	Shift in dietary choice with reduced animal protein; avoid food waste; avoid over-consumption	Avoid short life span products	Teleworking or telecommuting; active mobility such as walking and cycling	Social practices in energy saving; and lifestyle and behavioural changes
Infrastructure use	Enhance the role of choice architectures and information; financial incentives; waste management; recycling infrastructure	Reuse and recycling	Public transport; shared mobility; compact city; spatial planning	Compact cities; built environment; living floor space rationalisation; architectural design; feedback control systems
Technology adoption	Currently not applicable	Access to materials-efficient services; access to energy-efficient and CO_2-neutral materials	Electric vehicles; efficiency technologies	Adopting energy-efficient solutions; shift to renewables

Total emissions 2050
Socio-cultural factors
Infrastructure use
Technology adoption
Emissions that cannot be avoided or reduced through demand side options
Deforestation and land-use change
Economic potential without considering LUC

Figure TS.21: Demand-side mitigation can be achieved through changes in socio-cultural factors, infrastructure design and use, and technology adoption

Figure TS.21 legend: Mitigation response options related to demand for services have been categorised into three domains: 'socio-cultural factors', related to social norms, culture, and individual choices and behaviour; 'infrastructure use', related to the provision and use of supporting infrastructure that enables individual choices and behaviour; and 'technology adoption', which refers to the uptake of technologies by end users. Potentials in 2050 are estimated using the International Energy Agency's 2020 World Energy Outlook STEPS (Stated Policy Scenarios) as a baseline. This scenario is based on a sector-by-sector assessment of specific policies in place, as well as those that have been announced by countries by mid-2020. This scenario was selected due to the detailed representation of options across sectors and sub-sectors.
The heights of the coloured columns represent the potentials on which there is a high level of agreement in the literature, based on a range of case studies. The range shown by the dots connected by dotted lines represents the highest and lowest potentials reported in the literature which have low to medium levels of agreement.
The demand side potential of socio-cultural factors in the food system has two parts. The economic potential of direct emissions (mostly non-CO_2) demand reduction through socio-cultural factors alone is 1.9 $GtCO_2eq$ without considering land use change by diversion of agricultural land from food production to carbon sequestration. If further changes in land use enabled by this change in demand are considered, the indicative potential could reach 7 $GtCO_2eq$.
The electricity panel presents separately the mitigation potential from changes in electricity demand and changes associated with enhanced electrification in end use sectors. Electrification increases electricity demand, while it is avoided though demand-side mitigation strategies. Load management refers to demand side flexibility that can be achieved through incentive design like time of use pricing/monitoring by artificial intelligence, diversification of storage facilities etc. NZE (IEA Net Zero Emissions by 2050 Scenario) is used to compute the impact of end use sector electrification, while the impact of demand side response options is based on bottom-up assessments.
Dark grey columns show the emissions that cannot be avoided through demand-side mitigation options.
The table indicates which demand-side mitigation options are included. Options are categorised according to: socio-cultural factors, infrastructure use, and technology adoption.

Figure SPM.7 covers potential of demand-side options for the year 2050. Figure SPM.8 covers both supply- and demand-side options and their potentials for the year 2030.
{5.3, Figure 5.7, Supplementary Material 5.II}

***Decent living standards* (DLS) and *well-being for all (SDG 3)* are achievable if high-efficiency low-demand mitigation pathways are followed (*medium confidence*).** Minimum requirements of energy use consistent with enabling *well-being for all* is between 20 and 50 GJ cap^{-1} yr^{-1} depending on the context. (Figure TS.22) {5.2.2.1, 5.2.2.2, Box 5.3}

Alternative service provision systems, for example those enabled through digitalisation, sharing economy initiatives and circular economy initiatives, have to date made a limited contribution to climate change mitigation (*medium confidence*). While digitalisation through specific new products and applications holds potential for improvement in service-level efficiencies, without public policies and regulations, it also has the potential to increase consumption and energy use. Reducing the energy use of data centres, networks, and connected devices is possible in managing low-carbon digitalisation. Claims on the benefits of the circular economy for sustainability and climate change mitigation have limited evidence. (Box TS.12, Box TS.14) {5.3.4, Figure 5.12, Figure 5.13}

START BOX TS.12 HERE

Box TS.12: Circular Economy (CE)

In AR6, the Circular Economy (CE) concept {Annex I} is highlighted as an increasingly important mitigation approach that can help deliver human well-being by minimising waste of energy and resources. While definitions of CE vary, its essence is to shift away from linear "make and dispose" economic models to those that emphasize product longevity, reuse, refurbishment, recycling, and material efficiency, thereby enabling more circular material systems that reduce embodied energy and emissions. {5.3.4, 8.4, 8.5, 9.5, 11.3.3}

Whereas IPCC AR4 {WG III, Chapter 10} included a separate chapter on waste sector emissions and waste management practices, and AR5 {WG III, Chapter 10} reviewed the importance of "reduce, reuse, recycle" and related policies, AR6 focuses on how CE can reduce waste in materials production and consumption by optimising materials' end-use service utility. Specific examples of CE implementations, policies, and mitigation potentials are included in chapters 5, 8, 9, 11 and 12. {5.3, 8.4, 9.5, 11.3, 12.6}

CE is shown to empower new social actors in mitigation actions, given that it relies on the synergistic actions of producers, sellers, and consumers {11.3.3}. As an energy and resource demand-reduction strategy, it is consistent with high levels of human well-being {5.3.4.3} and ensures better environmental quality (Figure TS.22) {5.2.1}. It also creates jobs through increased sharing, reuse, refurbishment, and recycling activities. Therefore, CE contributes to several SDGs, including Clean Water and Sanitation (SDG6), Affordable Energy and Clean Energy (SDG7), Decent Work and Economic Growth (SDG8), Responsible Production and Consumption (SDG12) and Climate Action (SDG13). {11.5.3.2}

Emissions savings derive from reduced primary material production and transport. For example, in buildings, lifetime extension, material efficiency, and reusable components reduce embodied emissions by avoiding demand for structural materials {9.3, 9.5}. At regional scales, urban/industrial symbiosis reduce primary material demand through byproduct exchange networks {11.3.3}. CE strategies also exhibit enabling effects, such as material-efficient and circular vehicle designs that also improve fuel economy {10.2.2.2}. There is growing interest in "circular bioeconomy" concepts applied to bio-based materials {Box 12.2} and even a "circular carbon economy", wherein carbon captured via CCU {11.3.6} or CDR {3.4.6} is converted into reusable materials, which is especially relevant for the transitions of economies dependent on fossil fuel revenue. {12.6}

While there are many recycling policies, CE-oriented policies for more efficient material use with higher value retention are comparatively far fewer; these policy gaps have been attributed to institutional failures, lack of coordination, and lack of strong advocates {5.3, 9.5.3.6, Box 11.5, Box 12.2}. Reviews of mitigation potentials reveal unevenness in the savings of CE applications and potential risks of rebound effects {5.3}. Therefore, CE policies that identify system determinants maximize potential emissions reductions, which vary by material, location, and application.

There are knowledge gaps for assessing CE opportunities within mitigation models due to CE's many cross-sectoral linkages and data gaps related to its nascent state {3.4.4}. Opportunity exists to bridge knowledge from the Industrial Ecology field, which has historically studied CE, to the mitigation modelling community for improved analysis of interventions and policies for AR7. For instance, a global CE knowledge sharing platform is helpful for CE performance measurement, reporting and accounting. {5.3, 9.5, 11.7}

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Providing better services with less energy and resource input has high technical potential and is consistent with providing well-being for all (*medium confidence*). The assessment of 19 demand-side mitigation options and 18 different constituents of well-being showed that positive impacts on well-being outweigh negative ones by a factor of 11. {5.2, 5.2.3, Figure 5.6}

Demand-side mitigation options bring multiple interacting benefits (*high confidence*). Energy services to meet human needs for nutrition, shelter, health, etc. are met in many different ways with different emissions implications that depend on local contexts, cultures, geography, available technologies, and social preferences. In the near term, many less-developed countries, and poor people everywhere, require better access to safe and low-emissions energy sources to ensure decent living standards and increase energy savings from service improvements by about 20-25%. (Figure TS.22) {5.2, 5.4.5, Figure 5.3, Figure 5.4, Figure 5.5, Figure 5.6, Box 5.2, Box 5.3}

Granular technologies and decentralized energy end-use, characterised by modularity, small unit sizes and small unit costs, diffuse faster into markets and are associated with faster technological learning benefits, greater efficiency, more opportunities to escape technological lock-in, and greater employment (*high confidence*). Examples include solar PV systems, batteries, and thermal heat pumps. {5.3, 5.5, 5.5.3}

Wealthy individuals contribute disproportionately to higher emissions and have a high potential for emissions reductions while maintaining decent living standards and well-being *(high confidence)*. Individuals with high socio-economic status are capable of reducing their GHG emissions by becoming role models of low-carbon lifestyles, investing in low-carbon businesses, and advocating for stringent climate policies. {5.4.1, 5.4.3, 5.4.4, Figure 5.14}

Demand-side solutions require both motivation and capacity for change (*high confidence*). Motivation by individuals or households worldwide to change energy consumption behaviour is generally low. Individual behavioural change is insufficient for climate change mitigation unless embedded in structural and cultural change. Different factors influence individual motivation and capacity for change in different demographics and geographies. These factors go beyond traditional socio-demographic and economic predictors and include psychological variables such as awareness, perceived risk, subjective and social norms, values, and perceived behavioural control. Behavioural nudges promote easy behaviour change, e.g., "*Improve*" actions such as making investments in energy efficiency but fail to motivate harder lifestyle changes (*high confidence*). {5.4}

Behavioural interventions, including the way choices are presented to end users (an intervention practice known as choice architecture), work synergistically with price signals, making the combination more effective (*medium confidence*). Behavioural interventions through nudges, and alternative ways of redesigning and motivating decisions, alone provide small to medium contributions to reduce energy consumption and GHG emissions. Green defaults, such as automatic enrolment in "green energy" provision, are highly effective. Judicious labelling, framing, and communication of social norms can also increase the effect of mandates, subsidies, or taxes. {5.4, 5.4.1, Table 5.3, 5.3}

Cultural change, in combination with new or adapted infrastructure, is necessary to enable and realise many *Avoid* and *Shift* options (*medium confidence*). By drawing support from diverse actors, narratives of change can enable coalitions to form, providing the basis for social movements to campaign in favour of (or against) societal transformations. People act and contribute to climate change mitigation in their diverse capacities as consumers, citizens, professionals, role models, investors, and policymakers. {5.4, 5.5, 5.6}

Sectors	Mitigation strategies / Wellbeing dimensions	Food	Water	Air	Health	Sanitation	Energy	Shelter	Mobility	Education	Communication	Social protection	Participation	Personal Security	Social cohesion	Political stability	Economic stability	Material provision
	SDGs	2	6	7,11	3	6	7	11	11	4		1,2,8,10	5,10,16	5,16	10,16	11,16	8	9,12
Building	Sufficiency (adequate floor space, etc.)	[+1] ★★★	[+2] ★★★★	[+2] ★★★★★	[+3] ★★★★★	[+1] ★	[+3] ★★★★	[+1] ★	[+1] ★★	[+1] ★★	[+2] ★★★	[+1] ★★	[+1] ★★		[+2] ★★★★★		[+2] ★★★★	[+2] ★★★★
Building	Efficiency	[+2] ★	[+2] ★★★★	[+3/-1] ★★★★	[+3/-1] ★★★★★	[+1] ★	[+3] ★★★★	[+2] ★★★★		[+1] ★★★	[+1] ★★★		[+1] ★★★★	[+1] ★★★	[+2/-1] ★★★★		[+2] ★★★★★	[+2/-1] ★★★★
Building	Lower carbon and renewable energy	[+2/-1] ★★★	[+2/-1] ★★★★	[+3] ★★★★★	[+3] ★★★★★		[+3] ★★★★	[+1] ★★★	[+1] ★★★	[+1] ★★★	[+2] ★★★		[+1] ★★★	[+1] ★★★	[+2/-1] ★★★★		[+2/-1] ★★★★★	[+2] ★★★★
Food	Food waste	[+1] ★★★	[+2] ★★★★	[+2] ★★★★	[+2] ★★★	[+1] ★★	[+1] ★★★★				[+1] ★★	[-1/+1] ★★★	[+1] ★★★			[+1] ★	[+1] ★★	
Food	Over-consumption	[+1] ★	[+1/-1] ★	[+1/-1] ★	[+3] ★★★★		[+1/-1] ★						[+2] ★★★★			[+1] ★		
Food	Plant based diets	[+2] ★★★	[+2] ★★★★	[+3] ★★★★★	[+3] ★★★						[-1] ★★★	[+3] ★★★★★	[+1] ★★★★		[-1] ★	[+2] ★		
Transport	Teleworking and online education system	[+1] ★★		[+3] ★★★★	[+2] ★★★★		[+2] ★★★★	[+1] ★★	[+2] ★★★★	[-1] ★★★	[+2] ★★★★	[+1] ★★★★	[+2] ★★★★	[+1/-1] ★★★★	[+2] ★★★★	[+2] ★★★	[+2] ★★★	
Transport	Non-motorized transport	[+2] ★★	[+1] ★★	[+1] ★★★★★	[+3] ★★★★★		[+2] ★★★★		[+3] ★★★★★	[+1] ★★★★	[+3] ★★★	[+1] ★★★	[+1] ★★	[+2] ★★★★	[+2] ★★★	[+2] ★★	[+2] ★★★	
Transport	Shared mobility	[+1] ★★		[+3] ★★★	[+2] ★★★★		[+1] ★★★		[+2] ★★★★		[+1] ★★★	[+2] ★★★	[+1] ★★★	[+1/-1] ★★★	[+1/-1] ★★★★	[-1] ★★★★	[+2] ★★★★	[+2] ★★★★
Transport	Evs	[+1] ★★★		[+2] ★★★★	[+1] ★★★★	[+1] ★★★★	[+3 ★★★★		[+2] ★★★★			[+3] ★★★★★	[+2] ★★★				[+2] ★★★★	[-1] ★★
Urabn	Compact city	[+2/-1] ★★★	[+1] ★★	[+2/-1] ★★★	[+3/-1] ★★★★	[+1] ★★	[+3/-1] ★★★★★	[-1] ★★★★★	[+3] ★★★★★	[+1] ★★★★★	[+1/-1] ★★★	[+2] ★★	[+1] ★★	[+1] ★★★★	[+1/-1] ★★★★★		[+1] ★★★★	[+1] ★★
Urabn	Circular and shared economy	[+2] ★★★★	[+1] ★★★	[+2] ★★★	[+2] ★★★		[+3] ★★★	[+2/-1] ★★★	[+3] ★★★★★	[+1] ★★★★	[+1] ★★★★	[+1] ★★★	[+1] ★★★	[+2] ★★★★	[+1] ★★	[+1] ★★	[+2] ★★	[+3] ★★★
Urabn	Systems approach in urban policy and practice	[+1] ★★★	[+2] ★★★	[+2] ★★★	[+3] ★★★	[+1] ★★★	[+3] ★★★	[+2] ★★★	[+3] ★★★		[+1] ★★	[-1] ★★	[+1] ★★★	[+2] ★	[+1] ★★		[+1] ★★	[+3] ★★★★★
Urabn	Nature based solutions	[+2] ★★★	[+1/-1] ★★★★★	[+3/-1] ★★★★	[+3] ★★★★★	[+1] ★★★	[+3] ★★★	[+1/-1] ★★★	[+1] ★★★	[+2] ★★★★		[+2] ★★	[+3] ★★	[+1] ★★★	[+2/-2] ★★★		[+3] ★★★★	[+1] ★★
Industry	Using less material by design	[+2] ★★	[+2] ★★★	[+3] ★★★	[+2] ★★	[+2] ★★★	[+3] ★★★★	[+2] ★★★★	[+2] ★★★★	[+1] ★★	[+2] ★★★	[+1] ★★	[+1] ★★★	[+1] ★★	[+1] ★★	[+1] ★★	[+2] ★★★	[+3] ★★
Industry	Product life extension	[+2] ★★	[+2] ★★★	[+3] ★★★	[+2] ★★	[+2] ★★★	[+3] ★★★★	[+2] ★★★★	[+2] ★★★★	[+1] ★★	[+2] ★★★	[+1] ★★	[-1] ★★★★	[+1] ★★	[+1] ★★	[+1] ★★	[+2] ★★★	[+3] ★★
Industry	Energy Efficiency	[+2] ★★	[+2] ★★★	[+3] ★★★	[+1] ★★	[+2] ★★★	[+3] ★★★★	[+2] ★★★★	[+2] ★★★★	[+1] ★★	[+2] ★★★	[+2] ★★★★	[+2] ★★★	[+1] ★★		[+1] ★★	[+2] ★★★	[+2] ★★
Industry	Circular economy	[+2] ★★★	[+2] ★★★	[+3] ★★★	[+1] ★★	[+2] ★★★	[+3] ★★★★	[+2] ★★★★	[+2] ★★★★	[+1] ★★	[+2] ★★★	[+1] ★★	[+1] ★★★	[+2] ★★	[+1] ★★		[+2] ★★★	[+3] ★★

Legend
High positive impact [+3]
Medium positive impact [+2]
Low positive impact [+1]
Overall Neutral
No impact
Low negative impact [-1]
Medium negative impact [-2]
★ Confidence level

Figure TS.22: Demand side mitigation options, well-being and SDGs {Figure 5.6}

Collective action as part of social or lifestyle movements underpins system change (*high confidence*). Collective action and social organising are crucial to shift the possibility space of public policy on climate change mitigation. For example, climate strikes have given voice to youth in more than 180 countries. In other instances, mitigation policies allow the active participation of all stakeholders, resulting in building social trust, new coalitions, legitimising change, and thus initiate a positive cycle in climate governance capacity and policies. {5.4.2, Figure 5.14}

Transition pathways and changes in social norms often start with pilot experiments led by dedicated individuals and niche groups (*high confidence*). Collectively, such initiatives can find entry points to prompt policy, infrastructure, and policy reconfigurations, supporting the further uptake of technological and lifestyle innovations. Individuals' agency is central as social change agents and narrators of meaning. These bottom-up socio-cultural forces catalyse a supportive policy environment, which enables changes. {5.5.2}

The current effects of climate change, as well as some mitigation strategies, are threatening the viability of existing business practices, while some corporate efforts also delay mitigation action (*medium confidence*). Policy packages that include job creation programs can help to preserve social trust, livelihoods, respect, and dignity of all workers and employees involved. Business models that protect rent extracting behaviour may sometimes delay political action. Corporate advertisement and brand building strategies may also attempt to deflect corporate responsibility to individuals or aim to appropriate climate care sentiments in their own brand–building. {5.4.3, 5.6.4}

Middle actors – professionals, experts, and regulators – play a crucial albeit underestimated and underutilised role in establishing low-carbon standards and practices (*medium confidence*). Building managers, landlords, energy efficiency advisers, technology installers, and car dealers influence patterns of mobility and energy consumption by acting as middle actors or intermediaries in the provision of building or mobility services and need greater capacity and motivation to play this role. (Figure TS.20a) {5.4.3}

Social influencers and thought leaders can increase the adoption of low-carbon technologies, behaviours, and lifestyles (*high confidence*). Preferences are malleable and can align with a cultural shift. The modelling of such shifts by salient and respected community members can help bring about changes in different service provisioning systems. Between 10% and 30% of committed individuals are required to set new social norms. {5.2.1, 5.4}

TS. 5.9 Mitigation potential across sectors and systems

The total emission mitigation potential achievable by the year 2030, calculated based on sectoral assessments, is sufficient to reduce global greenhouse gas emissions to half of the current (2019) level or less (*high confidence*). This potential – 31 to 44 $GtCO_2$-eq – requires the implementation of a wide range of mitigation options. Options with mitigation costs lower than USD20 tCO_2^{-1} make up more than half of this potential and are available for all sectors. The market benefits of some options exceed their costs. (Figure TS.23) {12.2, Table 12.3}

Cross-sectoral considerations in mitigation finance are critical for the effectiveness of mitigation action as well as for balancing the often conflicting social, developmental, and environmental policy goals at the sectoral level *(medium confidence)*. True resource mobilisation plans that properly address mitigation costs and benefits at sectoral level cannot be developed in isolation of their cross-sectoral implications. There is an urgent need for multilateral financing institutions to align their frameworks and delivery mechanisms including the use of blended financing to facilitate cross-sectoral solutions as opposed to causing competition for resources among sectors. {12.6.4}

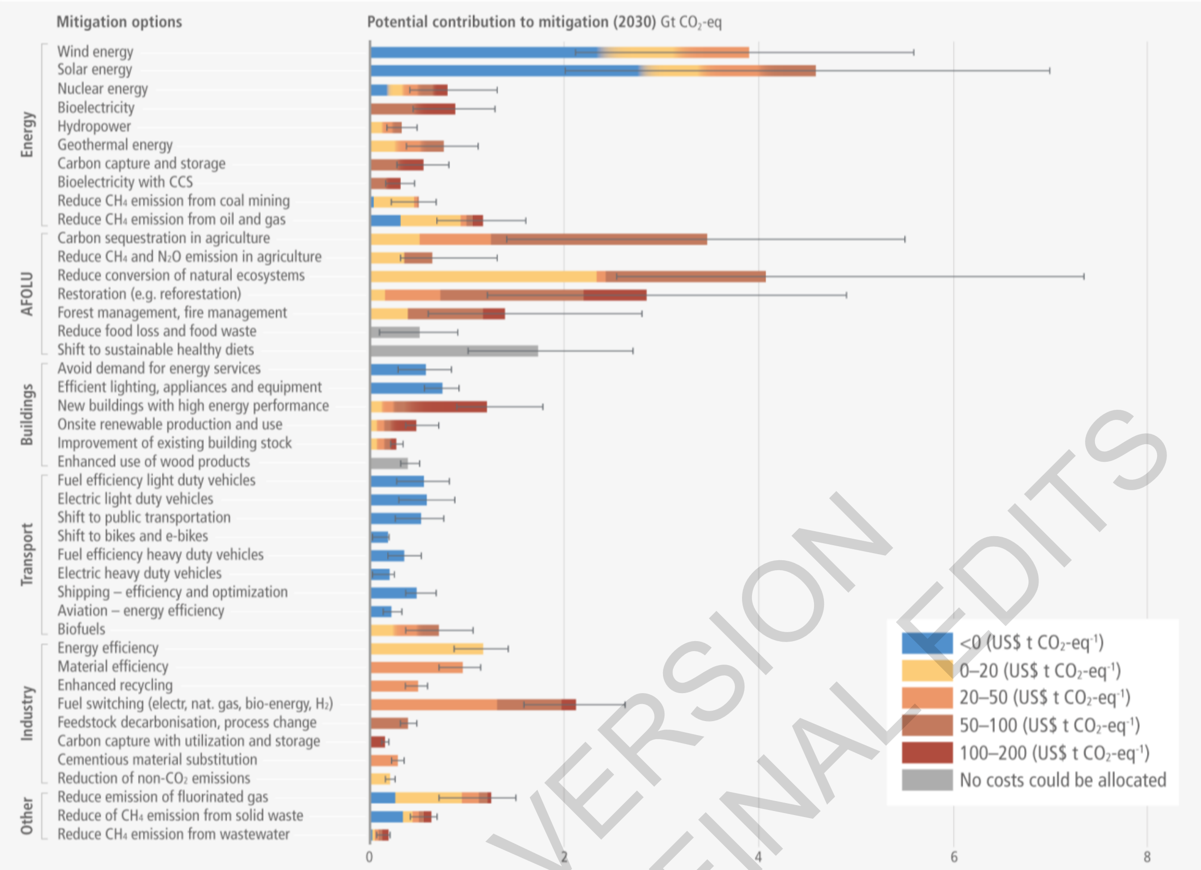


Figure TS.23*:* Overview of emission mitigation options and their cost and potential for the year 2030.

Figure TS.23 legend: The mitigation potential of each option is the quantity of net greenhouse gas emission reductions that can be achieved by a given mitigation option relative to specified emission baselines that reflects what would be considered current policies in the period 2015-2019. Mitigation options may overlap or interact and cannot simply be summed together.

The potential for each option is broken down into cost categories (see legend). Only monetary costs and revenues are considered. If costs are less than zero, lifetime monetary revenues are higher than lifetime monetary costs. For wind energy, for example, negative cost indicates that the cost is lower than that of fossil-based electricity production. The error bars refer to the total potential for each option. The breakdown into cost categories is subject to uncertainty. Where a smooth colour transition is shown, the breakdown of the potential into cost categories is not well researched, and the colours indicate only into which cost category the potential can predominantly be found in the literature.

{Figure SPM.8, 6.4, Table 7.3, Supplementary Material Table 9.2, Supplementary Material Table 9.3, 10.6, 11.4, Fig 11.13, 12.2, Supplementary Material 12.A.2.3}

Carbon leakage is a cross-sectoral and cross-country consequence of differentiated climate policy *(robust evidence, medium agreement)*. Carbon leakage occurs when mitigation measures implemented in one country/sector leads to increased emissions in other countries/sectors. Global commodity value chains and associated international transport are important mechanisms through which carbon leakage occurs. Reducing emissions from the value chain and transportation can offer opportunities to mitigate three elements of cross-sectoral spill-overs and related leakage: 1) domestic cross-sectoral spill-overs within the same country; 2) international spill-overs within a single sector resulting from substitution of domestic production of carbon-intensive goods with their imports from abroad; and 3) international cross-sectoral spill-overs among sectors in different countries. {12.6.3}

TS. 6 Implementation and enabling conditions

Chapters 13-16 address the enabling conditions that can accelerate or impede rapid progress on mitigation. Chapters 13 and 14 focus on policy, governance and institutional capacity, and international cooperation, respectively taking a national and international perspective; Chapter 15 focusses on investment and finance*;* and Chapter 16 focusses on innovation and technology. The assessment of social aspects of mitigation draws on material assessed in Chapter 5.

TS. 6.1 Policy and Institutions

Long-term deep emission reductions, including the reduction of emissions to net zero, is best achieved through institutions and governance that nurture new mitigation policies, while at the same time reconsidering existing policies that support the continued emission of GHGs (*high confidence*). To do so effectively, the scope of climate governance needs to include both direct efforts to target GHG emissions and indirect opportunities to tackle GHG emissions that result from efforts directed towards other policy objectives. {13.2, 13.5, 13.6, 13.7, 13.9}

Institutions and governance underpin mitigation by providing the legal basis for action. This includes setting up implementing organisations and the frameworks through which diverse actors interact *(medium evidence, high agreement)*. Institutions can create mitigation and sectoral policy instruments; policy packages for low-carbon system transition; and economy wide measures for systemic restructuring. {13.2, 13.7, 13.9}

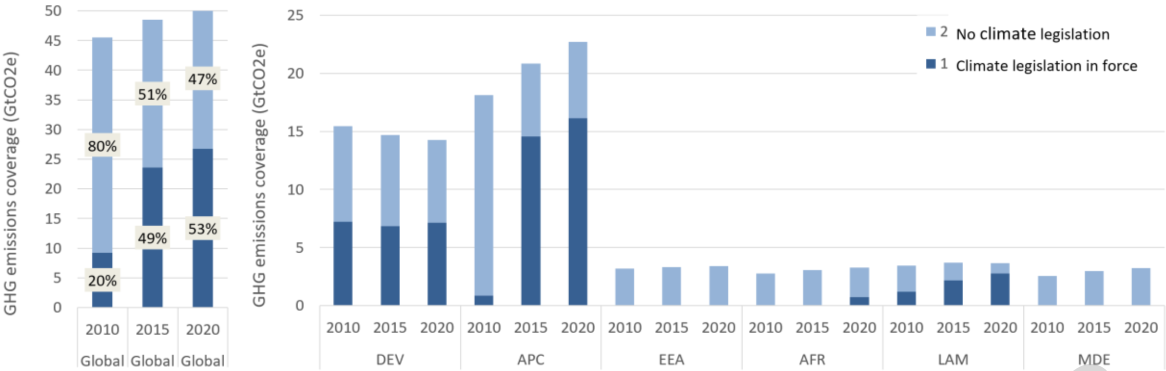
Policies have had a discernible impact on mitigation for specific countries, sectors, and technologies (*high confidence*), avoiding emissions of several GtCO$_2$-eq yr^{-1} *(medium confidence)*. Both market-based and regulatory policies have distinct, but complementary roles. The share of global GHG emissions subject to mitigation policy has increased rapidly in recent years, but big gaps remain in policy coverage, and the stringency of many policies falls short of what is needed to achieve the desired mitigation outcomes. (Box TS.13) {13.6, Cross-Chapter Box 10 in Chapter 14}

Climate laws enable mitigation action by signalling the direction of travel, setting targets, mainstreaming mitigation into sector policies, enhancing regulatory certainty, creating law-backed agencies, creating focal points for social mobilisation, and attracting international finance *(medium evidence, high agreement)*. By 2020, 'direct' climate laws primarily focused on GHG reductions were present in 56 countries covering 53% of global emissions (see Figure TS.24). More than 690 laws, including 'indirect' laws, however, may also have an effect on mitigation. Among direct laws, 'framework' laws set an overarching legal basis for mitigation either by pursuing a target and implementation approach, or by seeking to mainstream climate objectives through sectoral plans and integrative institutions. (Figure TS.24) {13.2}

Institutions can enable improved governance by coordinating across sectors, scales and actors, building consensus for action, and setting strategies *(medium evidence, high agreement)*. Institutions are more stable and effective when they are congruent with national contexts, leading to mitigation-focused institutions in some countries and the pursuit of multiple objectives in others. Sub-national institutions play a complementary role to national institutions by developing locally-relevant visions and plans, addressing policy gaps or limits in national institutions, building local administrative structures and convening actors for place-based decarbonisation. {13.2}

Mitigation strategies, instruments and policies that fit with dominant ideas, values and belief systems within a country or within a sector are more easily adopted and implemented *(medium confidence)*. Ideas, values and beliefs may change over time. Policies that bring perceived direct benefits, such as subsidies, usually receive greater support. The awareness of co-benefits for the public increases support of climate policies (*high confidence*). {13.2, 13.3, 13.4}

Panel a



Panel b

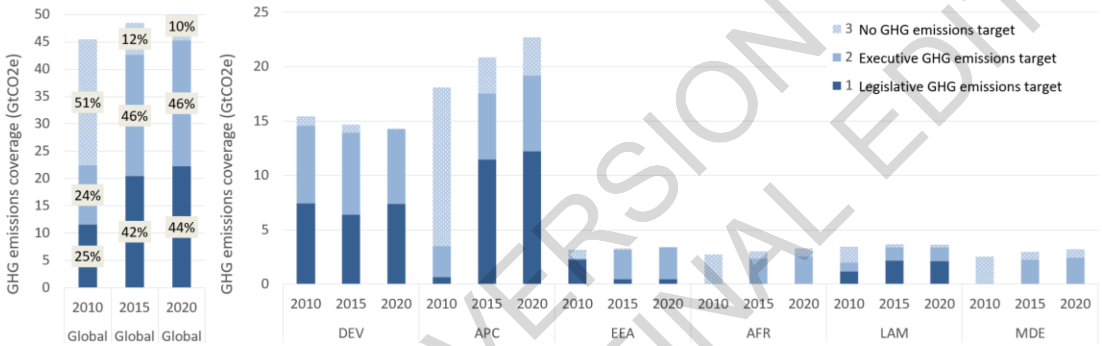


Figure TS.24: Prevalence of Legislation and Emissions Targets across Regions

Figure TS.24 legend: Panel a: Shares of global GHG emissions under national climate change legislations – in 2010, 2015 and 2020. Climate legislation is defined as an act passed by a parliament that includes the reduction of GHGs in its title or objectives.
Panel b: Shares of global GHG emissions under national climate emission targets – in 2010, 2015 and 2020. Emissions reductions targets were taken into account as a legislative target when they were defined in a law or as part of a country's submission under the Kyoto Protocol, or as an executive target when they were included in a national policy or official submissions under the UNFCCC. Targets were included if they were economy wide or included at least the energy sector. The proportion of national emissions covered are scaled to reflect coverage and whether targets are in GHG or CO_2 terms.
Emissions data used are for 2019. 2020 data was excluded as emissions shares across regions deviated from past patterns due to COVID-19. AR6 regions: DEV = Developed countries; APC = Asia and developing Pacific; EEA = Eastern Europe and West-Central Asia; AFR = Africa; LAM = Latin America and the Caribbean; MDE = Middle East. {Figure 13.1 and 13.2}

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Climate governance is constrained and enabled by domestic structural factors, but it is still possible for actors to make substantial changes *(medium evidence, high agreement)*. Key structural factors are domestic material endowments (such as fossil fuels and land-based resources); domestic political systems; and prevalent ideas, values and belief systems. Developing countries face additional material constraints in climate governance due to development challenges and scarce economic or natural resources. A broad group of actors influence how climate governance develop over time, including a range of civic organisations, encompassing both pro- and anti-climate action groups. {13.3, 13.4}

Sub-national actors are important for mitigation because municipalities and regional governments have jurisdiction over climate-relevant sectors such as land-use, waste and urban policy. They are able to experiment with climate solutions and can forge partnerships with the private sector and internationally to leverage enhanced climate action (*high confidence*). More than 10,500 cities and nearly 250 regions representing more than 2 billion people have pledged largely voluntary action to reduce emissions. Indirect gains include innovation, establishing norms and developing capacity. However, sub-national actors often lack national support, funding, and capacity to mobilize finance and human resources, and create new institutional competences. {13.5}

Climate litigation is growing and can affect the outcome and ambition of climate governance *(medium evidence, high agreement)*. Since 2015, at least 37 systemic cases have been initiated against states that challenge the overall effort of a state to mitigate or adapt to climate change. If successful, such cases can lead to an increase in a country's overall ambition to tackle climate change. Climate litigation has also successfully challenged governments' authorisations of high-emitting projects setting precedents in favour of climate action. Climate litigation against private sector and financial institutions is also on the rise. {13.4}

The media shapes the public discourse about climate mitigation. This can usefully build public support to accelerate mitigation action but may also be used to impede decarbonisation *(medium evidence, high agreement)*. Global media coverage (across a study of 59 countries) has been growing, from about 47,000 articles in 2016-17 to about 87,000 in 2020-21. Generally, the media representation of climate science has increased and become more accurate over time. On occasion, the propagation of scientifically misleading information by organized counter-movements has fuelled polarisation, with negative implications for climate policy. {13.4}

Explicit attention to equity and justice is salient to both social acceptance and fair and effective policymaking for mitigation (*high confidence*). Distributional implications of alternative climate policy choices can be usefully evaluated at city, local and national scales as an input to policymaking. It is anticipated that institutions and governance frameworks that enable consideration of justice and just transitions can build broader support for climate policymaking. {13.2, 13.6, 13.8, 13.9}

Carbon pricing is effective in promoting implementation of low-cost emissions reductions (*high confidence*). While the coverage of emissions trading and carbon taxes has risen to over 20 percent of global CO_2 emissions, both coverage and price are lower than is needed for deep reductions. Market mechanisms ideally are designed to be effective as well as efficient, balance distributional goals and find social acceptance. Practical experience has driven progress in market mechanism design, especially of emissions trading schemes. Carbon pricing is limited in its effect on adoption of higher-cost mitigation options, and where decisions are often not sensitive to price incentives such as in energy efficiency, urban planning, and infrastructure *(robust evidence, medium agreement)*. Subsidies have been used to improve energy efficiency, encourage the uptake of renewable energy and other sector-specific emissions saving options {13.6}

Carbon pricing is most effective if revenues are redistributed or used impartially (*high confidence*). A carbon levy earmarked for green infrastructures or saliently returned to taxpayers corresponding to widely accepted notions of fairness increases the political acceptability of carbon pricing. {5.6, Box 5.11}

Removing fossil fuel subsidies could reduce emissions by 1-10% by 2030 while improving public revenue and macroeconomic performance *(robust evidence, medium agreement)*. {13.6}

Regulatory instruments play an important role in achieving specific mitigation outcomes in sectoral applications (*high confidence*). Regulation is effective in particular applications and often enjoys greater political support, but tends to be more economically costly, than pricing instruments *(robust evidence, medium agreement).* Flexible forms of regulation (e.g., performance standards) have achieved aggregate goals for renewable energy generation, vehicle efficiency and fuel standards, and energy efficiency in buildings and industry. Infrastructure investment decisions are significant for mitigation because they lock in high- or low- emissions trajectories over long periods. Information and voluntary programs can contribute to overall mitigation outcomes *(medium evidence, high agreement).* Designing for overlap and interactions among mitigation policies enhances their effectiveness. {13.6}

National mitigation policies interact internationally with effects that both support and hinder mitigation action *(medium evidence, high agreement)*. Reductions in demand for fossil fuels tend to negatively affect fossil fuel exporting countries. Creation of markets for emission reduction credits tends to benefit countries able to supply credits. Policies to support technology development and diffusion tend to have positive spill over effects. There is no consistent evidence of significant emissions leakage or competitiveness effects between countries, including for emissions-intensive trade-exposed industries covered by emission trading systems *(medium confidence).* {13.6}

Policy packages are better able to support socio-technical transitions and shifts in development pathways toward low carbon futures than are individual policies (*high confidence*). For best effect, they need to be harnessed to a clear vision for change and designed with attention to local governance context. Comprehensiveness in coverage, coherence to ensure complementarity, and consistency of policies with the overarching vision and its objectives are important design criteria. Integration across objectives occurs when a policy package is informed by a clear problem framing and identification of the full range of relevant policy sub-systems. The climate policy landscape is outlined in Table TS.8, which maps framings of desired national policy outcomes to policymaking approaches. {13.7, Figure 13.6}

The co-benefits and trade-offs of integrating adaptation and mitigation are most usefully identified and assessed prior to policy making rather than being accidentally discovered (*high confidence*). This requires strengthening relevant national institutions to reduce silos and overlaps, increasing knowledge exchange at the country and regional levels, and supporting engagement with bilateral and multilateral funding partners. Local governments are well placed to develop policies that generate social and environmental co-benefits but to do so require legal backing and adequate capacity and resources. {13.8}

Climate change mitigation is accelerated when attention is given to integrated policy and economy wide approaches, and when enabling conditions (*governance, institutions, behaviour and lifestyle, innovation, policy,* and *finance*), are present *(robust evidence, medium agreement)*. Accelerating climate mitigation includes simultaneously weakening high carbon systems and encouraging low carbon systems; ensuring interaction between adjacent systems (e.g., energy and agriculture); overcoming resistance to policies (e.g., from incumbents in high carbon emitting industries), including by providing transitional support to the vulnerable and negatively affected by distributional impacts; inducing changes in consumer practices and routines; providing transition support; and addressing coordination challenges in policy and governance. Table TS.9 elucidates the complexity of policymaking in driving sectoral transitions by summarising case studies of sectoral transitions from Chapters 5-12. These real-world sectoral transitions reinforce critical lessons on policy integration. (Table TS.9) {13.7, 13.9}

Economy wide packages, including economic stimulus packages, can contribute to shifting sustainable development pathways and achieving net zero outcomes whilst meeting short term economic goals *(medium evidence, high agreement)*. The 2008-9 Global Recession showed that policies for sustained economic recovery go beyond short-term fiscal stimulus to include long-term commitments of public spending on the low carbon economy, pricing reform, addressing affordability, and minimising distributional impacts. COVID-19 spurred stimulus packages and multi-objective recovery policies may also have potential to meet short-term economic goals while enabling longer-term sustainability goals. (Table TS.8) {13.9}

Table TS.8: Mapping the Landscape of Climate Policy {Figure 13.6}

		Framing of Outcome	
		Enhancing Mitigation	**Addressing Multiple Objectives of Mitigation and Development**
Approach to Policymaking	**Shifting Incentives**	"Direct Mitigation Focus" *{2.8, 13.6}* *Objective:* Reduce GHG emissions now *Literature:* How to design and implement policy instruments, with attention to distributional and other concerns *Examples:* Carbon tax, cap and trade, border carbon adjustment, disclosure policies	"Co-benefits" *{5.6.2, 12.4.4, 17.3}* *Objective:* Synergies between mitigation and development *Literature:* Scope for and policies to realise synergies and avoid trade-offs across climate and development objectives *Examples:* Appliance standards, fuel taxes, community forest management, sustainable dietary guidelines, green building codes, packages for air pollution, packages for public transport
	Enabling Transition	"Socio-technical transitions" *{1.7.3, 5.5, 6.7, 10.8, Cross-Chapter Box 12 in Chapter 16)* *Objective:* Accelerate low-carbon shifts in socio-technical systems *Literature:* Understand socio-technical transition processes, integrated policies for different stages of a technology 'S curve' and explore structural, social and political elements of transitions *Examples:* Packages for renewable energy transition and coal phase-out; diffusion of electric vehicles, process and fuel switching in key industries	"System transitions to shift development pathways" *{7.4.5, 11.6.6, 13.9, 17.3.3, Cross-Chapter Box 5 in Chapter 4, Cross-Chapter Box 12 in Chapter 16}* *Objective:* Accelerate system transitions and shift development pathways to expand mitigation options and meet other development goals *Literature:* Examines how structural development patterns and broad cross-sector and economy wide measures drive ability to mitigate while achieving development goals through integrated policies and aligning enabling conditions *Examples:* Packages for sustainable urbanisation, land-energy-water nexus approaches, green industrial policy, regional just transition plans

Table TS.9: Case Studies of Integrated Policymaking for Sectoral Transitions

Real world sectoral transitions reinforce critical lessons on policy integration: a high-level strategic goal (column A), the need for a clear sectoral outcome framing (column B), a carefully coordinated mix of policy instruments and governance actions (column C), and the importance of context-specific governance factors (column D). Illustrative examples, drawn from sectors, help elucidate the complexity of policymaking in driving sectoral transitions.

A. Illustrative Case	B. Objective	C. Policy mix	D. Governance Context	
			Enablers	Barriers
Shift in mobility service provision in Kolkata, India {Box 5.8}	- Improve system efficiency, sustainability and comfort - Shift public perceptions of public transport	- Strengthen co-ordination between modes - Formalize and green auto-rickshaws - Procure fuel efficient, comfortable low floor AC buses - Ban cycling on busy roads - Deploy policy actors as change-agents, mediating between interest groups	- Cultural norms around informal transport sharing, linked to high levels of social trust - Historically crucial role of buses in transit - App-cab companies shifting norms and formalizing mobility sharing - Digitalisation and safety on board	- Complexity: multiple modes with separate networks and meanings - Pushback from equity-focused social movements against 'premium' fares, cycling ban
LPG Subsidy ("Zero Kero") Program, Indonesia {Box 6.3}	Decrease fiscal expenditures on kerosene subsidies for cooking	- Subsidize provision of Liquefied Petroleum Gas (LPG) cylinders and initial equipment - Convert existing kerosene suppliers to LPG suppliers	- Provincial Government and industry support in targeting beneficiaries and implementation - Synergies in kerosene and LPG distribution infrastructures	- Continued user preference for traditional solid fuels - Reduced GHG benefits as subsidy shifted between fossil fuels
Action Plan for Prevention and Control of Deforestation in the Legal Amazon, Brazil {Box 7.9}	Control deforestation and promote sustainable development	- Expand protected areas; homologation of indigenous lands - Improve inspections, satellite-based monitoring - Restrict public credit for enterprises and municipalities with high deforestation rates - Set up a REDD+ mechanism (Amazon Fund)	- Participatory agenda-setting process - Cross-sectoral consultations on conservation guidelines -Mainstreaming of deforestation in government programs and projects	- Political polarisation leading to erosion of environmental governance - Reduced representation and independence of civil society in decision-making bodies - Lack of clarity around land ownership
Climate smart cocoa (CSC) production, Ghana {Box 7.12}	- Promote sustainable intensification of cocoa production - Reduce deforestation - Enhance incomes and adaptive capacities	- Distribute shade tree seedlings - Provide access to agronomic information and agro-chemical inputs - Design a multi-stakeholder program including MNCs, farmers and NGOs	- Local resource governance mechanisms ensuring voice for smallholders - Community governance allowed adapting to local context - Private sector role in popularising CSC	- Lack of secure tenure (tree rights) - Bureaucratic and legal hurdles to register trees - State monopoly on cocoa marketing, export
Coordination mechanism for joining fragmented urban policymaking	Integrate policymaking across objectives, towards low-carbon urban development	- Combine central targets and evaluation with local flexibility for initiating varied policy experiments - Establish a local leadership team for coordinating	- Strong vertical linkages between central and local levels - Mandate for policy learning to inform national policy	- Challenging starting point - low share of renewable energy high dependency on fossil fuels

A. Illustrative Case	B. Objective	C. Policy mix	D. Governance Context	
			Enablers	Barriers
in Shanghai, China {Box 8.3}		cross-sectoral policies involving multiple institutions - Create a direct program fund for implementation and capacity-building	- Experience with mainstreaming mitigation in related areas (e.g., air pollution)	- Continued need for high investments in a developing context
Policy package for building energy efficiency, EU {Box SM 9.1}	Reduce energy consumption, integrating renewable energy and mitigating GHG emissions from buildings	- Energy performance standards, set at nearly zero energy for new buildings - Energy performance standards for appliances - Energy performance certificates shown during sale - Long Term Renovation Strategies	- Binding EU-level targets, directives and sectoral effort sharing regulations - Supportive urban policies, coordinated through city partnerships - Funds raised from allowances auctioned under the Emissions Trading Scheme (ETS)	- Inadequate local technical capacity to implement multiple instruments - Complex governance structure leading to uneven stringency
African Electromobility-Trackless trams with solar in Bulawayo and e-motorbikes in Kampala {Box 10.4}	- Leapfrog into a decarbonised transport future - Achieve multiple social benefits beyond mobility provision	- Develop urban centres with solar at station precincts - Public-private partnerships for financing - Sanction demonstration projects for new electric transit and new electric motorbikes (for freight)	- 'Achieving SDGs' was an enabling policy framing - Multi-objective policy process for mobility, mitigation and manufacturing - Potential for funding through climate finance - Co-benefits such as local employment generation	- Economic decline in the first decade of the 21st century - Limited fiscal capacity for public funding of infrastructure - Inadequate charging infrastructure for e-motorbikes
Initiative for a climate-friendly industry in North Rhine Westphalia (NRW), Germany {Box 11.3}	- Collaboratively develop innovative strategies towards a net zero GHG industrial sector, while securing competitiveness	- Build platform to bring together industry, scientists and government in self-organised innovation teams - Intensive cross-branch cooperation to articulate policy/infrastructure needs	- NRW is Germany's industrial heartland, with an export-oriented industrial base - Established government-industry ties - Active discourse between industry and public	- Compliance rules preventing in-depth co-operation
Food2030 Strategy, Finland {Box 12.2}	- Local, organic and climate friendly food production - Responsible and healthy food consumption - A competitive food supply chain	- Target funding and knowledge support for innovations - Apply administrative means (legislation, guidance) to increase organic food production and procurement - Use education and information instruments to shift behaviour (media campaigns, websites)	- Year-long deliberative stakeholder engagement process across sectors - Institutional structures for agenda-setting, guiding policy implementation and reflexive discussions	- Weak role of integrated impact assessments to inform agenda-setting - Monitoring and evaluation close to ministry in charge - Lack of standardised indicators of food system sustainability

START BOX TS.13 HERE

Box TS.13: Policy Attribution – Methodologies for- and estimations of- the macro-level impact of mitigation policies on indices of GHG mitigation

Policy attribution examines the extent to which *GHG emission reductions*, the *proximate drivers of emissions*, and the deployment of *technologies that reduce emissions* may be reasonably attributed to policies implemented prior to the observed changes. Such policies include regulatory instruments such as energy efficiency programmes or technical standards and codes, carbon pricing, financial support for low-carbon energy technologies and efficiency, voluntary agreements, and regulation of land use practices.

The vast majority of literature reviewed for this report examines the effect of particular instruments in particular contexts {13.6, 14.3, 16.4}, and only a small number directly or plausibly infer global impacts of policies. Policies also differ in design, scope, and stringency, may change over time as they require amendments or new laws, and often partially overlap with other instruments. These factors complicate analysis, because they give rise to the potential for double counting emissions reductions that have been observed. These lines of evidence on the impact of polices include:

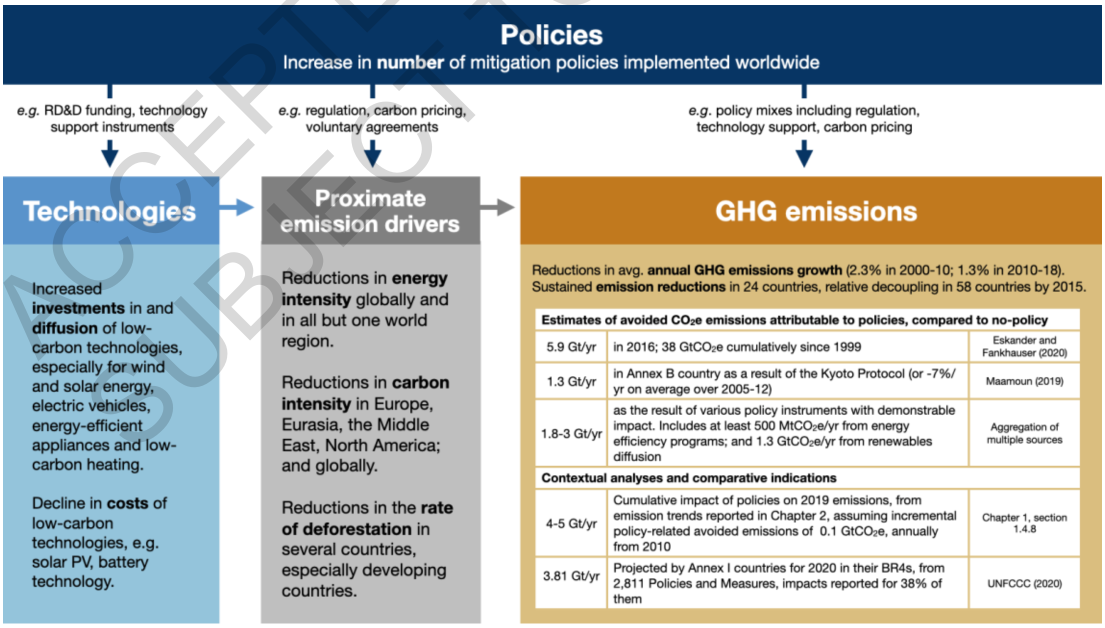
- ***GHG Emissions*** **–** Evidence from econometric assessments of the impact of policies in countries which took on Kyoto Protocol targets; decomposition analyses that identify policy-related, absolute reductions from historical levels in particular countries. {13.6.2, 14.3.3, Cross-Chapter Box 10 in Chapter 14}
- ***Proximate emission drivers*** **–** trends in the factors that drive emissions including reduced rates of deforestation {7.6.2}, industrial energy efficiency {Box 16.3}, buildings energy efficiency {Figure 2.22}, and the policy-driven displacement of fossil fuel combustion by renewable energy. (Box TS.13 Table 1, Box TS.13 Figure 1) {Chapters 2 and 6, Cross-Chapter Box 10 in Chapter 14}.
- ***Technologies*** – the literature indicates unambiguously that the rapid expansion of low-carbon energy technologies is substantially attributable to policy. {6.7.5, 16.5}

As illustrated in Box TS.13, Figure 1, these multiple lines of evidence indicate that point to policies having had a discernible impact on mitigation for specific countries, sectors, and technologies (*high confidence*), avoiding emissions of several GCO_2-eq yr^{-1} globally *(medium confidence)*.

Box TS.13 Table 1: The effects of policy on GHG emissions, drivers of emissions, and technology deployment

Sector	Effects on Emissions	Effects on Immediate Drivers	Effects on Low-carbon Technology
Energy supply {Chapter 6}	Carbon pricing, emissions standards, and technology support have led to declining emissions associated with the supply of energy	Carbon pricing and technology support have led to improvements in the efficiency of energy conversion	A variety of market-based instruments, especially technology support policies have led to high diffusion rates and cost reductions for renewable energy technologies.
AFOLU {Chapter 7}	Regulation of land-use rights and practices have led to falling aggregate AFOLU-sector emissions	Regulation of land-use rights and practices, payments for ecosystem service, and offsets have led to decreasing rates of deforestation *(medium confidence)*	
Buildings {Chapter 9}	Regulatory standards have led to reduced emissions from new buildings	Regulatory standards, financial support for building renovation and market-based instruments have led to improvements in building and building system efficiencies	Technology support and regulatory standards have led to adoption of low-carbon heating systems and high efficiency appliances
Transport {Chapter 10}	Vehicle standards, land-use planning, and carbon pricing have led to avoided emissions in ground transportation	Vehicle standard, carbon pricing, and support for electrification have led to automobile efficiency improvements	Technology support and emissions standards have increased diffusion rates and cost reductions for electric vehicles
Industry {Chapter 11}		Carbon pricing has led to efficiency improvements in industrial facilities.	

Note: Statements describe the effects of policies across those countries where policies are in place. Unless otherwise noted, all findings are of *high confidence*



Box TS.13, Figure 1: Policy impacts on key outcome indices: GHG emissions, proximate emission drivers, and technologies, including several lines of evidence on GHG abatement attributable to policies. {Cross-Chapter Box 10 Figure 1 in Chapter 14}

END BOX TS.13 HERE

TS. 6.2 International cooperation

International cooperation is having positive and measurable results (*high confidence*). The Kyoto Protocol led to measurable and substantial avoided emissions, including in 20 countries with Kyoto first commitment period targets that have experienced a decade of declining absolute emissions. It also built national capacity for GHG accounting, catalysed the creation of GHG markets, and increased investments in low-carbon technologies. Other international agreements and institutions have led to avoided CO_2 emissions from land-use practices, as well as avoided emissions of some non-CO_2 greenhouse gases. (*medium confidence*) {14.3, 14.5, 14.6}

New forms of international cooperation have emerged since AR5 in line with an evolving understanding of effective mitigation policies, processes, and institutions. Both new and pre-existing forms of co-operation are vital for achieving climate mitigation goals in the context of sustainable development (*high confidence*). While previous IPCC assessments have noted important synergies between the outcomes of climate mitigation and achieving sustainable development objectives, there now appear to be synergies between the two processes themselves (*medium confidence*). Since AR5, international cooperation has shifted towards facilitating national level mitigation action through numerous channels, including though processes established under the UNFCCC regime and through regional and sectoral agreements and organisations. {14.2, 14.3, 14.5, 14.6}

Participation in international agreements and transboundary networks is associated with the adoption of climate policies at the national and sub-national levels, as well as by non-state actors (*high confidence*). International cooperation helps countries achieve long-term mitigation targets when it supports development and diffusion of low-carbon technologies, often at the level of individual sectors, which can simultaneously lead to significant benefits in the areas of sustainable development and equity (*medium confidence*). {14.2, 14.3, 14.5, 14.6}

International cooperation under the UN climate regime took an important new direction with the entry into force of the 2015 Paris Agreement, which strengthened the objective of the UN climate regime, including its long-term temperature goal, while adopting a different architecture to that of the Kyoto Protocol (*high confidence*). The core national commitments under the Kyoto Protocol were legally binding quantified emission targets for developed countries tied to well-defined mechanisms for monitoring and enforcement. By contrast, the commitments under the Paris Agreement are primarily procedural, extend to all parties, and are designed to trigger domestic policies and measures, enhance transparency, and stimulate climate investments, particularly in developing countries, and to lead iteratively to rising levels of ambition across all countries. Issues of equity remain of central importance in the UN climate regime, notwithstanding shifts in the operationalisation of 'common but differentiated responsibilities and respective capabilities' from Kyoto to Paris. {14.3}

There are conflicting views on whether the Paris Agreement's commitments and mechanisms will lead to the attainment of its stated goals (*medium confidence*). Arguments in support of the Paris Agreement are that the processes it initiates and supports will in multiple ways lead, and indeed have already led, to rising levels of ambition over time. The recent proliferation of national mid-century net zero GHG targets can be attributed in part to the Paris Agreement. Moreover, its processes and commitments will enhance countries' abilities to achieve their stated level of ambition, particularly among developing countries. Arguments against the Paris Agreement are that it lacks a mechanism to review the adequacy of individual Parties' nationally determined contributions (NDCs), that collectively current NDCs are inconsistent in their level of ambition with achieving the Paris Agreement's long-term temperature goal, that its processes will not lead to sufficiently rising levels of ambition in the NDCs, and that NDCs will not be achieved because the targets, policies and measures they contain are not legally binding at the international level. To some extent, arguments on both sides are aligned with different analytic frameworks, including assumptions about the main barriers to mitigation that international cooperation can help overcome. The extent to which countries increase the ambition of their NDCs and ensure they are effectively implemented will depend in part on the successful implementation of the support mechanisms in the Paris Agreement, and in turn will determine whether the goals of the Paris Agreement are met (*high confidence*). {14.2, 14.3, 14.4}

International cooperation outside the UNFCCC processes and agreements provides critical support for mitigation in particular regions, sectors and industries, for particular types of emissions, and at the sub- and trans-national levels (*high confidence*). Agreements addressing ozone depletion, transboundary air pollution, and release of mercury are all leading to reductions in the emissions of specific greenhouse gases. Cooperation is occurring at multiple governance levels including cities. Transnational partnerships and alliances involving non-state and sub-national actors are also playing a growing role in stimulating low-carbon technology diffusion and emissions reductions (*medium confidence*). Such transnational efforts include those focused on climate litigation; the impacts of these are unclear but promising. Climate change is being addressed in a growing number of international agreements operating at sectoral levels, as well as within the practices of many multilateral organisations and institutions. Sub-global and regional cooperation, often described as climate clubs, can play an important role in accelerating mitigation, including the potential for reducing mitigation costs through linking national carbon markets, although actual examples of these remain limited. {14.2, 14.4, 14.5, 14.6}

International cooperation will need to be strengthened in several key respects in order to support mitigation action consistent with limiting temperature rise to well below 2°C in the context of sustainable development and equity *(high confidence)*. Many developing countries' NDCs have components or additional actions that are conditional on receiving assistance with respect to finance, technology development and transfer, and capacity building, greater than what has been provided to date. Sectoral and sub-global cooperation is providing critical support, and yet there is room for further progress. In some cases, notably with respect to aviation and shipping, sectoral agreements have adopted climate mitigation goals that fall far short of what would be required to achieve the long-term temperature goal of the Paris Agreement. Moreover, there are cases where international cooperation may be hindering mitigation efforts, namely evidence that trade and investment agreements, as well as agreements within the energy sector, impede national mitigation efforts (*medium confidence*). International cooperation is emerging but so far fails to fully address transboundary issues associated with solar radiation modification and carbon dioxide removal. {14.2, 14.3, 14.4, 14.5, 14.6, Cross-Working Group Box 4 in Chapter 14}

TS. 6.3 Societal aspects of mitigation

Social equity reinforces capacity and motivation for mitigating climate change (*medium confidence*). Impartial governance such as fair treatment by law-and-order institutions, fair treatment by gender, and income equity, increases social trust, thus enabling demand-side climate policies. High status (often high carbon) item consumption may be reduced by taxing absolute wealth without compromising well-being. {5.2, 5.4.2, 5.6}

Policies that increase the political access and participation of women, racialised, and marginalised groups, increase the democratic impetus for climate action (*high confidence*). Including more differently situated knowledge and diverse perspectives makes climate mitigation policies more effective. {5.2, 5.6}

Greater contextualisation and granularity in policy approaches better addresses the challenges of rapid transitions towards zero-carbon systems (*high confidence*). Larger systems take more time to evolve, grow, and change compared to smaller ones**.** Creating and scaling up entirely new systems takes longer than replacing existing technologies and practices. Late adopters tend to adopt faster than early pioneers. Obstacles and feasibility barriers are high in the early transition phases. Barriers decrease as a result of technical and social learning processes, network building, scale economies, cultural debates, and institutional adjustments. {5.5, 5.6}

Mitigation policies that integrate and communicate with the values people hold are more successful (*high confidence*). Values differ between cultures. Measures that support autonomy, energy security and safety, equity and environmental protection, and fairness resonate well in many communities and social groups. Changing from a commercialised, individualised, entrepreneurial training model to an education cognizant of planetary health and human well-being can accelerate climate change awareness and action. {5.4.1, 5.4.2}

Changes in consumption choices that are supported by structural changes and political action enable the uptake of low-carbon choices (*high confidence*). Policy instruments applied in coordination can help to accelerate change in a consistent desired direction. Targeted technological change, regulation, and public policy can help in steering digitalisation, the sharing economy, and circular economy towards climate change mitigation. (Box TS.12, Box TS.14) {5.3, 5.6}

Complementarity in policies helps in the design of an optimal demand-side policy mix (*medium confidence*). In the case of energy efficiency, for example, this may involve CO_2 pricing, standards and norms, and information feedback. {5.3, 5.4, 5.6}

TS. 6.4 Investment and finance

Finance to reduce net GHG emissions and enhance resilience to climate impacts is a critical enabling factor for the low carbon transition. Fundamental inequities in access to finance as well as finance terms and conditions, and countries' exposure to physical impacts of climate change overall, result in a worsening outlook for a global just transition *(high confidence)*. Decarbonising the economy requires global action to address fundamental economic inequities and overcome the climate investment trap that exists for many developing countries. For these countries the costs and risks of financing often represent a significant challenge for stakeholders at all levels. This challenge is exacerbated by these countries' general economic vulnerability and indebtedness. The rising public fiscal costs of mitigation, and of adapting to climate shocks, is affecting many countries and worsening public indebtedness and country credit ratings at a time when there were already significant stresses on public finances. The COVID-19 pandemic has made these stresses worse and tightened public finances still further. Other major challenges for commercial climate finance include: the mismatch between capital and investment needs, home bias[23] considerations, differences in risk perceptions for regions, as well as limited institutional capacity to ensure safeguards are effective. (*high confidence*) {15.2, 15.6.3}

Investors, central banks, and financial regulators are driving increased awareness of climate risk. This increased awareness can support climate policy development and implementation *(high confidence)*. {15.2, 15.6} Climate-related financial risks arise from physical impacts of climate change (already relevant in the short term), and from a disorderly transition to a low carbon economy. Awareness of these risks is increasing, leading also to concerns about financial stability. Financial regulators and institutions have responded with multiple regulatory and voluntary initiatives to assess and address these risks. Yet despite these initiatives, climate-related financial risks remain greatly underestimated by financial institutions and markets, limiting the capital reallocation needed for the low-carbon transition. Moreover, risks relating to national and international inequity – which act as a barrier to the transformation – are not yet reflected in decisions by the financial community. Stronger steering by regulators and policy makers has the potential to close this gap. Despite the increasing attention of investors to climate change, there is limited evidence that this attention has directly impacted emission reductions. This leaves high uncertainty, both near-term (2021-30) and longer-term (2021-50), on the feasibility of an alignment of financial flows with the Paris Agreement goals (*high confidence*). {15.2, 15.6}

Progress on the alignment of financial flows with low GHG emissions pathways remains slow. There is a climate financing gap which reflects a persistent misallocation of global capital *(high confidence)* {15.2, 15.3}. Persistently high levels of both public and private fossil-fuel related financing continue to be of major concern despite promising recent commitments. This reflects policy misalignment, the current perceived risk-return profile of fossil fuel-related investments, and political economy constraints (*high confidence*). Estimates of climate finance flows[24] exhibit highly divergent patterns across regions and sectors and a slowing growth {15.3}. When the perceived risks are too high, the misallocation of abundant savings persists and investors refrain from investing in infrastructure and industry in search of safer financial assets, even earning low or negative real returns. (*high confidence*) {15.2, 15.3}

FOOTNOTE [23] Most of climate finance stays within national borders, especially private climate flows (over 90%). The reasons for this range from national policy support, differences in regulatory standards, exchange rate, political and governance risks, to information market failures.

FOOTNOTE [24] Climate finance flows refers to local, national, or transnational financing from public, private, and alternative sources, to support mitigation and adaptation actions addressing climate change.

Global climate finance is heavily focused on mitigation (more than 90% on average between 2017-2020) (*high confidence*) {15.4, 15.5}. This is despite the significant economic effects of climate change's expected physical impacts, and the increasing awareness of these effects on financial stability. To meet the needs for rapid deployment of mitigation options, global mitigation investments are expected to need to increase by the factor of three to six (*high confidence*). The gaps represent a major challenge for developing countries, especially Least Developed Countries (LDCs), where flows have to increase by the factor of four to eight for specific sectors like AFOLU, and for specific groups with limited access to, and high costs of, climate finance (*high confidence*) (Figure TS.25) {15.4, 15.5}. The actual size of sectoral and regional climate financing gaps is only one component driving the magnitude of the challenge. Financial and economic viability, access to capital markets, appropriate regulatory frameworks, and institutional capacity to attract and facilitate investments and ensure safeguards are decisive to scaling-up funding. Soft costs for regulatory environment and institutional capacity, upstream funding needs as well as R&D and venture capital for development of new technologies and business models are often overlooked despite their critical role to facilitate the deployment of scaled-up climate finance *(high confidence)*. {15.4.1, 15.5.2}

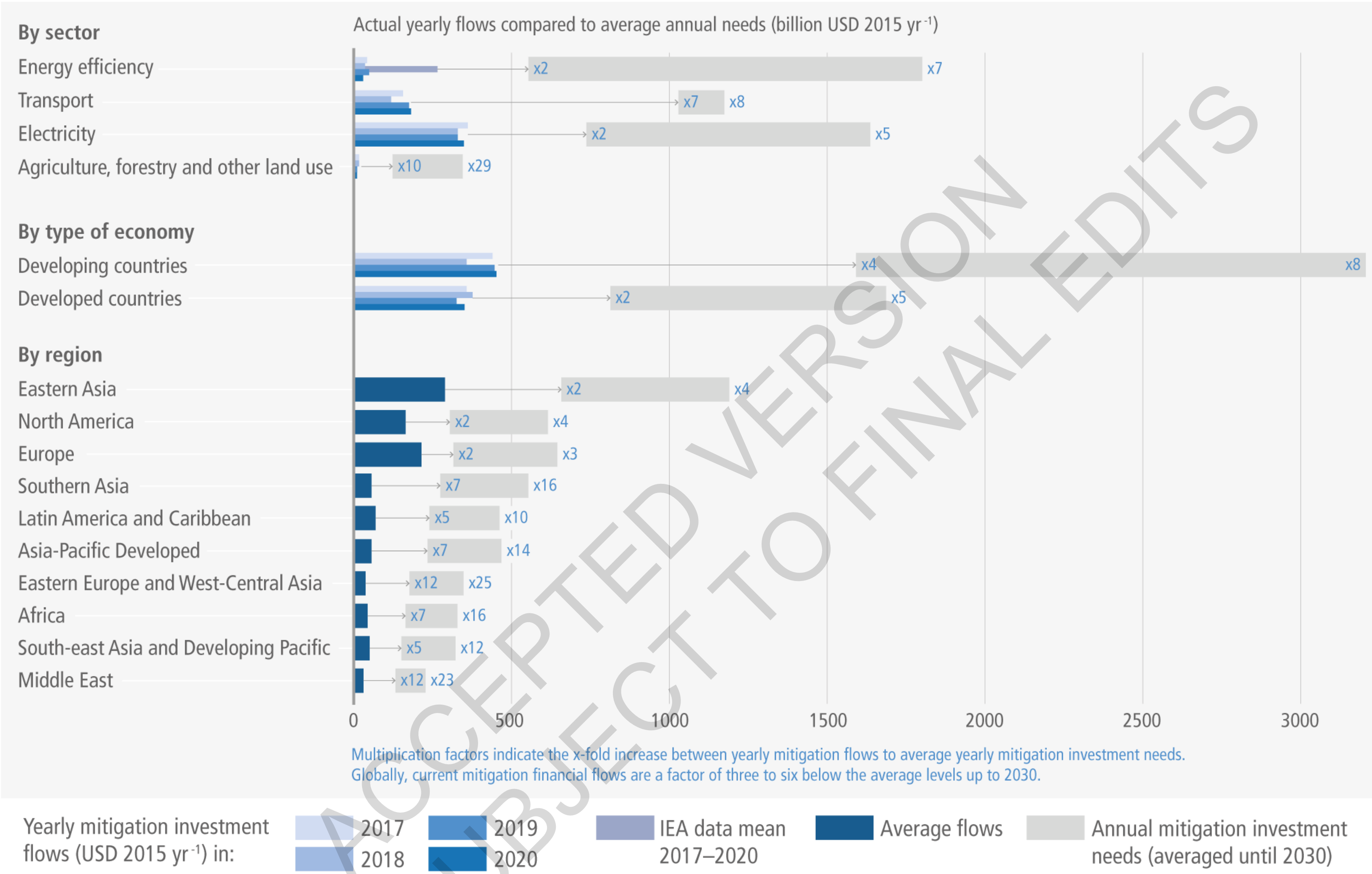


Figure TS.25: Mitigation investment flows fall short of investment needs across all sectors and types of economy, particularly in developing countries.

Figure TS.25 legend: Breakdown of average mitigation investment flows and investment needs until 2030 (USD billion). Given the multiple sources and lack of harmonised methodologies, the data presented here can be considered only as indicative of the size and pattern of investment gaps. For full information of sources see chapter 15 Figure 15.4. Mitigation investment flows and investment needs shown by sector (energy efficiency, transport, electricity, and agriculture, forestry and land use), by type of economy, and by region (see Annex II Part I Section 1 for the classification schemes for countries and areas). Blue bars display data on mitigation investment flows for four years: 2017, 2018, 2019 and 2020 by sector and by type of economy. For the regional breakdown, the annual average mitigation investment flows for 2017-2019 are shown. The grey bars show the minimum and maximum level of global annual mitigation investment needs in the assessed scenarios averaged until 2030. Multiplication factors show the ratio of global average yearly mitigation investment needs (averaged until 2030) and current yearly mitigation flows (averaged for 2017-2020). The lower multiplication factor refers to the lower end of the range of investment needs. The upper multiplication factor refers to the upper range of investment needs. Data on mitigation investment flows does not include technical assistance (i.e., policy and national budget support or capacity building) and other non-technology deployment financing. Adaptation pegged transactions are also excluded. Data on mitigation investment needs does not include needs for infrastructure investment or investment related to meeting the SDGs. {15.3, 15.4, 15.5, Table 15.2, Table 15.3, Table 15.4}

The relatively slow implementation of commitments by countries and stakeholders in the financial sector to scale up climate finance reflects neither the urgent need for ambitious climate action, nor the economic rationale for ambitious climate action *(high confidence)*. Delayed climate investments and financing – and limited alignment of investment activity with the Paris Agreement – will result in significant carbon lock-ins, stranded assets, and other additional costs. This will particularly impact urban infrastructure and the energy and transport sectors *(high confidence)*. A common understanding of debt sustainability and debt transparency, including negative implications of deferred climate investments on future GDP, and how stranded assets and resources may be compensated, has not yet been developed *(medium confidence)*. {15.6}

There is a mismatch between capital availability in the developed world and the future emissions expected in developing countries (*high confidence*). This emphasizes the need to recognize the explicit and positive social value of global cross-border mitigation financing. A significant push for international climate finance access for vulnerable and poor countries is particularly important given these countries' high costs of financing, debt stress and the impacts of ongoing climate change *(high confidence)*. {15.2, 15.3.2.3, 15.5.2, 15.6.1, 15.6.7}

Innovative financing approaches could help reduce the systemic under-pricing of climate risk in markets and foster demand for investment opportunities aligned with the Paris Agreement goals. Approaches include de-risking investments, robust 'green' labelling and disclosure schemes, in addition to a regulatory focus on transparency and reforming international monetary system financial sector regulations *(medium confidence)*. Green bond markets and markets for sustainable finance products have grown significantly since AR5 and the landscape continues to evolve. Underpinning this evolution is investors' preference for scalable and identifiable low-carbon investment opportunities. These relatively new labelled financial products will help by allowing a smooth integration into existing asset allocation models. *(high confidence)* Green bond markets and markets for sustainable finance products have also increased significantly since AR5, but challenges nevertheless remain, in particular there are concerns about 'greenwashing' and the limited application of these markets to developing countries (*high confidence*). {15.6.2, 15.6.6}

New business models (e.g., pay-as-you-go) can facilitate the aggregation of small-scale financing needs and provide scalable investment opportunities with more attractive risk-return profiles (*high confidence*). Support and guidance for enhancing transparency can promote capital markets' climate financing by providing quality information to price climate risks and opportunities. Examples include SDG and environmental, social and governance (ESG) disclosure, scenario analysis and climate risk assessments, including the Task Force on Climate-Related Financial Disclosures (TCFD). The outcome of these market-correcting approaches on capital flows cannot be taken for granted, however, without appropriate fiscal, monetary and financial policies. Mitigation policies will be required to enhance the risk-weighted return of low emission and climate resilient options, accelerate the emergence and support for financial products based on real projects, such as green bonds, and phase out fossil fuel subsidies. Greater public-private cooperation can also encourage the private sector to increase and broaden investments, within a context of safeguards and standards, and this can be integrated into national climate change policies and plans (*high confidence*). {15.1, 15.2.4, 15.3.1, 15.3.2, 15.3.3, 15.5.2, 15.6.1, 15.6.2, 15.6.6, 15.6.7, 15.6.8}

Ambitious global climate policy coordination and stepped-up public climate financing over the next decade (2021–2030) can help redirect capital markets and overcome challenges relating to the need for parallel investments in mitigation. It can also help address macroeconomic uncertainty and alleviate developing countries' debt burden post-COVID-19 *(high confidence)*. Providing strong climate policy signals helps guide investment decisions. Credible signalling by governments and the international community can reduce uncertainty for financial decision-makers and help reduce transition risk. In addition to indirect and direct subsidies, the public sector's role in addressing market failures, barriers, provision of information, and risk sharing can encourage the efficient mobilisation of private sector finance *(high confidence).* {15.2, 15.6.1, 15.6.2} The mutual benefits of coordinated support for climate mitigation and adaptation in the next decade for both developed and developing regions could potentially be very high in the post-COVID era. Climate compatible stimulus packages could significantly reduce the macro-financial uncertainty generated by the pandemic and increase the sustainability of the world economic recovery. {15.2, 15.3.2.3, 15.5.2, 15.6.1, 15.6.7} Political leadership and intervention remain central to addressing uncertainty, which is a fundamental barrier for the redirection of financial flows. Existing policy misalignments – for example in fossil fuel subsidies – undermine the credibility of public commitments, reduce perceived transition risks and limit financial sector action *(high confidence).* {15.2, 15.3.3, 15.6.1, 15.6.2, 15.6.3}

The greater the urgency of action to remain on a 1.5°C pathway, the greater need for parallel investment decisions in upstream and downstream parts of the value chain (*high confidence)***.** Greater urgency also reduces the lead times to build trust in regulatory frameworks. Consequently, many investment decisions will need to be made based on the long-term global goals. This highlights the importance of trust in political leadership which, in turn, affects risk perception and ultimately financing costs *(high confidence).* {15.6.1, 15.6.2}

Accelerated international cooperation on finance is a critical enabler of a low-carbon and just transition *(very high confidence*). Scaled-up public grants for adaptation and mitigation and funding for low-income and vulnerable regions, especially in Sub-Saharan Africa, may have the highest returns. key options include: increased public finance flows from developed to developing countries beyond USD100 billion-a-year; shifting from a direct lending modality towards public guarantees to reduce risks and greatly leverage private flows at lower cost; local capital markets development; and, changing the enabling operational definitions. A coordinated effort to green the post-pandemic recovery is also essential in countries facing much higher debt costs. (*high confidence*) {15.2, 15.6}

TS. 6.5 Innovation, technology development and transfer

Innovation in climate mitigation technologies has seen enormous activity and significant progress in recent years. Innovation has also led to, and exacerbated, trade-offs in relation to sustainable development. Innovation can leverage action to mitigate climate change by reinforcing other interventions. In conjunction with other enabling conditions innovation can support system transitions to limit warming and help shift development pathways. The currently widespread implementation of solar PV and LED lighting, for instance, could not have happened without technological innovation. Technological innovation can also bring about new and improved ways of delivering services that are essential to human well-being (*high confidence*) {16.1, 16.3, 16.4, 16.6}. At the same time as delivering benefits, innovation can result in trade-offs that undermine both progress on mitigation and progress towards other sustainable development goals. Trade-offs include negative externalities – for instance greater environmental pollution and social inequalities – rebound effects leading to lower net emission reductions or even increases in emissions, and increased dependency on foreign knowledge and providers *(high confidence)*. Effective governance and policy have the potential to avoid and minimise such misalignments (*medium evidence, high agreement*). {16.2, 16.3, 16.4, 16.5.1, 16.6}

A systemic view of innovation to direct and organize the processes has grown over the last decade. This systemic view of innovation takes into account the role of actors, institutions, and their interactions and can inform how innovation systems that vary across technologies, sectors and countries, can be strengthened (*high confidence*) {16.2, 16.3, 16.5}. Where a systemic view of innovation has been taken, it has enabled the development and implementation of indicators that are better able to provide insights in innovation processes. This, in turn, has enabled the analysis and strengthening of innovation systems. Traditional quantitative innovation indicators mainly include R&D investments and patents. Figure TS.26 illustrates that energy-related RD&D has risen slowly in the last two decades, and that there has been a reorientation of the portfolio of funded energy technologies. Systemic indicators of innovation, however, go well beyond these approaches. They include structural innovation system elements including actors and networks, as well as indicators for how innovation systems function, such as access to finance, employment in relevant sectors, and lobbying activities {16.3.4, Table 16.7}. For example, in Latin America, monitoring systemic innovation indicators for the effectiveness of agroecological mitigation approaches has provided insights on the appropriateness and social alignment of new technologies and practices {Box 16.5}. Climate-energy-economy models, including integrated assessment models, generally employ a stylised and necessarily incomplete view of innovation, and have yet to incorporate a systemic representation of innovation systems. {16.2.4, Box 16.1}

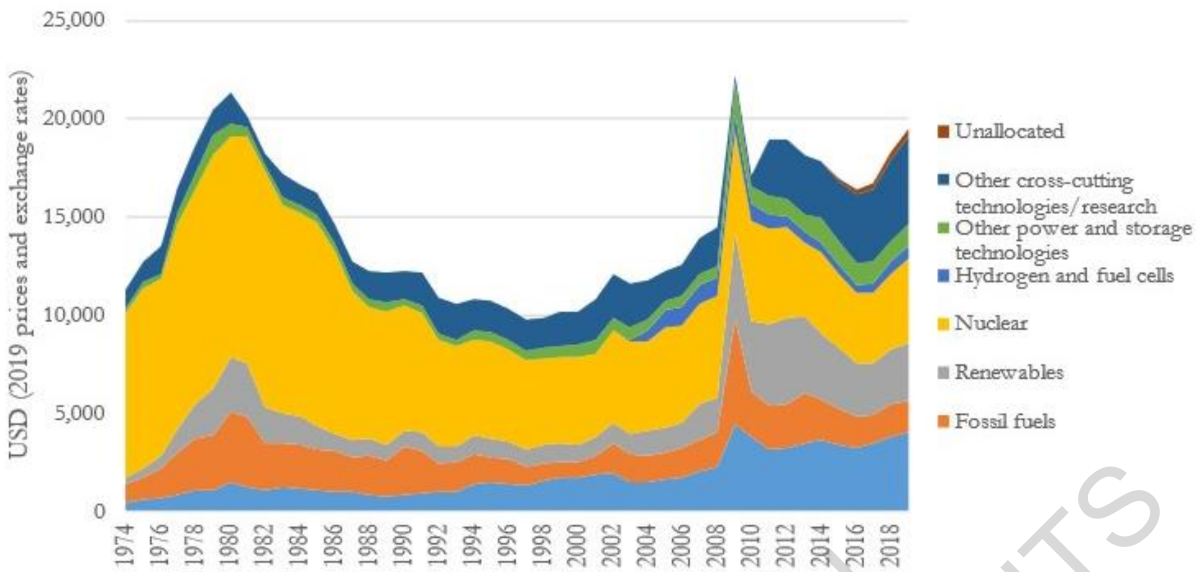


Figure TS.26: Fraction of public energy research, development and demonstration (RD&D (spending by technology over time for IEA (largely OECD) countries between 1974 and 2018. {Box 16.3 Figure 1}

A systemic perspective on technological change can provide insights to policymakers supporting their selection of effective innovation policy instruments *(high confidence)* {16.4, 16.5}. A combination of scaled-up innovation investments with demand-pull interventions can achieve faster technology unit cost reductions and more rapid scale-up than either approach in isolation. These innovation policy instruments would nonetheless have to be tailored to local development priorities, to the specific context of different countries, and to the technology being supported. The timing of interventions and any trade-offs with sustainable development also need to be addressed. Public R&D funding and support as well as innovation procurement have shown to be valuable for fostering innovation in small to medium cleantech firms (Figure TS.27) {16.4.4.3}. Innovation outcomes of policy instruments not necessarily aimed at innovation, such as feed-in tariffs, auctions, emissions trading schemes, taxes and renewable portfolio standards, vary from negligible to positive for climate change mitigation. Some specific designs of environmental taxation can also result in negative distributional outcomes {16.4.4}. Most of the available literature and evidence on innovation systems come from industrialised countries and larger developing countries. However, there is a growing body of evidence from developing countries and small island developing states (SIDS). {16.4, 16.5, 16.7}

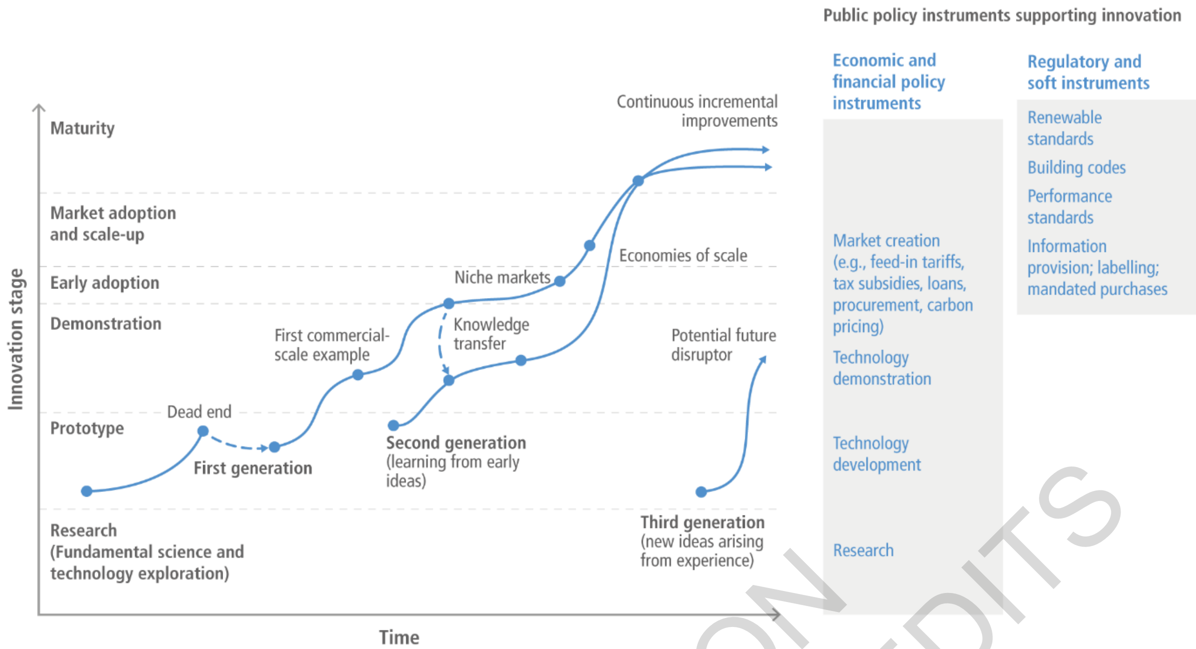


Figure TS.27: Technology innovation process and the (illustrative) roles of different public policy instruments (on the right-hand side). {Figure 16.1}

Figure TS.27 legend: Note that, demand pull instruments in the regulatory instrument category, for instance, can also shape the early stages of the innovation process. Their position on the latter stages is highlighted in this figure just because typically these instruments have been introduced in latter stages of the development of the technology. {16.4.4}

Experience and analyses show that technological change is inhibited if technological innovation system functions are not adequately fulfilled; this inhibition occurs more often in developing countries *(high confidence)*. Examples of such functions are knowledge development, resource mobilisation, and activities that shape the needs, requirements and expectations of actors within the innovation system (guidance of the search). Capabilities play a key role in these functions, the build-up of which can be enhanced by domestic measures, but also by international cooperation. For instance, innovation cooperation on wind energy has contributed to the accelerated global spread of this technology. As another example, the policy guidance by the Indian government, which also promoted development of data, testing capabilities and knowledge within the private sector, has been a key determinant of the success of an energy-efficiency programme for air conditioners and refrigerators in India. {16.3, 16.5, 16.6, Cross-Chapter Box 12 in Chapter 16, Box 16.3}

Consistent with innovation system approaches, the sharing of knowledge and experiences between developed and developing countries can contribute to addressing global climate and the SDGs. The effectiveness of such international cooperation arrangements, however, depends on the way they are developed and implemented (*high confidence*). The effectiveness and sustainable development benefits of technology sharing under market conditions appears to be determined primarily by the complexity of technologies, local capabilities and the policy regime. This suggests that the development of planning and innovation capabilities remains necessary, especially in least-developed countries and SIDS. International diffusion of low-emission technologies is also facilitated by knowledge spill overs from regions engaged in clean R&D (*medium confidence*). {16.2}

The evidence on the role of intellectual property rights (IPR) in innovation is mixed. Some literature suggests that it is a barrier while other sources suggests that it is an enabler to the diffusion of climate-related technologies *(medium confidence)*. There is agreement that countries with well-developed institutional capacity may benefit from a strengthened IPR regime, but that countries with limited capabilities might face greater barriers to innovation as a consequence. This enhances the continued need for capacity building. Ideas to improve the alignment of the global IPR regime and addressing climate change include specific arrangements for least-developed countries, case-by-case decision-making and patent-pooling institutions. {16.2.3, 16.5, Box 16.10}

Although some initiatives have mobilised investments in developing countries, gaps in innovation cooperation remain, including in the Paris Agreement instruments. These gaps could be filled by enhancing financial support for international technology cooperation, by strengthening cooperative approaches, and by helping build suitable capacity in developing countries across all technological innovation system functions (*high confidence*). The implementation of current arrangements of international cooperation for technology development and transfer, as well as capacity building, are insufficient to meet climate objectives and contribute to sustainable development. For example, despite building a large market for mitigation technologies in developing countries, the lack of a systemic perspective in the implementation of the Clean Development Mechanism, operational since the mid-2000s, has only led to some technology transfer, especially to larger developing countries, but limited capacity building and minimal technology development (*medium confidence)*. In the current climate regime, a more systemic approach to innovation cooperation could be introduced by linking technology institutions, such as the Technology Mechanism, and financial actors, such as the financial mechanism. {16.5.3}

Countries are exposed to sustainable development challenges in parallel with the challenges that relate to climate change. Addressing both sets of challenges simultaneously presents multiple and recurrent obstacles that systemic approaches to technological change could help resolve, provided they are well managed *(high confidence)*. Obstacles include both entrenched power relations dominated by vested interests that control and benefit from existing technologies, and governance structures that continue to reproduce unsustainable patterns of production and consumption (*medium confidence*). Studies also highlight the potential of cultural factors to strongly influence the pace and direction of technological change. Sustainable solutions require adoption and mainstreaming of locally novel technologies that can meet local needs, and simultaneously address the SDGs. Acknowledging the systemic nature of technological innovation – which involve many levels of actors, stages of innovation and scales – can lead to new opportunities to shift development pathways towards sustainability. {16.4, 16.5, 16.6}

Strategies for climate change mitigation can be most effective in accelerating transformative change when actions taken to strengthen one set of enabling conditions also reinforce and strengthen the effectiveness of other enabling conditions *(medium confidence)*. Applying transition or system dynamics to decisions can help policy makers take advantage of such high-leverage intervention points, address the specific characteristics of technological stages, and respond to societal dynamics. Inspiration can be drawn from the global unit cost reductions of solar PV, which were accelerated by a combination of factors interacting in a mutually reinforcing way across a limited group of countries (*high confidence*). {Box 16.2, Cross-Chapter Box 12 in Chapter 16}. Transitions can be accelerated by policies appropriately targeted, which may be grouped in different 'pillars of policy'. The relative importance of different 'pillars' differs according to stage of the transition. (see Figure TS.28) {1.2.3}

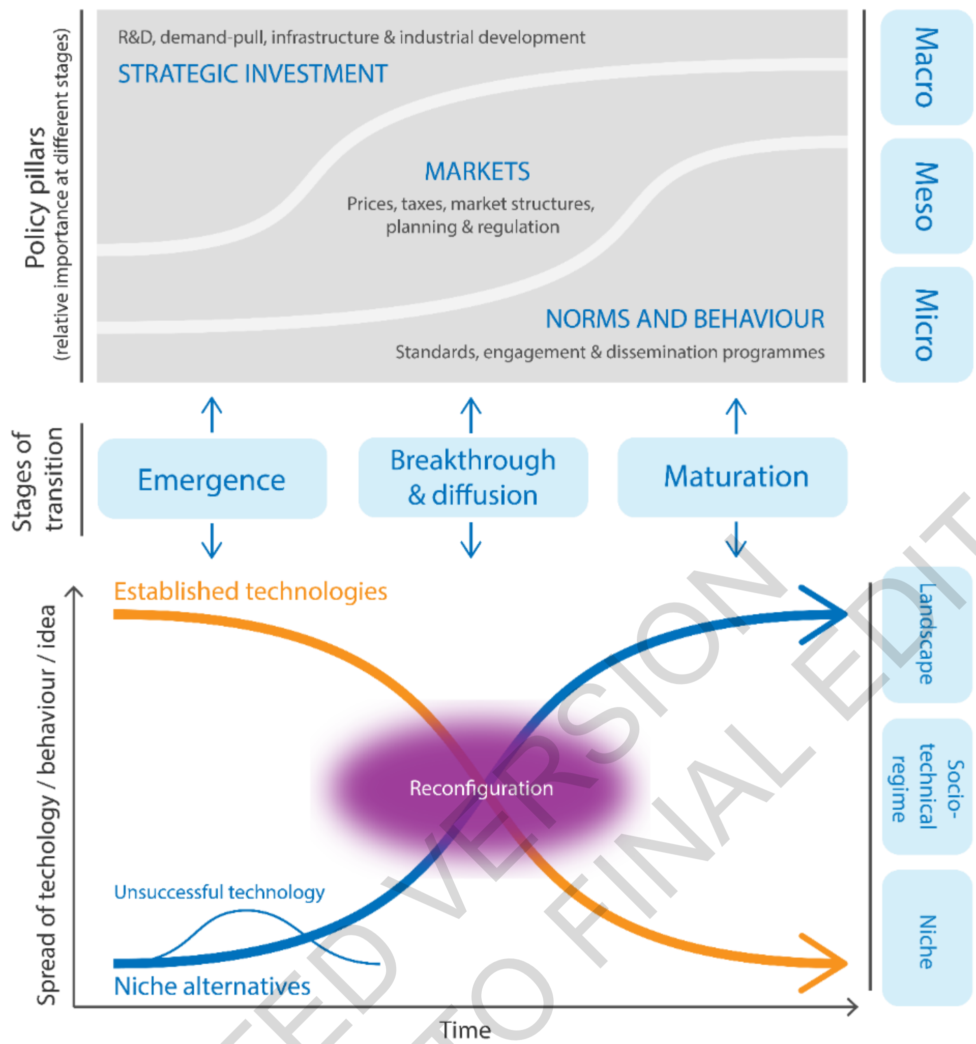


Figure TS.28: Transition dynamics: levels, policies and processes. {Figure 1.7}

The relative importance of different 'pillars of policy' differs according to stage of the transition. The lower panel illustrates growth of innovative technologies or practices, which if successful, emerge from niches into an S-shape dynamic of exponential growth. The diffusion stage often involves new infrastructure and reconfiguration of existing market and regulatory structures. During the phase of more widespread diffusion, growth levels off to linear, then slows as the industry and market matures. The processes displace incumbent technologies/practices which decline, initially slowly but then at an accelerating pace. Many related literatures identify three main levels with different characteristics, most generally termed *micro*, *meso* and *macro*.

Better and more comprehensive data on innovation indicators can provide timely insights for policy makers and policy design locally, nationally and internationally, especially for developing countries, where such insights are often missing. Data needed include those that can show the strength of technological, sectoral and national innovation systems. It is also necessary to validate current results and generate insights from theoretical frameworks and empirical studies for developing countries' contexts. Innovation studies on adaptation and mitigation other than energy and ex-post assessments of the effectiveness of various innovation-related policies and interventions, including R&D, would also provide benefits. Furthermore, methodological developments to improve the ability of IAMs to capture energy innovation system dynamics and the relevant institutions and policies (including design and implementation), would allow for more realistic assessment. {16.2, 16.3, 16.7}

START BOX TS.14 HERE

Box TS.14 Digitalisation

Digital technologies can promote large increases in energy efficiency through coordination and an economic shift to services, but they can also greatly increase energy demand because of the energy used in digital devices (*high confidence*). {Cross-Chapter Box 11 in Chapter 16, 16.2}

Digital devices, including servers, increase pressure on the environment due to the demand for rare metals and end-of-life disposal. The absence of adequate governance in many countries can lead to harsh working conditions and unregulated disposal of electronic waste. Digitalisation also affects firms' competitiveness, the demand for skills, and the distribution of, and access to resources. The existing digital divide, especially in developing countries, and the lack of appropriate governance of the digital revolution can hamper the role that digitalisation could play in supporting the achievement of stringent mitigation targets. At present, the understanding of both the direct and indirect impacts of digitalisation on energy use, carbon emissions and potential mitigation is limited (*medium confidence*).

The digital transformation is a megatrend that is fundamentally changing all economies and societies, albeit in very different ways depending on the level of development of a given country and on the nature of its economic system. Digital technologies have significant potential to contribute to decarbonisation due to their ability to increase energy and material efficiency, make transport and building systems less wasteful, and improve the access to services for consumers and citizens. Yet, if left unmanaged, the digital transformation will probably increase energy demand, exacerbate inequities and the concentration of power, leaving developing economies with less access to digital technologies behind, raise ethical issues, reduce labour demand and compromise citizens' welfare. Appropriate governance of the digital transformation can ensure that digitalisation works as an enabler, rather than as a barrier and further strain in decarbonisation pathways. Governance can ensure that digitalisation not only reduces GHG emissions intensity but also contributes to reducing absolute GHG emission, constraining run-away consumption. {Cross-Chapter Box 11 in Chapter 16, 16.2}

Digital technologies have the potential to reduce energy demand in all end-use sectors through steep improvements in energy efficiency. This includes material input savings and increased coordination as they allow the use of fewer inputs to perform a given task. Smart appliances and energy management, supported by choice architectures, economic incentives and social norms, effectively reduce energy demand and associated GHG emissions by 5-10% while maintaining equal service levels. Data centres can also play a role in energy system management, for example by waste heat utilisation where district heat systems are close by; temporal and spatial scheduling of electricity demand can provide about 6% of the total potential demand response. {5.5, Cross-Chapter Box 11 Table 1 in Chapter 16}

Digital technologies, analytics and connectivity consume large amounts of energy implying higher direct energy demand and related carbon emissions. Global energy demand from digital appliances reached 7.14 EJ in 2018. The demand for computing services increased by 550% between 2010 and 2018 and is now estimated at 1% of global electricity consumption. Due to efficiency improvements, the associated energy demand increased only modestly, by about 6% from 2000 to 2018. {Box 9.5}

System-wide effects endanger energy and GHG emission savings. Rising demand can diminish energy savings, and also produce run-away effects associated with additional consumption and GHG emissions if left unregulated. Savings are varied in smart and shared mobility systems, as ride hailing increases GHG emissions due to deadheading, whereas shared pooled mobility and shared cycling reduce GHG emissions, as occupancy levels and/or weight per person kilometre transported improve. Systemic effects have wider boundaries of analysis and are more difficult to quantify and investigate but are nonetheless very relevant. Systemic effects tend to have negative impacts, but policies and adequate infrastructures and choice architectures can help manage and contain these. {5.3, 5.4, 5.6}

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TS. 7 Mitigation in the context of sustainable development

Accelerating climate mitigation *in the context of sustainable development* involves not only expediting the pace of change but also addressing the underlying drivers of vulnerability and emissions. Addressing these drivers can enable diverse communities, sectors, stakeholders, regions and cultures to participate in just, equitable and inclusive processes that improve the health and well-being of people and the planet. Looking at climate change from a justice perspective also means placing the emphasis on: i) the protection of vulnerable populations from the impacts of climate change, ii) mitigating the effects of low-carbon transformations, and iii) ensuring an equitable decarbonised world (*high confidence*). {17.1}

The SDG framework[25] can serve as a template to evaluate the long-term implications of mitigation on sustainable development and vice versa (*high confidence*). Understanding the co-benefits and trade-offs associated with mitigation is key to understanding how societies prioritise among the various sectoral policy options (*medium confidence*). Areas with anticipated trade-offs include food and biodiversity, energy affordability/access, and mineral resource extraction. Areas with anticipated co-benefits include health, especially regarding air pollution, clean energy access and water availability. The possible implementation of the different sectoral mitigation options therefore depends on how societies prioritise mitigation versus other products and services: not least, how societies prioritise food, material well-being, nature conservation and biodiversity protection, as well as considerations such as their future dependence on CDR. Figure TS.29 summarises the assessment of where key synergies and trade-offs exist between mitigation options and the SDGs. (Figure TS.29, Figure TS.31, Table TS.7) {12.3, 12.4, 12.5, 12.6.1, Figure 3.39, Figure 17.1}

The beneficial and adverse impacts of deploying climate-change mitigation and adaptation responses are highly context-specific and scale-dependent. There are synergies and trade-offs between adaptation and mitigation as well as synergies and trade-offs with sustainable development (*high confidence*). Strong links also exists between sustainable development, vulnerability and climate risks, as limited economic, social and institutional resources often result in low adaptive capacities and high vulnerability, especially in developing countries. Resource limitations in these countries can similarly weaken the capacity for climate mitigation and adaptation. The move towards climate-resilient societies requires transformational or deep systemic change. This has important implications for countries' sustainable development pathways *(medium evidence, high agreement).* (Box TS.3, Figure TS.29) {4.5, Figure 4.9, 17.3.3}

FOOTNOTE [25] The 17 SDGs are at the heart of the UN 2030 Agenda for Sustainable Development, adopted by all United Nations Member States in 2015.

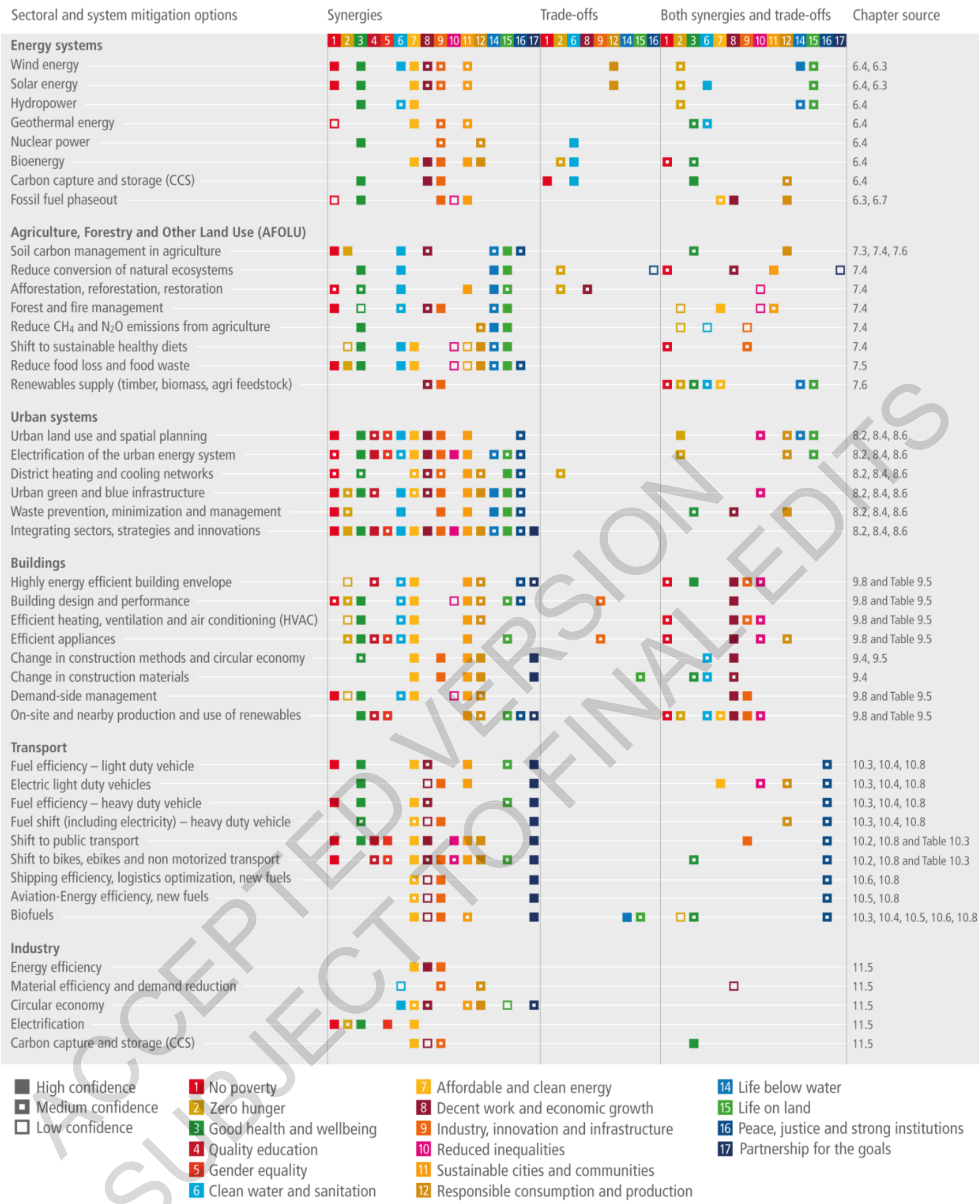


Figure TS.29: Mitigation options have synergies with many Sustainable Development Goals, but there are trade-offs associated with some options especially when implemented at scale. The synergies and trade-offs vary widely and depend on the context

Figure TS.29 legend: Figure TS.29 presents a summary of the chapter-level qualitative assessment of the synergies and trade-offs for selected mitigation options. Overlaps may exist in the mitigation options assessed and presented by sector and system, and interlinkages with the SDGs might differ depending on the application of that option by sector. Interactions of mitigation options with the SDGs are context-specific and dependent on the scale of implementation. For some mitigation options, these scaling and context-specific issues imply that there are both synergies and trade-offs in relation to specific SDGs. The SDGs are displayed as coloured squares. They indicate whether a synergy, trade-off or both synergies and trade-offs exist between the SDG and the mitigation option. Confidence levels are indicated through the solidity of the squares. A solid square indicates high confidence, a partially filled square indicates medium confidence, and an outlined square indicates low confidence. The final column in the figure provides a line of sight to the chapters that provide details on context-specificity and scale of implementation. {6.3, 6.4, 6.7, 7.3, 7.4, 7.5, 7.6, 8.2, 8.4, 8.6, 9.4, 9.5, 9.8, Table 9.5, 10.3, 10.4, 10.5, 10.6, 10.8, 11.5, Table 10.3, 17.3, Figure 17.1, Supplementary Material Table 17.1, Annex II Part IV Section 12}

Many of the potential trade-offs between mitigation and other sustainable development outcomes depend on policy design and can be compensated or avoided with additional policies and investments, or through policies that integrate mitigation with other SDGs *(high confidence)*. Targeted SDG policies and investments, for example in the areas of healthy nutrition, sustainable consumption and production, and international collaboration, can support climate change mitigation policies and resolve or alleviate trade-offs. Trade-offs can also be addressed by complementary policies and investments, as well as through the design of cross-sectoral policies integrating mitigation with the SDGs, and in particular: good health and well-being (SDG 3), zero hunger and nutrition (SDG 2), responsible consumption and production (SDG 12), reduced inequalities (SDG 10) and life on land (SDG 15). (Figure TS.29, Figure TS.30) {3.7}

***Decent living standards*, which encompasses many SDG dimensions, are achievable at lower energy use than previously thought (*high confidence*).** Mitigation strategies that focus on lowering demand for energy and land-based resources exhibit reduced trade-offs and negative consequences for sustainable development relative to pathways involving either high emissions and climate impacts or pathways with high consumption and emissions that are ultimately compensated by large quantities of BECCS. Figure TS.30 illustrates how, in the case of pathways *likely* limiting warming to 1.5°C, sustainable development policies can lead to overall benefits compared to mitigation policies alone. (Figure TS.22, Figure TS.30) {3.7, 5.2}

The timing of mitigation actions and their effectiveness will have significant consequences for broader sustainable development outcomes in the longer term *(high confidence)*. Ambitious mitigation can be considered a precondition for achieving the SDGs. {3.7}

Adopting coordinated cross-sectoral approaches to climate mitigation can target synergies and minimise trade-offs, both between sectors and between sustainable development objectives (*high confidence*). This requires integrated planning using multiple-objective-multiple-impact policy frameworks. Strong inter-dependencies and cross-sectoral linkages create both opportunities for synergies and need to address trade-offs related to mitigation options and technologies. This can only be done if coordinated sectoral approaches to climate change mitigation policies are adopted that mainstream these interactions and ensure local people are involved in the development of new products, as well as production and consumption practices. For instance, there can be many synergies in urban areas between mitigation policies and the SDGs but capturing these depends on the overall planning of urban structures and on local integrated policies such as combining affordable housing and spatial planning with walkable urban areas, green electrification and clean renewable energy *(medium confidence)*. Integrated planning and cross-sectoral alignment of climate change policies are also particularly evident in developing countries' NDCs under the Paris Agreement, where key priority sectors such as agriculture and energy are closely aligned with the proposed mitigation and adaptation actions and the SDGs. {12.6.2, Supplementary Material Table 17.1, 17.3.3}

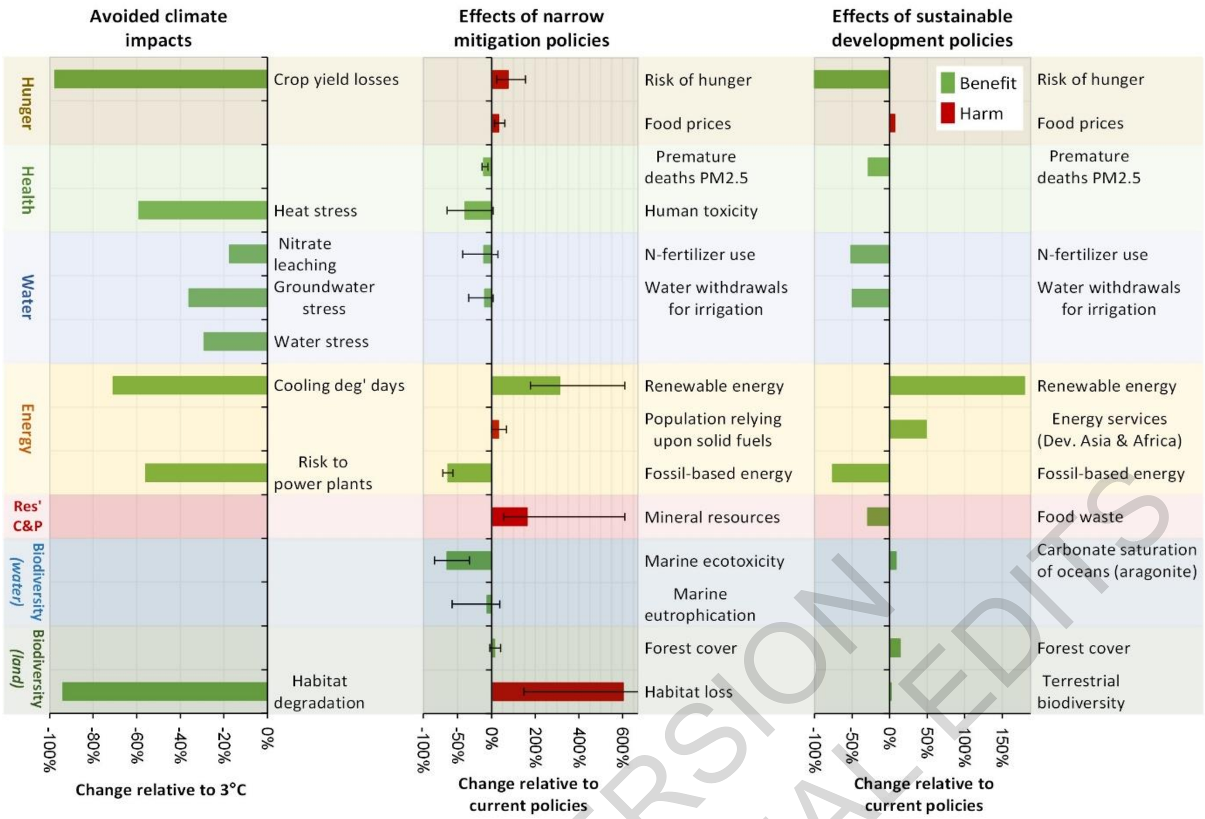


Figure TS.30: Impacts on SDGs of mitigation *likely* limiting warming to 1.5°C with narrow mitigation policies vs broader sustainable development policies

Figure TS.30 legend: Left: benefits of mitigation from avoided impacts. Middle: sustainability co-benefits and trade-offs of narrow mitigation policies (averaged over multiple models). Right: sustainability co-benefits and trade-offs of mitigation policies integrating sustainable development goals. Scale: 0% means no change compared to 3°C (left) or current policies (middle and right). Green values correspond to proportional improvements, red values to proportional worsening. Note: only the left panel considers climate impacts on sustainable development; the middle and right panels do not. "Res' C&P" stands for Responsible Consumption and Production (SDG 12). {Figure 3.39}

The feasibility of deploying response options is shaped by barriers and enabling conditions across geophysical, environmental-ecological, technological, economic, socio-cultural, and institutional dimensions (*high confidence*). Accelerating the deployment of response options depends on reducing or removing barriers across these dimensions, as well on establishing and strengthening enabling conditions. Feasibility is context-dependent, and also depends on the scale and the speed of implementation. For example: the institutional, legal and administrative capacity to support deployment varies across countries; the feasibility of options that involve large-scale land use changes is highly context dependent; spatial planning has a higher potential in early stages of urban development; the geophysical potential of geothermal is site specific; and cultural and local conditions may either inhibit or enable demand-side responses. Figure TS.31 summarises the assessment of barriers and enablers for a broad range of sector specific, and cross sectoral response options. (Box TS.15) {6.4, 7.4, 8.5, 9.10, 10.8, 12.3}

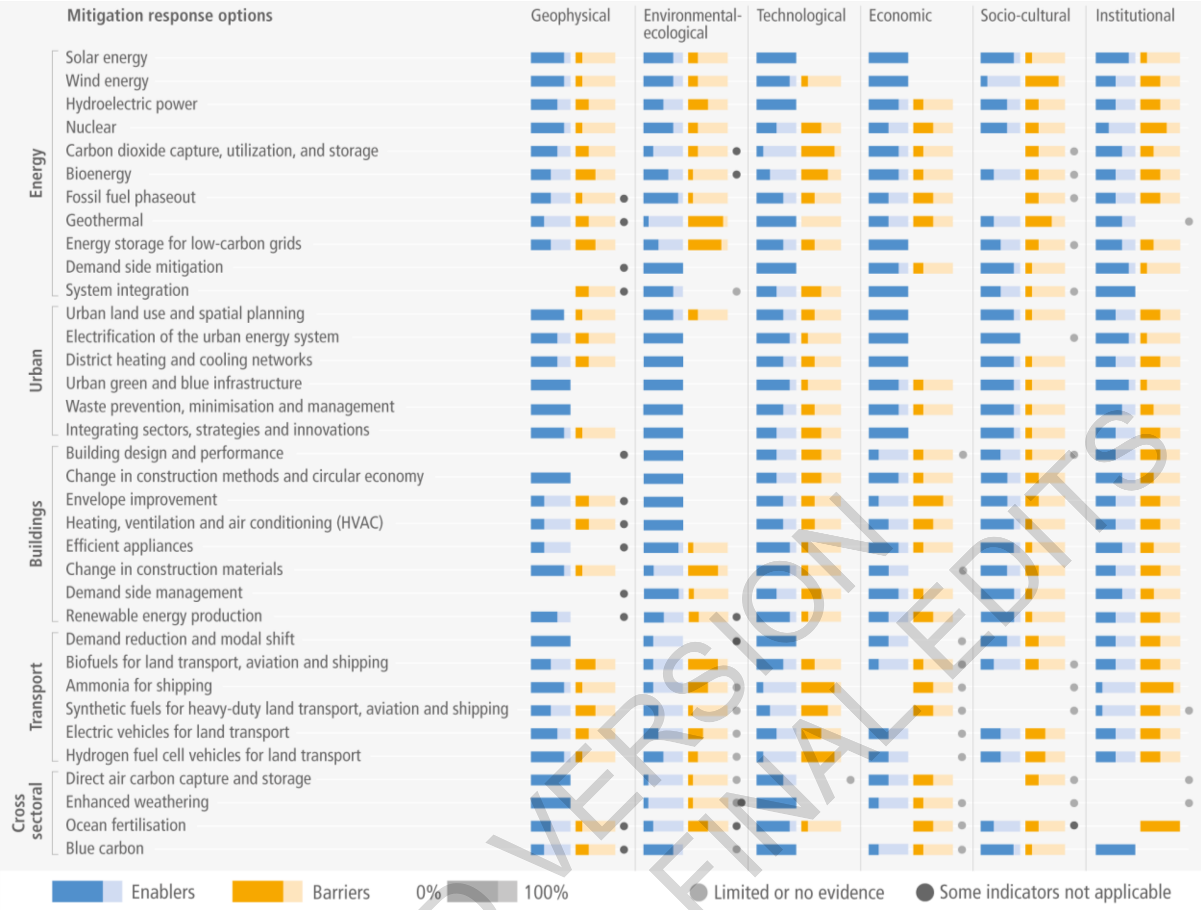


Figure TS.31 Geophysical, environmental-ecological, technological, economic, socio-cultural and institutional factors can enable or act as barriers to the deployment of response options

Figure TS.31 legend: chapter-level assessment for selected mitigation options. Overlaps may exist in the mitigation options assessed and presented by sector and system, and feasibility might differ depending on the demarcation of that option in each sector. Chapters 6, 8, 9, 10, and 12 assess mitigation response options across six feasibility dimensions: *geophysical*, *environmental-ecological*, *technological*, *economic*, *socio-cultural and institutional*. AFOLU (Ch7) and industry (Ch11) are not included because of the heterogeneity of options in these sectors. For each dimension, a set of feasibility indicators was identified. Examples of indicators include impacts on land use, air pollution, economic costs, technology scalability, public acceptance and political acceptance (see Box TS.15, and Annex II Part IV Section 11 for a detailed explanation). An indicator could refer to a barrier or an enabler to implementation, or could refer to both a barrier or an enabler, depending on the context, speed, and scale of implementation. Dark blue bars indicate the extent of enablers to deployment within each dimension. This is shown relative to the maximum number of possible enablers, as indicated by the light blue shading. Dark orange bars indicate the extent of barriers to deployment within each dimension. This is shown relative to the maximum number of possible barriers, as indicated by light orange shading. A light grey dot indicates that there is limited or no evidence to assess the option. A dark grey dot indicates that one of the feasibility indicators within that dimension is not relevant for the deployment of the option. The relevant sections in the underlying chapters include references to the literature on which the assessment is based and indicate whether the feasibility of an option varies depending on context (e.g., region), scale (e.g., small, medium, full scale), speed (e.g., implementation in 2030 versus 2050) and warming level (e.g., 1.5°C versus 2°C). {6.4, 8.5, 9.10, 10.8, 12.3, Annex II Part IV Section 11}

Alternative mitigation pathways are also associated with different feasibility challenges *(high confidence)*. These challenges are multi-dimensional, context-dependent, malleable to policy and to technological and societal trends. They can also be reduced by putting in place appropriate enabling conditions. Figure TS.32 highlights the dynamic and transient nature of feasibility risks. These risks are transient and concentrated in the decades before mid-century. Figure TS.32 also illustrates how different feasibility dimensions pose differentiated challenges: for example, institutional feasibility challenges are shown as *unprecedented* for a high proportion of scenarios, in line with the qualitative literature, but moving from 2030 to 2050 and 2100 these challenges decrease.

The feasibility challenges associated with mitigation pathways are predominantly *institutional* and *economic* rather than *technological* and *geophysical (medium confidence)*. The rapid pace of technological development and deployment in mitigation scenarios is not incompatible with historical records, but rather, institutional capacity is a key limiting factor for a successful transition. Emerging economies appear to have highest feasibility challenges in the short- to medium- term. This suggests a key role of policy and technology as enabling factors. (Figure TS.32) {3.8}

Pathways relying on a broad portfolio of mitigation strategies are more robust and resilient (*high confidence*). Portfolios of technological solutions reduce the feasibility risks associated with the low carbon transition. (Figure TS.31, Figure TS.32, Box TS.15) {3.8}

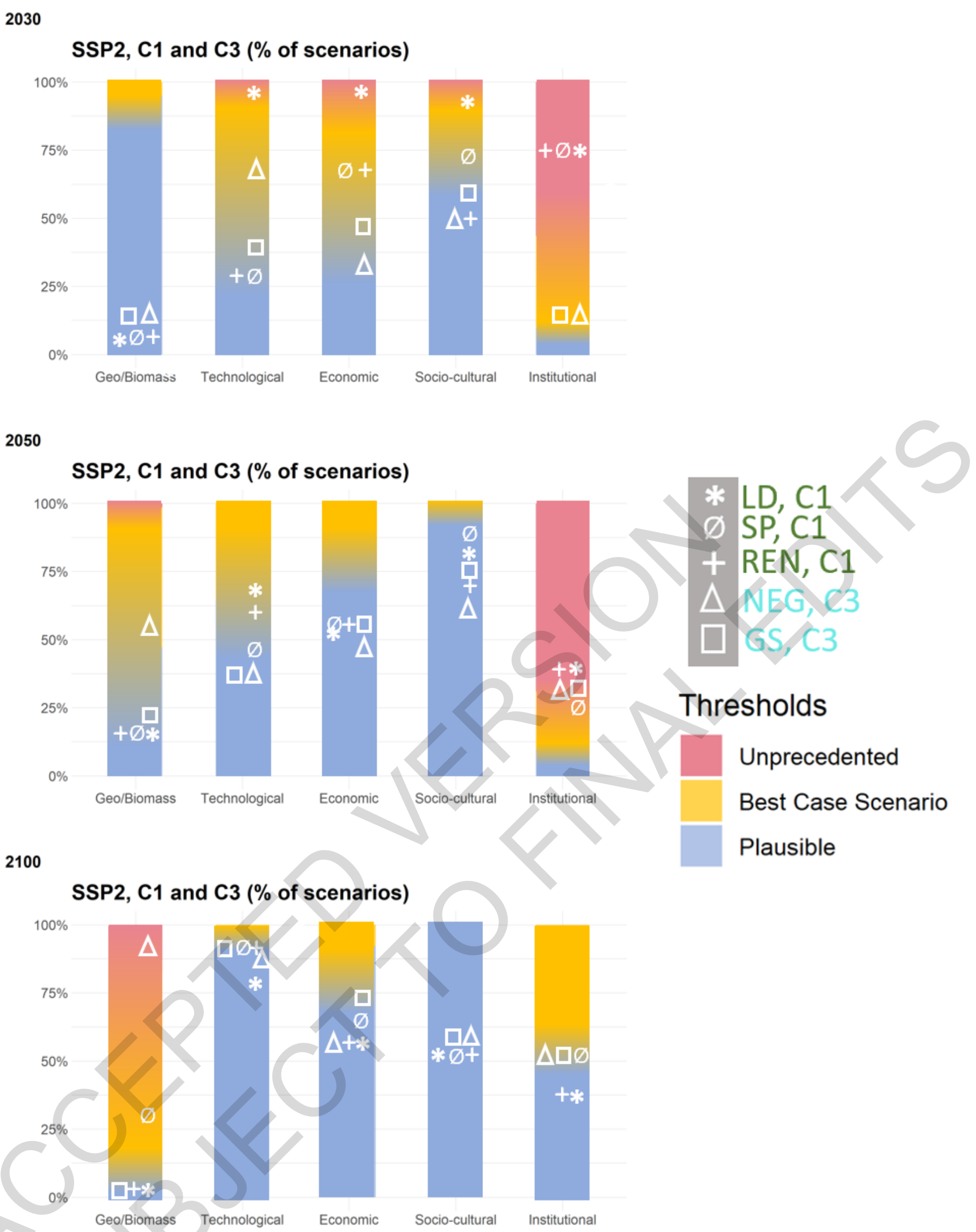


Figure TS.32: The feasibility of mitigation scenarios

Figure TS.32 legend: Figure shows the proportion scenarios in the AR6 scenarios database – falling withing the warming level classifications C1 and C3 (**C1:** below 1.5°C, no or limited overshoot; **C3:** *likely* below 2°C) – that exceed threshold values in 2030, 2050 and 2100 for five dimensions of feasibility (See Box TS.5, Box TS.15). The feasibility dimensions shown are: *geophysical, technological, economic, socio-cultural and institutional*. The thresholds shown are: i) *plausible* – range of values based on past historical trends or other peer reviewed assessments; ii) *best case scenario* – range of values assuming major political support or technological breakthrough; iii) *unprecedented* – values going beyond those observed or reported in peer reviewed assessments. Overlayed are the Illustrative Mitigation Pathways consistent with SSP2 (LD, SP, Ren: C1 category; Neg, GS: C3 category). The positioning of the illustrative pathways is simply indicative of the general trade-offs over time and across the feasibility dimensions it is not determined mathematically. (Box TS.5) {3.8}

START BOX TS.15 HERE

Box TS.15: A harmonised approach to assessing feasibility

The assessment of feasibility in this report aims to identify barriers and enablers to the deployment of mitigation options and pathways. The assessment organises evidence to support policy decisions, and decisions on actions, that would improve the feasibility of mitigation options and pathways by removing relevant barriers and by strengthening enablers of change.

The feasibility of mitigation response options

Mitigation response options are assessed against six dimensions of feasibility. Each dimension comprises a key set of indicators that can be evaluated by combining various strands of literature. {Annex II Part IV Section 11, Table 6.1}

Box TS.15 Table.1: Feasibility dimensions and indicators to assess the barriers and enablers of implementing mitigation options

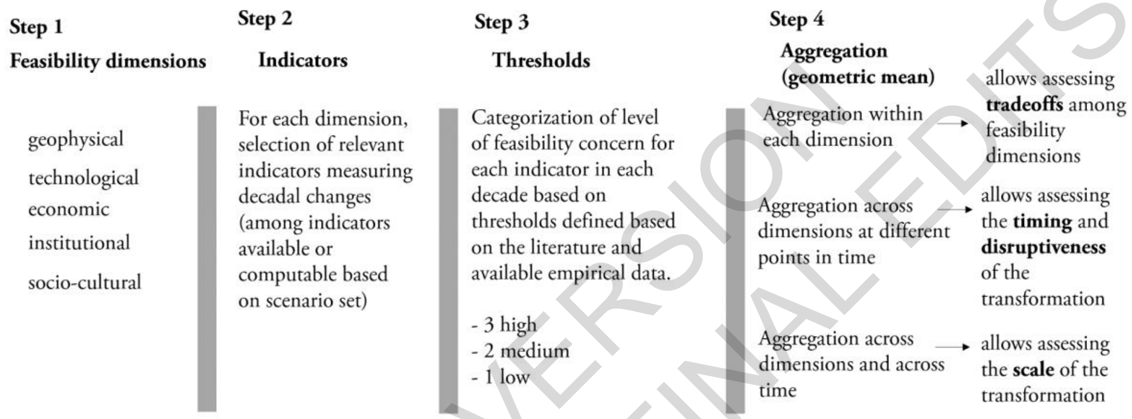
Feasibility dimension	Indicators
Geophysical feasibility	Availability of required geophysical resources: • Physical potential • Geophysical resource availability • Land use
Environmental-ecological feasibility	Impacts on environment: • Air pollution • Toxic waste, ecotoxicity and eutrophication • Water quantity and quality • Biodiversity
Technological feasibility	Extent to which the technology can be implemented at scale soon • Simplicity • Technology scalability • Maturity and technology readiness
Economic feasibility	Financial costs and economic effects • Costs now, in 2030 and in the long term • Employment effects and economic growth
Socio-cultural feasibility	Public engagement and support, and social impacts: • Public acceptance • Effects on health and well-being • Distributional effects
Institutional feasibility	Institutional conditions that affect the implementation of the response option • Political acceptance • Institutional capacity and governance, cross-sectoral coordination • Legal and administrative capacity

The assessment – undertaken by the sectoral chapters in this report – evaluates to what extent each indicator (listed in Box TS.15 Table.1) would be an enabler or barrier to implementation using a scoring methodology (described in detail in Annex II Part IV Section 11). When appropriate, it is also indicated whether the feasibility of an option varies across context, scale, time and temperature goal. The resulting scores provide insight into the extent to which each feasibility dimension enables or inhibits the deployment of the relevant option. It also provides insight into the nature of the effort needed to reduce or remove barriers thereby improving the feasibility of individual options. {Annex II Part IV Section 11}

The feasibility of mitigation scenarios

Scenarios provide internally consistent projections of emission reduction drivers and help contextualize the scale of deployment and interactions of mitigation strategies. Recent research has proposed and operationalised frameworks for the feasibility assessment of mitigation scenarios. In this report the feasibility assessment of scenarios uses an approach that involves developing a set of multi-dimensional metrics capturing the *timing, disruptiveness* and the *scale* of the transformative change within five dimensions: *geophysical, technological, economic, socio-cultural and institutional,* as illustrated in Box TS.15 Figure 1.

More than 20 indicators were chosen to represent feasibility dimensions that could be related to scenario metrics. Thresholds of feasibility risks of different intensity were obtained through empirical analysis of historical data and assessed literature. Details of indicators, thresholds, and how they were applied is reported in Annex II Part IV Section 11. {3.8}



Box TS.15 Figure 1: Steps involved in evaluating the feasibility of scenarios {Figure 3.41}

Note: In this approach the *environmental-ecological* dimension is captured through different scenarios' categories.

END BOX TS.15 HERE

A wide range of factors have been found to enable sustainability transitions, ranging from technological innovations to shifts in markets, and from policies and governance arrangements to shifts in belief systems and market forces (*high confidence*). Many of these factors have come together in a co-evolutionary process that has unfolded globally, internationally and locally over several decades (*low evidence, high agreement*). Those same conditions that may serve to impede the transition (i.e., organisational structure, behaviour, technological lock-in) can also 'flip' to enable both the transition and the framing of sustainable development policies to create a stronger basis for policy support (*high confidence*). It is important to note that strong shocks to these systems, including accelerating climate change impacts, economic crises and political changes, may provide crucial openings for accelerated transitions to sustainable systems. For example, re-building more sustainably after an extreme event, or renewed public debate about the drivers of social and economic vulnerability to multiple stressors *(medium confidence).* {17.4}

While transition pathways will vary across countries it is anticipated that they will be challenging in many contexts (*high confidence*). Climate change is the result of decades of unsustainable production and consumption patterns, as well as governance arrangements and political economic institutions that lock in resource-intensive development patterns (*high confidence*). Resource shortages, social divisions, inequitable distributions of wealth, poor infrastructure and limited access to advanced technologies and skilled human resources can constrain the options and capacity of developing countries to achieve sustainable and just transitions (*medium evidence, high agreement*) {17.1.1}. Reframing development objectives and shifting development pathways towards sustainability can help transform these patterns and practices, allowing space to transform unsustainable systems (*medium evidence, high agreement*). {1.6, Cross-Chapter Box 5 in Chapter 4, 17.1, 17.3}

The landscape of transitions to sustainable development is changing rapidly, with multiple transitions already underway. This creates the room to manage these transitions in ways that prioritise the needs of workers in vulnerable sectors (e.g., land, energy) to secure their jobs and maintain secure and healthy lifestyles (*medium evidence, high agreement*). {17.3.2}

Actions aligning sustainable development, climate mitigation and partnerships can support transitions. Strengthening different stakeholders' "response capacities" to mitigate and adapt to a changing climate will be critical for a sustainable transition (*high confidence*). {17.1}

Accelerating the transition to sustainability will be enabled by explicit consideration being given to the principles of justice, equality and fairness (*high confidence*). {5.2, 5.4, 5.6, 13.2, 13.6, 13.8, 13.9,17.4}

Chapter 1: Introduction and Framing

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Date of Draft: 27/11/2021

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Executive Summary

Global greenhouse gas (GHG) emissions continued to rise to 2019: the aggregate reductions implied by current Nationally Determined Contributions (NDCs) to 2030 would still make it impossible to limit warming to 1.5°C with no or limited overshoot, and would only be compatible with *likely limiting warming* below 2°C if followed by much steeper decline, hence limiting warming to either level implies accelerated mitigation actions at all scales (*robust evidence, high agreement)*. Since the IPCC's Fifth Assessment Report (AR5), important changes that have emerged include the specific objectives established in the Paris Agreement of 2015 (for temperature, adaptation and finance), rising climate impacts, and higher levels of societal awareness and support for climate action. The growth of global GHG emissions has slowed over the past decade, and delivering the updated NDCs to 2030 would turn this into decline, but the implied global emissions by 2030 exceed pathways consistent with 1.5°C by a large margin, and are near the upper end of the range of modelled pathways which keep temperatures *likely* below 2°C. Continuing investments in carbon-intensive activities at scale will heighten the multitude of risks associated with climate change and impede societal and industrial transformation towards low carbon development. Meeting the long-term temperature objective in the Paris Agreement therefore implies a rapid turn to an accelerating decline of GHG emissions towards 'net zero', which is implausible without urgent and ambitious action at all scales. The unprecedented COVID-19 pandemic has had far-reaching impacts on the global economic and social system, and recovery will present both challenges and opportunities for climate mitigation. {1.2, 1.3, 1.5, 1.6, Chapters 3 and 4}.

While there are some trade-offs, effective and equitable climate policies are largely compatible with the broader goal of sustainable development and efforts to eradicate poverty as enshrined in the 17 Sustainable Development Goals (SDGs) *(robust evidence, high agreement)*. Climate mitigation is one of many goals that societies pursue in the context of sustainable development, as evidenced by the wide range of the SDGs. Climate mitigation has synergies and/or trade-offs with many other SDGs. There has been a strong relationship between development and GHG emissions, as historically both per capita and absolute emissions have risen with industrialisation. However, recent evidence shows countries can grow their economies while reducing emissions. Countries have different priorities in achieving the SDGs and reducing emissions as informed by their respective national conditions and capabilities. Given the differences in GHG emissions contributions, degree of vulnerabilities and impacts, as well as capacities within and between nations, equity and justice are important considerations for effective climate policy and for securing national and international support for deep decarbonisation. Achieving sustainable global development and eradicating poverty as enshrined in the 17 SDGS would involve effective and equitable climate policies at all levels from local to global scale. Failure to address questions of equity and justice over time can undermine social cohesion and stability. International co-operation can enhance efforts to achieve ambitious global climate mitigation in the context of sustainable development. {1.4, 1.6, Chapters 2, 3, 4, 5, 13 and 17}.

The transition to a low carbon economy depends on a wide range of closely intertwined drivers and constraints, including policies and technologies where notable advances over the past decade have opened up new and large-scale opportunities for deep decarbonisation, and for alternative development pathways which could deliver multiple social and developmental goals (*robust evidence, medium agreement).* Drivers for and constraints against low carbon societal transition comprise *economic and technological* factors (the means by which services such as food, heating and shelter are provided and for whom, the emissions intensity of traded products, finance, and investment), *socio-political issues* (political economy, equity and fairness, social innovation and behaviour change), and *institutional factors* (legal framework and institutions, and the quality of international cooperation). In addition to being deeply intertwined all the factors matter to varying degrees, depending on prevailing social, economic, cultural and political context. They often exert both push and pull forces at the same time, within and across different scales. The development and deployment of innovative technologies and systems at scale are important for achieving deep decarbonisation. In recent years, the cost of several low carbon technologies has declined sharply, alongside rapid deployment. Over twenty countries have also sustained emission reductions, and many more have accelerated energy efficiency and/or land-use improvements. Overall, however the global contribution is so far modest, at a few billion tonnes (tCO_2e) of avoided emissions annually. {1.3, 1.4, Chapters 2, 4,13,14}.

Accelerating mitigation to prevent dangerous anthropogenic interference within the climate system will require the integration of broadened assessment frameworks and tools that combine multiple perspectives, applied in a context of multi-level governance *(robust evidence, medium agreement)*. Analysing a challenge on the scale of fully decarbonising our economies entails integration of multiple analytic frameworks. Approaches to risk assessment and resilience, established across IPCC Working Groups, are complemented by frameworks for probing the challenges in implementing mitigation. *Aggregate Frameworks* include cost-effectiveness analysis towards given objectives, and cost-benefit analysis, both of which have been developing to take fuller account of advances in understanding risks and innovation, the dynamics of emitting systems and of climate impacts, and welfare economic theory including growing consensus on long-term discounting. *Ethical frameworks* consider the fairness of processes and outcomes which can help ameliorate distributional impacts across income groups, countries and generations. *Transition and transformation frameworks* explain and evaluate the dynamics of transitions to low-carbon systems arising from interactions amongst levels, with inevitable resistance from established socio-technical structures. *Psychological, behavioural and political frameworks* outline the constraints (and opportunities) arising from human psychology and the power of incumbent interests. A comprehensive understanding of climate mitigation must combine these multiple frameworks. Together with established risk frameworks, collectively these help to explain potential synergies and trade-offs in mitigation, imply a need for a wide portfolio of policies attuned to different actors and levels of decision-making, and underpin 'just transition' strategies in diverse contexts. {1.2.2, 1.7, 1.8}.

The speed, direction and depth of any transition will be determined by choices in the, environmental, technological, economic, socio-cultural and institutional realms *(robust evidence, high agreement).* Transitions in specific systems can be gradual or rapid and disruptive. The pace of a transition can be impeded by 'lock-in' generated by existing physical capital, institutions, and social norms. The interaction between power, politics and economy is central in explaining why broad commitments do not always translate to urgent action. At the same time, attention to and support for climate policies and low carbon societal transition has generally increased, as the impacts have become more salient. Both public and private financing and financial structures strongly affect the scale and balance of high and low carbon investments. COVID-19 has strained public finances, and integrating climate finance into ongoing recovery strategies, nationally and internationally, can accelerate the diffusion of low carbon technologies and also help poorer countries to minimise future stranded assets. Societal & behavioural norms, regulations and institutions are essential conditions to accelerate low carbon transitions in multiple sectors, whilst addressing distributional concerns endemic to any major transition. {1.3.3, Cross-Chapter Box 1 in this chapter, 1.4, 1.8, Chapters 2-4 and 15}.

Achieving the global transition to a low-carbon, climate-resilient and sustainable world requires purposeful and increasingly coordinated planning and decisions at many scales of governance including local, subnational, national and global levels *(robust evidence, high agreement)*. Accelerating mitigation globally would imply strengthening policies adopted to date, expanding the effort across options, sectors, and countries, and broadening responses to include more diverse actors and societal processes at multiple – including international – levels. Effective governance of climate change entails strong action across multiple jurisdictions and decision-making levels, including regular evaluation and learning. Choices that cause climate change as well as the processes for making and implementing relevant decisions involve a range of non-nation state actors such as cities, businesses, and civil society organisations. At global, national and subnational levels, climate change actions are interwoven with and embedded in the context of much broader social, economic and political goals. Therefore, the governance required to address climate change has to navigate power, political, economic, and social dynamics at all levels of decision making. Effective climate-governing institutions, and openness to experimentation on a variety of institutional arrangements, policies and programmes can play a vital role in engaging stakeholders and building momentum for effective climate action. {1.4, 1.9, Chapters 8, 15, 17}.

1.1 Introduction

This Report (WGIII) aims to assess new literature on climate mitigation including implications for global sustainable development. In this Sixth Assessment Cycle the IPCC has also published three Special Reports[1] all of which emphasise the rising threat of climate change and the implications for more ambitious mitigation efforts at all scales. At the same time, the Paris Agreement (PA) and the UN 2030 Agenda for Sustainable Development with its 17 Sustainable Development Goals (SDGs), both adopted in 2015, set out a globally agreed agenda within which climate mitigation efforts must be located. Along with a better understanding of the physical science basis of climate change (AR6 WGI), and vulnerabilities, impacts, and adaptation (AR6 WGII), the landscape of climate mitigation has evolved substantially since Fifth Assessment Report (AR5).

Since AR5, (IPCC 2014a) climate mitigation policies around the world have grown in both number and shape (Chapter 13). However, while the average rate of annual increase of CO_2 emissions has declined (Section 1.3.2) GHG emissions globally continued to rise, underlining the urgency of the mitigation challenge (Chapters 2, 3). Over twenty countries have cut absolute emissions alongside sustained economic growth, but the scale of mitigation action across countries remains varied and generally much slower than the pace required to meet the goals of the Paris Agreement (Section 1.3.2 in this chapter and Section 2.7.2 in Chapter 2). Per-capita GHG emissions between countries even at similar stages of economic development (based on GDP per capita) vary by a factor of three (Figure 1.6) and by more than two on consumption basis (Section 2.3 in Chapter 2).

The Special Report on 1.5ºC underlined that humanity is now living with the "unifying lens of the Anthropocene" (SR 1.5 IPCC 2018a, 52 & 53), that requires a sharpened focus on the impact of human activity on the climate system and the planet more broadly given 'planetary boundaries' (Steffen et al. 2015) including interdependencies of climate change and biodiversity (Dasgupta 2021). Recent literature assessed by WGs I and II of this AR6 underlines the urgency of climate action as cumulative CO_2 emissions, along with other greenhouses gases, drives the temperature change. Across AR6, global temperature changes are defined relative to the period 1850-1900, as in SR1.5 and collaboration with WGI enabled the use of AR6-calibrated emulators to assure consistency across the three Working Groups. The remaining 'carbon budgets' (see Annex I) associated with 1.5°C and 2°C temperature targets equate to about one (for 1.5°C) to three (for 2°C) decades of current emissions, as from 2020, but with significant variation depending on multiple factors including other gases (Figure 2.7 in Chapter

FOOTNOTE[1] These are the 'Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty' (hereafter SR1.5, 2018) (IPCC 2018b); the 'Special Report on Climate Change and Land' (SRCCL) (IPCC 2019c); and the 'Special Report on the Ocean and Cryosphere in a Changing Climate' (SROCC) (IPCC 2019b).

2; Cross-Working Group Box 1 in Chapter 3). For an outline of the WGIII approach to mitigation scenarios, emission pathways implied by the Paris goals, and timing of peak and 'net zero' (Annex I and FAQ 1.3), see Section 1.5, and Chapter 3.

Strong differences remain in responsibilities for, and capabilities to, take climate action within and between countries. These differences, as well as differences in the impact of climate change, point to the role of collective action in achieving urgent and ambitious global climate mitigation in the context of sustainable development, with attention to issues of equity and fairness as highlighted in several chapters of the report (Chapters 4, 5, 14, 15, 17).

Innovation and industrial development of key technologies in several relevant sectors have transformed prospects for mitigation at much lower cost than previously assessed (Chapters 2 and 6–12). Large reductions in the cost of widely-available renewable energy technologies, along with energy efficient technologies and behavioural changes (Chapters 5 and 9–11), can enable societies to provide services with much lower emissions. However, there are still significant differences in the ability to access and utilise low carbon technologies across the world (Chapter 4, 15, 16). New actors, including cities, businesses, and numerous non-state transnational alliances have emerged as important players in the global effort to tackle climate change (Chapters 13–16).

Along with continued development of concepts, models and technologies, there have been numerous insights from both the successes and failures of mitigation action that can inform future policy design and climate action. However, to date, policies and investments are still clearly inadequate to put the world in line with the PA's aims (Chapters 13, 15).

The greater the inertia in emission trends and carbon-intensive investments, the more that CO_2 will continue to accumulate (Hilaire et al. 2019; IPCC 2019a). Overall, the literature points to the need for a more dynamic consideration of intertwined challenges concerning the transformation of key GHG emitting systems: to minimise the trade-offs, and maximise the synergies, of delivering deep decarbonisation whilst enhancing sustainable development.

This Chapter introduces readers to the AR6 WGIII Report and provides an overview of progress and challenges, in three parts. Part A, introduces the climate mitigation challenge, provides key findings and developments since previous assessment, and reviews the main drivers for, and constraints against accelerated climate action. Part B provides an assessment of the key frameworks for understanding the climate mitigation challenge covering broad approaches like sustainable development and more specific economic, political and ethical framings. Part C briefly highlights the role of governance for steering and coordinating efforts to accelerate globally effective and equitable climate mitigation, notes the gaps in knowledge that have been identified in the process of assessment and provides a road map to the rest of the Report.

1.2 Previous Assessments

1.2.1 Key findings from Previous Assessment Reports

Successive WGIII IPCC Assessments have emphasised the importance of climate mitigation along with the need to consider broader societal goals especially sustainable development. Key insights from AR5 and the subsequent three Special Reports (IPCC 2019b, 2018b, 2019c) are summarised below.

AR5 projected that in baseline scenarios (i.e. based on prevailing trends without explicit additional mitigation efforts), Agriculture, Forestry and Other Land Uses (AFOLU) would be the only sector where emissions could fall by 2100, with some CO_2 removal (IPCC 2014b, p. 17). Direct CO_2 emissions from energy were projected to double or even triple by 2050 (IPCC 2014b, p. 20) due to global population and economic growth, resulting in global mean surface temperature increases in 2100 from 3.7°C to 4.8°C compared to pre-industrial levels. AR5 noted that mitigation effort and the costs associated with ambitious mitigation differ significantly across countries, and in 'globally cost-effective' scenarios, the biggest reductions (relative to projections) occur in the countries with the highest future emissions in the baseline scenarios (IPCC 2014b, p. 17). Since most physical capital (e.g. power plants, buildings, transport infrastructure) involved in GHG emissions is long-lived, the timing of the shift in investments and strategies will be crucial (IPCC 2014b, p. 18).

A key message from recent Special Reports is the urgency to mitigate GHG emissions in order to avoid rapid and potentially irreversible changes in natural and human systems (IPCC 2019b, 2018b, 2019a). Successive IPCC reports have drawn upon increasing sophistication of modelling tools to project emissions in the absence of ambitious decarbonisation action, as well as the emission pathways that meet long term temperature targets. The SR1.5 examined pathways limiting warming to 1.5°C, compared to historical baseline of 1850-1900, finding that "in pathways with no or limited overshoot of 1.5°C, global net anthropogenic CO_2 emissions decline by about 45% from 2010 levels by 2030, reaching net zero around 2050" (2045–2055 interquartile range); with 'overshoot' referring to higher temperatures, then brought down by 2100 through 'net negative' emissions. It found this would require rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems (*high confidence*) (IPCC 2018b).

SR1.5 found that the Nationally Determined Contributions (NDCs) as declared under the Paris Agreement (PA) would not limit warming to 1.5 C; despite significant updates to NDCs in 2020/21, this remains the case though delivery of these more ambition NDCs would somewhat enhance the prospects for staying below 2°C (Section 1.3.3).

AR5 WGIII and the Special Reports analysed economic costs associated with climate action. The estimates vary widely depending on the assumptions made as to how ordered the transition is, temperature target, technology availability, the metric or model used, among others (Chapter 6). Modelled direct mitigation costs of pathways to 1.5°C, with no/limited overshoot, span a wide range, but were typically 3-4 times higher than in pathways to 2°C (*high confidence*), before taking account of benefits, including significant reduction in loss of life and livelihoods, and avoided climate impacts (IPCC 2018b).

Successive IPCC Reports highlight a strong connection between climate mitigation and sustainable development. Climate mitigation and adaptation goals have synergies and trade-offs with efforts to achieve sustainable development, including poverty eradication. A comprehensive assessment of climate policy therefore involves going beyond a narrow focus on specific mitigation and adaptation options to incorporate climate issues into the design of comprehensive strategies for equitable sustainable development. At the same time, some climate mitigation policies can run counter to sustainable development and eradicating poverty, which highlights the need to consider trade-offs alongside benefits. Examples include synergies between climate policy and improved air quality, reducing premature deaths and morbidity (IPCC 2014b Fig SPM.6; AR6 WG1 sections 6.6.3 and 6.7.3), but there would be trade-offs if policy raises net energy bills, with distributional implications. The Special Report on Climate Change and Land (SRCCL) also emphasises important synergies and trade-offs, bringing new light on the link between healthy and sustainable food consumption and emissions caused by the agricultural sector. Land-related responses that contribute to climate change adaptation and mitigation can also combat desertification and land degradation and enhance food security (IPCC 2019a).

Previous ARs have detailed the contribution of various sectors and activities to global GHG emissions. When indirect emissions (mainly from electricity, heat and other energy conversions) are included, the four main consumption (end-use) drivers are industry, AFOLU, buildings and transport (Chapter 2,

Figure 2.14), though the magnitude of these emissions can vary widely between countries. These – together with the energy and urban systems which feed and shape end-use sectors – define the sectoral chapters in this AR6 WGIII report.

Estimates of emissions associated with production and transport of internationally traded goods were first presented in AR5 WGIII, which estimated the 'embodied emission transfers' from upper-middle-income countries to industrialised countries through trade at about 10 percent of CO_2 emissions in each of these groups (IPCC 2014a Fig TS.5). The literature on this and discussion on their accounting has grown substantially since then (Chapters 2 & 8).

The atmosphere is a shared global resource and an integral part of the "global commons". In the depletion/restoration of this resource, myriad actors at various scales are involved, for instance, individuals, communities, firms and states. *Inter alia*, international cooperation to tackle ozone depletion and acid rain offer useful examples. AR5 noted that greater cooperation would ensue if policies are perceived as fair and equitable by all countries along the spectrum of economic development–implying a need for equitable sharing of the effort. A key takeaway from AR5 is that climate policy involves value judgement and ethics. (IPCC 2014a Box TS.1 "*People and countries have rights and owe duties towards each other. These are matters of justice, equity, or fairness. They fall within the subject matter of moral and political philosophy, jurisprudence, and economics*." p. 37). International cooperation and collective action on climate change alongside local, national, regional and global policies will be crucial to solve the problem, and this report notes cooperative approaches beyond simple 'global commons' framings (Chapters 13, 14).

AR5 (all Working Group Reports) also underlined that climate policy inherently involves risk and uncertainty (in nature, economy, society and individuals). To help evaluate responses, there exists a rich suite of analytical tools, for example, cost-benefit analysis, cost-effectiveness analysis, multi-criteria analysis, expected utility theory and catastrophe and risk models. All have pros and cons, and have been further developed in subsequent literature and AR6 (next section).

Recent Assessments (IPCC 2014a, 2018b) began to consider the role of individual behavioural choices and cultural norms in driving energy and food patterns. Notably, SR1.5 (Section 4.4.3 in Chapter 4) outlined emerging evidence on the potential for changes in behaviour, lifestyle and culture to contribute to decarbonisation (and lower the cost); for the first time, AR6 devotes a whole chapter (Chapter 5) to consider these and other underlying drivers of energy demand, food choices and social aspects.

1.2.2 Developments in Climate Science, Impacts and Risk

The assessment of the Physical Science Basis (IPCC WGI AR6) documents sustained and widespread changes in the atmosphere, cryosphere, biosphere and ocean, providing unequivocal evidence of a world that has warmed, associated with rising atmospheric CO_2 concentrations reaching levels not experienced in at least the last 2 million years. Aside from temperature, other clearly discernible, human-induced changes beyond natural variations include declines in Arctic Sea ice and glaciers, thawing of permafrost, and a strengthening of the global water cycle (WG1 SPM A.2, B.3 and B.4). Oceanic changes include rising sea level, acidification, deoxygenation, and changing salinity (WG1 SPM B.3). Over land, in recent decades, both frequency and severity have increased for hot extremes but decreased for cold extremes; intensification of heavy precipitation is observed in parallel with a decrease in available water in dry seasons, along with an increased occurrence of weather conditions that promote wildfires.

In defining the objective of international climate negotiations as being to 'prevent dangerous anthropogenic interference' (Article 2 UNFCCC 1992), the UNFCCC underlines the centrality of risk framing in considering the threats of climate change and potential response measures. Against the background of 'unequivocal' (AR4) evidence of human-induced climate change, and the growing experience of direct impacts, the IPCC has sought to systematise a robust approach to risk and risk management.

In AR6 the IPCC employs a common risk framing across all three working groups and provides guidance for more consistent and transparent usage (AR6 WGI Cross-Chapter Box 3 in Chapter 1; AR6 WGII 1.4.1; IPCC risk guidance). AR6 defines risk as "the potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems" (Annex I), encompassing risks from both potential impacts of climate change and human responses to it (Reisinger et al. 2020). The risk framing includes steps for identifying, evaluating, and prioritising current and future risks; for understanding the interactions among different sources of risk; for distributing effort and equitable sharing of risks; for monitoring and adjusting actions over time while continuing to assess changing circumstances; and for communications among analysts, decision-makers, and the public.

Climate change risk assessments face challenges including a tendency to mis-characterise risks and pay insufficient attention to the potential for surprises (Weitzman 2011; Aven and Renn 2015; Stoerk et al. 2018). Concepts of resilience and vulnerability provide overlapping, alternative entry points to understanding and addressing the societal challenges caused and exacerbated by climate change (AR6, WGII, Chapter 1.2.1).

AR6 WGII devotes a full chapter (17) to 'Decision-Making Options for Managing Risk', detailing the analytic approaches and drawing upon the *Cynefin* classification of Known, Knowable, Complex and Chaotic systems (17.3.1). With deep uncertainty, risk management often aims to identify specific combinations of response actions and enabling institutions that increase the potential for favourable outcomes despite irreducible uncertainties (AR6 WGII Chapter 17 Cross-Chapter Box DEEP; also (Marchau et al. 2019; Doukas and Nikas 2020).

Literature trying to quantify the cost of climate damages has continued to develop. Different methodologies systematically affect outcomes, with recent estimates based on empirical approaches – econometric measurements based on actual impacts – 'categorically higher than estimates from other approaches' (Cross-Working Group Box ECONOMIC in WGII Chapter 16, Section 16.6.2). This, along with other developments strengthen foundations for calculating a 'social cost of carbon'. This informs a common metric for comparing different risks and estimating benefits compared to the costs of GHG reductions and other risk-reducing options (Section 1.7.1); emissions mitigation itself also involves multiple uncertainties, which alongside risks can also involve potential opportunities (Section 1.7.3).

Simultaneously, the literature increasingly emphasises the importance of multi-objective risk assessment and management (e.g., representative key risks in WGII Chapter 16), which may or may not correlate with any single estimate of economic value (AR6 WGII 1.4.1; IPCC risk guidance). Given the deep uncertainties and risks, the goals established (notably in the Paris Agreement and SDGs) reflect negotiated outcomes informed by the scientific assessment of risks.

1.3 The Multilateral Context, Emission Trends and Key Developments

Since AR5, there have been notable multilateral efforts which help determine the context for current and future climate action. This section summarises key features of this evolving context.

1.3.1 The 2015 Agreements

In 2015 the world concluded four major agreements that are very relevant to climate action. These include: the Paris Agreement under the 1992 United Nations Framework Convention on Climate

Change (UNFCCC), the UN agreements on Disaster Risk Reduction (Sendai) and Finance for Development (Addis Ababa), and the Sustainable Development Goals (SDGs).

The Paris Agreement (PA). The Paris Agreement aims to "hold the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels" (UNFCCC 2015), alongside goals for adaptation (IPCC WGII), and 'aligning financial flows' (below) , so as "to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty."

The Paris Agreement is predicated on encouraging progressively ambitious climate action from all countries on the basis of Nationally Determined Contributions (Rajamani 2016; Clémençon 2016). The NDC approach requires countries to set their own level of ambitions for climate change mitigation but within a collaborative and legally binding process to foster ambition towards the agreed goals (Falkner 2016a; Bodansky 2016). The PA entered into force in November 2016 and as of February 2021 it has 190 Parties (out of 197 Parties to the UNFCCC).

The PA also underlines "the principle of common but differentiated responsibilities and respective capabilities, in the light of different national circumstances" (PA Article 2 para 2), and correspondingly that "developed country Parties should continue taking the lead by undertaking economy-wide absolute emission reductions". It states that developing country Parties should continue enhancing their mitigation efforts, and are encouraged to move over time towards economy-wide emission reduction or limitation targets in the light of different national circumstances.

The Paris Agreement's mitigation goal implies "to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century" (PA Article 4 para 1). The Paris Agreement provides for 5-yearly stocktakes in which Parties have to take collective stock on progress towards achieving its purposes and its long-term goal in the light of equity and available best science (PA Article 14). The first global stocktake is scheduled for 2023. (PA Article 14 para 3).

The Paris Agreement aims to make 'finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development' (PA Article 2.1C). In keeping with the acknowledged context of global sustainable development and poverty eradication, and the corresponding aims of aligning finance and agreed differentiating principles as indicated above, "…the developed country parties are to assist developing country parties with financial resources" (PA Article 9). The Green Climate Fund (GCF), an operating entity of the UNFCCC Financial Mechanism to finance mitigation and adaptation efforts in developing countries (GCF 2020), was given an important role in serving the Agreement and supporting PA goals.. The GCF gathered pledges worth USD 10.3 billion, from developed and developing countries, regions, and one city (Paris) (Antimiani et al. 2017; Bowman and Minas 2019). Financing has since increased but remains short of the goal to mobilise USD100 billion by 2020 (Chapter 15).

Initiatives contributing to the Paris Agreement goals include the Non-State Actor Zone for Climate Action (NAZCA or now renamed as Global Climate Action) portal, launched at COP20 (December 2014) in Lima, Peru, to support city-based actions for mitigating climate change (Mead 2015) and Marrakech Partnership for Global Climate Action which is a UNFCCC-backed series of events intended to facilitate collaboration between governments and the cities, regions, businesses and investors that must act on climate change.

Details of the Paris Agreement, evaluation of the Kyoto Protocol, and other key multilateral developments since AR5 relevant to climate mitigation including the CORSIA aviation agreement adopted under ICAO, the IMO shipping strategy, and the Kigali Amendment to the Montreal Protocol on HFCs, are discussed in Chapter 14.

SDGs. In September 2015, the UN endorsed a universal agenda – 'Transforming our World: the 2030 Agenda for Sustainable Development'. The agenda adopted 17 non-legally-binding SDGs and 169 targets to support people, peace, prosperity, partnerships and the planet. While climate change is explicitly listed as SDG13, the pursuit of the implementation of the UNFCCC is relevant for a number of other goals including SDG 7 (clean energy for all), 9 (sustainable industry), and 11 (sustainable cities), 12 (responsible consumption and production) as well as those relating to life below water (14) and on land (15) (Biermann et al. 2017). Mitigation actions could have multiple synergies and trade-offs across the SDGs (Chapter 17; Pradhan et al. 2017) and their net effects depend on the pace and magnitude of changes, the specific mitigation choices and the management of the transition. This suggests that mitigation must be pursued in the broader context of sustainable development as explained in Section 1.6

Finance. The Paris Agreement's finance goal (above) reflects a broadened focus, beyond the costs of climate adaptation and mitigation, to recognising that a structural shift towards low carbon climate-resilient development pathways requires large scale investments that engage the wider financial system (15.1 and 15.2.4). The SR1.5C report estimated that 1.5ºC pathways would require *increased investment* of 0.5-1% of global GDP between now and 2050, which is up to 2.5% of global savings / investment over the period. For low- and middle-income countries, SDG-compatible infrastructure investments in the most relevant sectors are estimated to be around 4-5% of their GDP, and 'infrastructure investment paths compatible with full decarbonisation in the second half of the century need not cost more than more-polluting alternatives' (Rozenberg and Fay 2019).

The parallel 2015 UN Addis Ababa Conference on Finance for Development, and its resulting Action Agenda, aims to 'address the challenge of financing … to end poverty and hunger, and to achieve sustainable development in its three dimensions through promoting inclusive economic growth, protecting the environment, and promoting social inclusion.' The Conference recognises the significant potential of regional co-operation and provides a forum for discussing the solutions to common challenges faced by developing countries (15.6.4).

Alongside this, private and blended climate finance is increasing but is still short of projected requirements consistent with Paris Agreement goals (15.3.2.1). The financing gap is particularly acute for adaptation projects, especially in vulnerable developing countries. From a macro-regulatory perspective, there is growing recognition that substantial financial value may be at risk from changing regulation and technology in a low-carbon transition, with potential implications for global financial stability (15.6.3). To date, the most significant governance development is the Financial Stability Board's Task Force on Climate-related Financial Disclosure (TCFD) and its recommendations that investors and companies consider climate change risks in their strategies and capital allocation, so investors can make informed decisions (TCFD 2018), welcomed by over 500 financial institutions and companies as signatories, albeit with patchy implementation (1.4. 4; 15.6.3).

Talanoa Dialogue and Just Transition. As mandated at Paris COP21 and launched at COP23, the 'Talanoa Dialogue' (UNFCCC 2018a) emphasised holistic approaches across multiple economic sectors for climate change mitigation. At COP24 also, the Just Transition Silesia Declaration, focusing on the need to consider social aspects in designing policies for climate change mitigation was signed by 56 heads of state (UNFCCC 2018b). This underlined the importance of aiming for a 'just transition' in terms of reducing emissions, at the same time preserving livelihoods and managing economic risks for countries and communities that rely heavily on emissions-intensive technologies for domestic growth (Markkanen and Anger-Kraavi 2019), and for maintaining ecosystem integrity through nature-based solutions.

1.3.2 Global and regional emissions

Global GHG emissions have continued to rise since AR5, though the average rate of emissions growth slowed, from 2.4% (from 2000-2010) to 1.3% for 2010-2019 (Figure 1.1). After a period of exceptionally rapid growth from 2000 as charted in AR5, global fossil-fuel- and industry-related (FFI) CO_2 emissions almost plateaued between 2014 and 2016 (while the global economy continued to expand (World Bank 2020), but increased again over 2017-19, the average annual growth rate for all GHGs since 2014 being around 0.8%% yr^{-1} (IPCC/EDGAR emissions database). Important driving factors include population and GDP growth, as illustrated in panels (b) and (c) respectively. The pause in emissions growth reflected interplay of strong energy efficiency improvements and low-carbon technology deployment, but these did not expand fast enough to offset the continued pressures for overall growth at global level (UNEP 2018a; IEA 2019a). However, since 2013/14, the decline in global emissions intensity (GHG/GDP) has accelerated somewhat, and global emissions growth has averaged slightly slower than population growth (Figure 1.1d), which if sustained would imply a peak of global CO_2 (GHG) emissions per-capita, at about $5tCO_2$/person (/$7tCO_2e$/person) respectively.

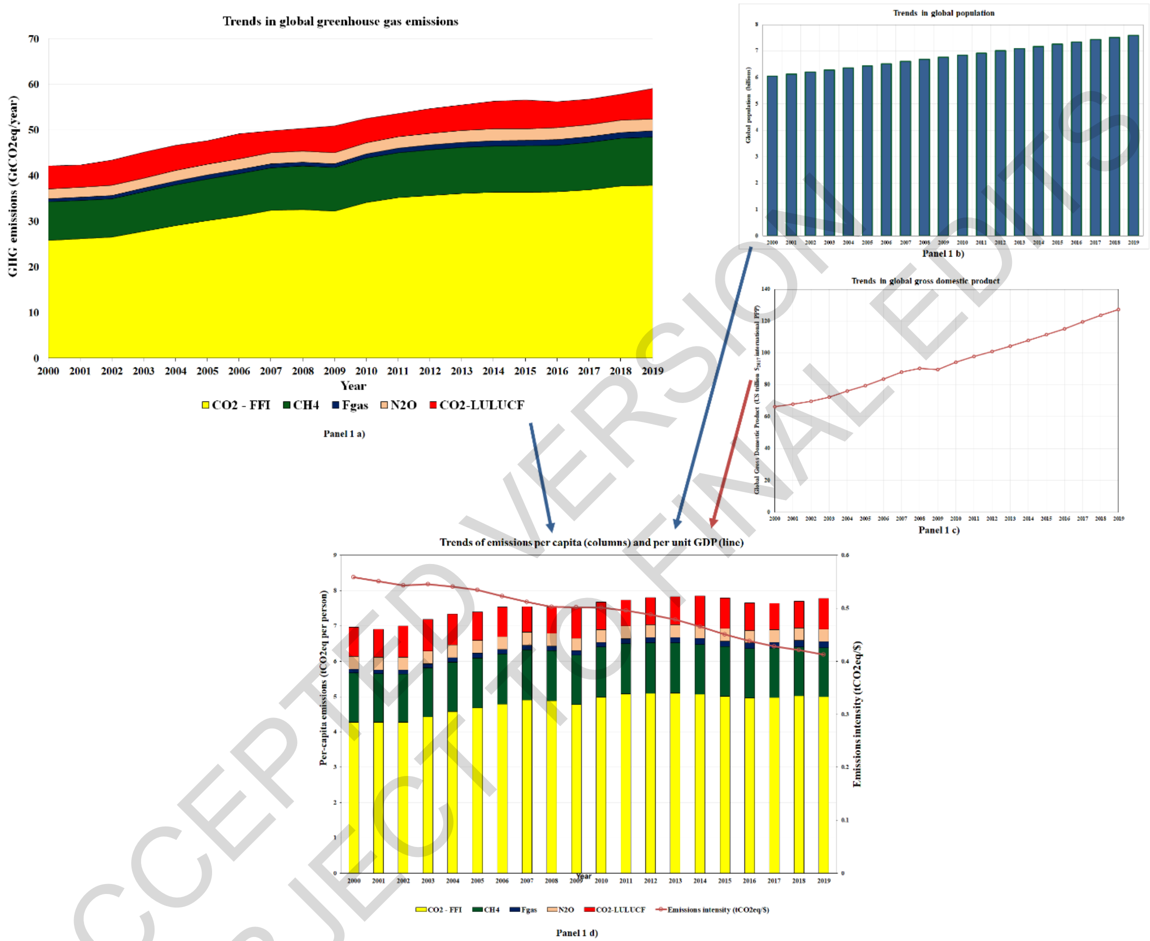

Figure 1.1: Global emission trends since 2000 by groups of gases: absolute, per-capita, and intensity

Note: Shows CO_2 from fossil fuel combustion and industrial processes (FFI); CO_2 from Agriculture, Forestry and Other Land use (AFOLU); methane (CH_4); nitrous oxide (N_2O); fluorinated gases (F-gases). Gases reported in Gt CO_2eq converted based on AR6 global warming potentials with 100-year time horizon (GWP-100).

Due to its much shorter lifetime, methane has disproportionate impact on near-term temperature, and is estimated to account for almost a third of the warming observed to date (AR6 WG1 SPM; WG-III Chapter 2, Figure 2.4). Methane reductions could be particularly important in relation to near- and medium-term temperatures, including through counteracting the impact of reducing short-lived aerosol pollutants which have an average cooling effect.[2]

The land-use component of CO_2 emissions has different drivers and particularly large uncertainties (Chapter 2, Figures 2.2, 2.5), hence is shown separately. Also, compared to AR5, new evidence showed that the AFOLU CO_2 estimates by the global models assessed in this report are not necessarily comparable with national GHG inventories, due to different approaches to estimate the 'anthropogenic' CO_2 sink. Possible ways to reconcile these discrepancies are discussed in Chapter 7.

Regional trends have varied. Emissions from most countries continued to grow, but in absolute terms, 32 countries reduced energy-and-industry-CO_2 emissions for at least a decade, and 24 reduced overall GHG (CO_2-eq) emissions over the same period, but only half of them by more than 10% over the period in each case (Chapter 2).[3] In total, developed country emissions barely changed from 2010, whilst those from the rest of the world grew.

Figure 1.2 shows the distribution of regional CO_2 (GHG emissions) (a) per capita and (b) per GDP based on purchasing power parity (GDP_{ppp}) of different country groupings in 2019. Plotted against population and GDP respectively, the area of each block is proportional to the region's emissions. Compared to the equivalent presentations in 2004 (AR4, SPM.3) and 2010 (AR5, Figure 1.8), East Asia now forms substantially the biggest group, whilst at about 8(/10tCO_2eq) per person, its emissions per-capita remain about half that of north America. In contrast, a third of the world's population, in southern Asia and Africa, emit on average under 2 (2.5tCO_2eq) per person, little more than in the previous Assessments. Particularly for these regions there continue to be substantial differences in the GDP, life expectancy and other measures of wellbeing (see Figure 1.6).

FOOTNOTE[2] Indeed, cooling effects of anthropogenic aerosols (organic carbon, black carbon, sulphates, nitrates), which are also important components of local air pollution (Myhre et al. 2013; WGI SPM D1.7) may in global average be of similar magnitude to warming from methane at present. Mitigation which reduces such aerosol masking could thereby increase global temperatures, and reducing methane emissions would offset this much more rapidly than reducing CO_2 because of its relatively short lifetime, with the combined effects which could counterbalance each other (WGI SPM D1.7). Methane is thus particularly important in determining whether or when 1.5C is reached for example.

FOOTNOTE 3 With some exclusions for countries which were very small or undergoing economic collapse: Energy- and Industry-CO2 emissions in 2018 were below 2010 levels in 32 developed countries, but only in 24 when including other GHGs. Reductions were by less than 10% in half these countries. Data from Chapter 2: see (2.2.3) and Figure 2.11 for panel of countries that have sustained territorial emission reductions longer than 10 years, as analysed in Lamb et al. (2021), and decomposition analysis of national trends in Xia et al. (2021). The previously rising trend of 'outsourced/embodied emissions' associated with goods imported into developed countries peaked in 2006, but detailed data on this are only available EEI-CO2, to 2018 (Section 2.3 in Chapter 2). See Chapter 3 for reduction rates associated with 1.5 and 2°C.

Emissions per unit GDP are much less diverse than per-capita, and have also converged significantly. Poorer countries tend to show higher energy/ emissions per unit GDP partly because of higher reliance on basic industries, and this remains the case, though in general their energy/GDP has declined faster.

Many developed country regions are net importers of energy-intensive goods, and emissions are affected by the accounting of such 'embodied emissions'. Panels (c) and (d) show results (only available for CO_2, to 2018) on the basis of consumption-footprints which include emissions embodied in traded goods. This makes modest changes to the relative position of different regions (for further discussion see Chapter 2).

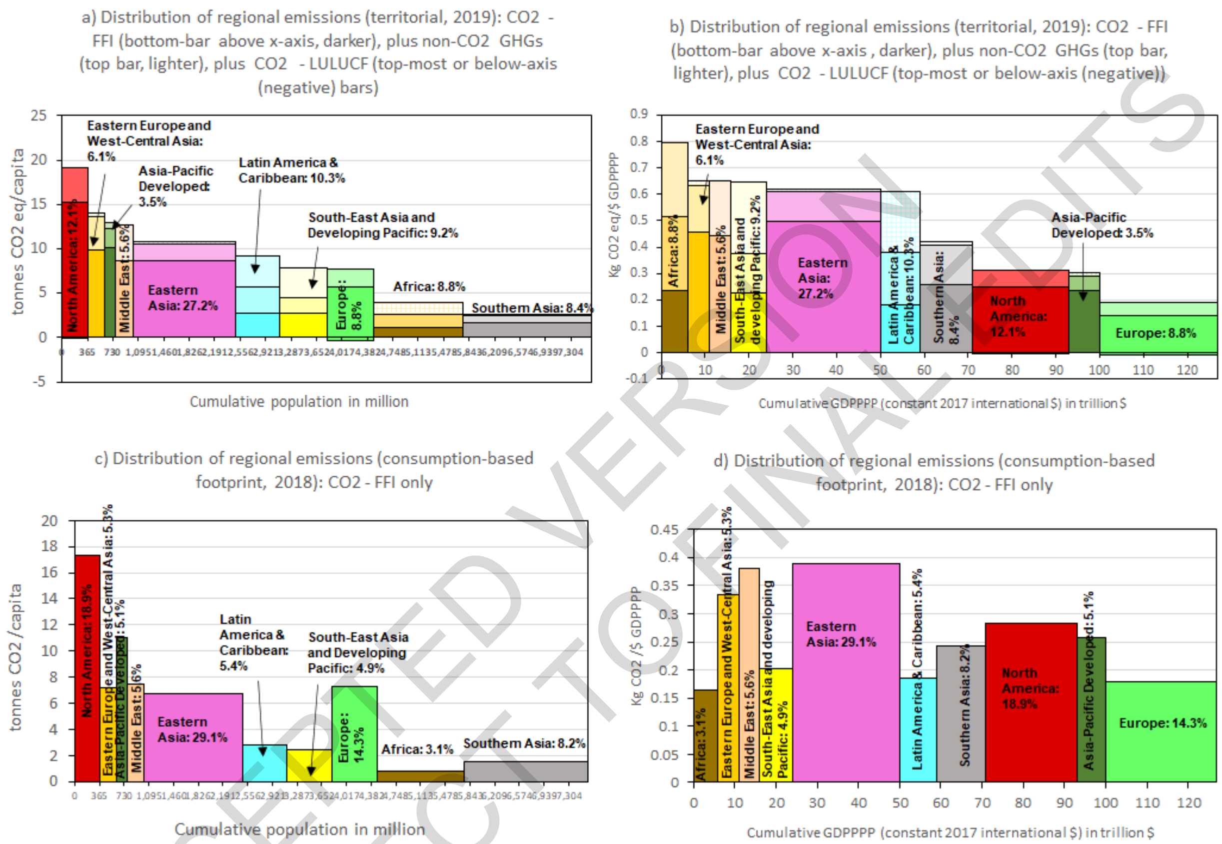

Figure 1.1: Distribution of regional GHG emissions for 10 broad global regions according to territorial accounting (panels a & b, GHG emissions) and consumption-based accounting (panels c & d, CO_2-FFI emissions only).

GHG emissions are categorised into: Fossil fuel and industry (CO_2-FFI), Land use, land use change, forestry (CO_2-LULUCF) and other greenhouse gases (methane, nitrous oxide, Fgas - converted to 100-year global warming potentials). Per-capita GHGs for territorial (panel a) and CO_2-FFI emissions vs population for consumption-based accounting (panel c). Panels b & d: GHG emissions per unit GDPppp vs GDPppp, weighted with purchasing power parity for territorial accounting (panel b), CO_2-FFI emissions per unit GDPppp for consumption-based accounting (panel d). The area of the rectangles refers to the total emissions for each regional category, with the height capturing per-capita emissions (panels a and c) or emissions per unit GDPppp (panels b and d), and the width proportional to the population of the regions and GDPppp. Emissions from international aviation and shipping (2.4% of the total GHG emissions) are not included.

While extreme poverty has fallen in more than half of the world's economies in recent years, nearly one-fifth of countries faced poverty rates above 30% in 2015 (below USD1.90 a day), reflecting large income inequality (Laborde Debucquet and Martin 2017; Rozenberg and Fay 2019). Diffenbaugh and Burke (2019) find that global warming already has increased global economic inequality, even if between-country inequalities have decreased over recent decade. The distributional implications between regional groups of different in the 'shared socioeconomic pathways (SSPs)' diverge according to the scenario (Frame et al. 2019).

An important recent development has been commitments by many countries, now covering a large majority of global emissions, to reach net zero CO_2 or greenhouse gas emissions (Chapter 3).[4] Furthermore, globally, net zero targets (whether CO_2 or GHG) have been adopted by about 823 cities and 101 regions (Chapter 8).

1.3.3 Some Other Key Trends and Developments

The **COVID-19 pandemic** profoundly impacted economy and human society, globally and within countries. As detailed in Cross-Chapter Box 1, some of its impacts will be long lasting, permanent even, and there are also lessons relevant to climate change. The direct impact on emissions projected for rest of this decade are modest, but the necessity for economic recovery packages creates a central role for government-led investment, and may change the economic fundamentals involved for some years to come.

The COVID-19 aftermath consequently also changes the economic context for mitigation (Sections 15.2 and 15.4 in Chapter 15). Many traditional forms of economic analysis (expressed as general equilibrium) assume that available economic resources are fully employed, with limited scope for beneficial economic 'multiplier effects' of government-led investment. After COVID-19 however, no country is in this state. Very low interest rates amplify opportunities for large-scale investments which could bring 'economic multiplier' benefits, especially if they help to build the industries and infrastructures for further clean growth (Hepburn et al. 2020). However, the capability to mobilise low interest finance vary markedly across countries and large public debts - including bringing some developing countries close to default - undermine both the political appetite and feasibility of large-scale clean investments. In practice the current orientation of COVID-19 recovery packages is very varied, pointing to a very mixed picture about whether or not countries are exploiting this opportunity (Cross-Chapter Box 1).

START CROSS-CHAPTER BOX 1 HERE

Cross-chapter Box 1 The COVID-19 crisis: lessons, risks and opportunities for mitigation

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The COVID-19 pandemic triggered the deepest global economic contraction as well as CO_2 emission reductions since the Second World War (Section 2.2.2.1 in Chapter 2; AR6 WGI Box 6.1 in Chapter 6) (Le Quéré et al. 2020b;). While emissions and most economies are expected to rebound in 2021-2022 (IEA 2021), some impacts of the pandemic (eg. aspects of economy, finance and transport-related emission

FOOTNOTE[4] Continually updated information on net-zero commitments is available at https://www.zerotracker.net drivers) may last far longer. COVID-19 pushed more than 100 million people back into extreme poverty, and reversed progress towards some other SDGs including health, life expectancy and child literacy (UN DESA 2021). Health impacts and the consequences of deep economy-wide shocks may last many years even without significant future recurrence (Section 15.6.3 in Chapter 15). These changes, as well as the pandemic response actions, bring both important risks as well as opportunities for accelerating mitigation (Chapters 1, 5, 10 and 15).

Lessons. Important lessons can be drawn from the pandemic to climate change including the value of forward-looking risk management, the role of scientific assessment, preparatory action and international process and institutions (1.3, Chapter 5). There had been long-standing warnings of pandemic risks, and precursors – with both pandemic and climate risks being identified by social scientists as 'uncomfortable knowledge', or 'unknown knowns' which tend to be marginalised in practical policy (Rayner 2012; Sarewitz 2020). This echoes long-standing climate literature on potential 'high impact' events, including those *perceived* as low probability (Dietz 2011; Weitzman 2011). The costs of preparatory action, mainly in those countries that had suffered from earlier pandemics were negligible in comparison, suggesting the importance not just of knowledge but its effective communication and embodiment in society (Chapter 5). (Klenert et al. 2020) offer five early lessons for climate policy, concerning: the cost of delay; the bias in human judgement; the inequality of impacts; the need for multiple forms of international cooperation; and finally, 'transparency in value judgements at the science-policy interface'.

Emissions and behavioural changes. Overall, global CO_2 FFI emissions declined by about 5.8% (5.1% to 6.3%) from 2019 to 2020, or about 2.2 (1.8-2.4) $GtCO_2$ in total (Section 2.2.2 in Chapter 2). Analysis from previous economic crises suggest significant rebound in emissions without policy-induced structural shifts (2.2.2.1; Figure 2.5) (Jaeger et al. 2020). Initial projections suggest the COVID aftermath may reduce emissions by 4-5% over 2025 - 2030 (Shan and Et.al 2020; Reilly et al. 2021), below a 'no-pandemic' baseline The long-term impacts on behaviour, technology and associated emissions remain to be seen, but may be particularly significant in transport - lockdowns reduced mobility-related emissions, alongside two major growth areas: electronic communications replacing many work and personal travel requirements (Section 4.4.3.4 in Chapter 4 and Chapter 10); and, revitalised local active transport and e-micromobility (Earley and Newman 2021). Temporary 'clear skies' may also have raised awareness of the potential environment and health co-benefits of reduced fossil fuel use particularly in urban areas (Section 8.7 in Chapter 8), with evidence also indicating that air pollution itself amplified vulnerability to COVID-19 (Wu et al. 2020; Gudka et al. 2020). The significant impacts on passenger aviation are projected to extend not just through behavioural changes, but also fleet changes from retiring older planes, and reduced new orders indicating expectations of reduced demand and associated GHG emissions until 2030 (Section 5.1.2 in Chapter 5 and Section 10.5 in Chapter 10; AR6 WGI Box 6.1 in Chapter 6). However, air cargo has recovered more rapidly (IATA 2020), possibly enhanced by online ordering.

Fiscal, growth and inequality impacts. Aspects of the global and regional economic crises from COVID-19 may prevail much longer than the crisis itself, potentially compromising mitigation. Most countries have undertaken unprecedented levels of short-term public expenditures. The IMF projects sovereign debt to GDP to have increased by 20% in advanced economies and 10% in emerging economies by the end of 2021 (IMF 2020). This is likely to slow economic growth, and may squeeze financial resources for mitigation and relevant investments for many years to come (15.2.3, 15.6.3). COVID-19 further lowered interest rates which should facilitate low carbon investment, but pandemic responses have increased sovereign debt across countries in all income bands (IMF 2021), and particularly in some developing economies and regions has caused debt distress (Bulow et al. 2021) widening the gap in developing countries' access to capital (Hourcade et al. 2021b) (Section 15.6.3 in Chapter 15). After decades of global progress in reducing poverty, COVID-19 has pushed hundreds of millions of people below poverty thresholds and raises the spectre of intersecting health and climate crises that are devastating for the most vulnerable (5.1.2 Box 5.1). Like those of climate change, pandemic impacts fall heavily on disadvantaged groups, exacerbate the uneven distribution of future benefits, amplify existing inequities, and introduce new ones. Increased poverty also hinders efforts towards sustainable low-carbon transitions (1.6).

Impacts on profitability and investment. COVID-19-induced demand reduction in electricity disproportionally affected coal power plants, whilst transport reduction most affected oil (IEA 2020a). This accelerated pre-existing decline in the relative profitability of most fossil fuel industries (Ameli et al. 2021) Renewables were the only energy sector to increase output (IEA 2020a). Within the context of a wider *overall* reduction in energy investment this prompted a substantial *relative* shift towards low carbon investment particularly by the private sector (IEA 2020b; Rosembloom and Markard 2020; 15.2.1, 15.3.1, 15.6.1).

Post-pandemic recovery pathways provide an opportunity to attract finance into accelerated and transformative low-carbon public investment (15.2, 15.6.3). In most countries, COVID-19 has increased unemployment and/or state-supported employment. There is a profound difference between short-term 'bail-outs' to stem unemployment, and the orientation of new public investment. The public debt is mirrored by large pools of private capital. During deep crises like that of the COVID-19, economic multipliers of stimulus packages can be high (Hepburn et al., 2020), so much so that fiscal injections can then generate multipliers from 1.5 to 2.5, weakening the alleged crowding-out effect of public stimulus (Auerbach and Gorodnichenko 2012; Blanchard and Leigh 2013; Section 15.2.3 in Chapter 15).

Recovery packages are motivated by assessments that investing in can boost the macroeconomic effectiveness ('multipliers') of public spending, crowd-in and revive private investment (Hepburn et al. 2020). There are clear reasons why a low-carbon response can create more enduring jobs, better aligned to future growth sectors: by also crowding-in and reviving private investment (e.g. from capital markets and institutional investors, including the growing profile of Environment and Social Governance (ESG) and green bond markets (15.6)), this can boost the effectiveness of public spending (IMF 2020). Stern and Valero (Stern and Valero 2021) argue that investment in low-carbon innovation and its diffusion, complemented by investments in sustainable infrastructure, are key to shape environmentally sustainable and inclusive growth in the aftermath of the COVID-19 pandemic crisis. This would be the case both for high-income economies on the global innovation frontier, and to promote sustainable development in poorer economies.

A study with a global general equilibrium model (Liu et al. 2021)finds that because the COVID-19 economic aftermath combines negative impacts on employment and consumption, a shift from employment and consumption taxes to carbon or other resource- related taxes would enhance GDP by 1.7% in 2021 relative to 'no policy', in addition to reducing CO_2 and other pollutants. A post-Keynesian model of wider 'green recovery' policies (Pollitt et al. 2021) finds a short-run benefit of around 3.5% GDP (compared to 'no policy'), and even c. 1% above a recovery boosted by cuts in consumption taxes, the latter benefit sustained through 2030 - outperforming an equivalent conventional stimulus package while reducing global CO_2 emissions by 12%.

Orientation of recovery packages. The large public spending on supporting or stimulating economies, exceeding USD12tn by October 2020, dwarfs clean energy investment needs and hence could either help to solve the combined crises, or result in high-carbon lock-in (Andrijevic et al. 2020). The short-term 'bailouts' to date do not foster climate resilient long-term investments and have not been much linked to climate action, (Sections 15.2.3 and 15.6.3 in Chapter 15): in the G20 counties, 40% of energy-related support spending went to the fossil fuel industry compared to 37% on low-carbon energy (EPT 2020). Recovery packages are also at risk of being 'colourless' (Hepburn et al., 2020) though some countries and regions have prioritised green stimulus expenditures for example as part of 'Green New Deal' (Rochedo et al. 2021; Section 13.9.6 in Chapter 13 and Section 15.6.3 in Chapter 15).

Integrating analyses. The response to COVID-19 also reflects the relevance of combining multiple analytic frameworks spanning economic efficiency, ethics and equity, transformation dynamics, and psychological and political analyses (Section 1.7). As with climate impacts, not only has the global burden of disease been distributed unevenly, but capabilities to prevent and treat disease were asymmetrical and those in greatest vulnerability often had the least access to human, physical, and financial resources (Ruger and Horton 2020). 'Green' versus 'brown' recovery has corresponding distributional consequences between these and 'green' producers, suggesting need for differentiated policies with international coordination (Le Billon et al. 2021). This illustrates the role of 'just transition' approaches to global responses including the value of integrated, multi-level governance (Section 1.7 in this Chapter, Section 4.5 in Chapter 4 and Section 17.1 in Chapter 17).

Crises and opportunities: the wider context for mitigation and transformation. The impacts of COVID-19 have been devastating in many ways, in many countries, and may distract political and financial capacity away from efforts to mitigate climate change. Yet, studies of previous post-shock periods suggest that waves of innovation that are ready to emerge can be accelerated by crises, which may prompt new behaviours, weaken incumbent ('meso-level') systems, and prompt rapid reforms (Section 1.6.5; Roberts and Geels 2019a). Lessons from the collective effort to 'flatten the curve' during the pandemic, illustrating aspects of science-society interactions for public health in many countries, may carry over to climate mitigation, and open new opportunities (Section 5.1.2 in Chapter 5). COVID-19 appears to have accelerated the emergence of renewable power, electromobility and digitalisation (Newman 2020; Sectiopn 5.1.2 in Chapter 5, Section 6.3 in Chapter 6, Section 10.2 in Chapter 10). Institutional change is often very slow but major economic dislocation can create significant opportunities for new ways of financing and enabling 'leapfrogging' investment to happen (Section 10.8 in Chapter 10). Given the unambiguous risks of climate change, and consequent stranded asset risks from new fossil fuel investments (Box 6.11), the most robust recoveries are likely to be those which emerge on lower carbon and resilient pathways (Obergassel et al. 2020). Noting the critical global post-COVID-19 challenge as the double-impact of heightened credit risk in developing countries, along with indebtedness in developed countries, (Hourcade et al. 2021a) estimate that a 'multilateral' sovereign guarantee structure to underwrite low carbon investments could leverage projects up to 15 times its value, contributing to shifting development pathways consistent with the SDGs and Paris goals.

COVID- 19 can thus be taken as a reminder of the urgency of addressing climate change, a warning of the risk of future stranded assets (Rempel and Gupta 2021; and Chapter 17), but also an opportunity for a cleaner recovery.

END CROSS-CHAPTER BOX 1 HERE

In addition to developments in climate science, emissions, the international agreements in 2015, and the recent impact of COVID-19, a few other key developments have strong implications for climate mitigation.

Cheaper Renewable Energy Technologies: Most striking, the cost of solar PV has fallen by a factor of 5-10 in the decade since the IPCC *Special Report on Renewable Energy* (IPCC 2011a) and other data inputting to the AR5 assessments, The SR1.5 reported major cost reductions, the IEA (2020) *World Energy Outlook* described PV as now 'the cheapest electricity in history' for projects that 'tap low cost finance and high quality resources.' Costs and deployment both vary widely between different countries (chapter 6, 9, 12) but costs are still projected to continue falling (Vartiainen et al. 2020). Rapid technological developments have occurred in many other low-carbon technologies including batteries and electric vehicles (see 1.4.3), IT and related control systems, with progress also where electrification is not possible (Chapters 2, 6, 11)

Civil society pressures for stronger action. Civic engagement increased leading up to the Paris Agreement (Bäckstrand and Lövbrand 2019) and after. Youth movements in several countries show young people's awareness about climate change, evidenced by the school strikes for the climate (Hagedorn et al. 2019; Buettner 2020; Walker 2020; Thackeray et al. 2020). Senior figures across many religions (Francis 2015; IFEES 2015) stressed the duty of humanity to protect future generations and the natural world, and warned about the inequities of climate change. Growing awareness of local environmental problems such as air pollution in Asia and Africa (Karlsson et al. 2020), and the threat to indigenous people rights and existence has also fuelled climate activism (Etchart 2017). Grass-root movements (Cheon and Urpelainen 2018; Fisher et al. 2019), build political pressure for accelerating climate change mitigation, as does increasing climate litigation (Setzer and Vanhala 2019; Chapters 13 and 14).

Climate policies also encounter resistance. However there are multiple sources of resistance to climate action in practice. Corporations and trade associations often lobby against measures they deem detrimental (Section 1.4.6). The emblematic 'yellow vest' movement in France was triggered by higher fuel cost as a result of CO_2 tax hike (Lianos 2019; Driscoll 2021), though it had broader aspect of income inequality and other social issues. There is often mismatch between concerns on climate change and people's willingness to pay for mitigation. For example, whilst most Americans believe climate change is happening, 68% said in a survey they would oppose climate policies that added just USD10/month to electricity bills (EPIC et al. 2019), and worry about energy costs can eclipse those about climate change elsewhere (Poortinga et al. 2018; Chapter 13).

Global trends contrary to multilateral cooperation. State-centred politics and geopolitical/geo-economic tensions seem to have become more prominent across many countries and issues (WEF 2019). In some cases, multilateral cooperation could be threatened by trends such as rising populism, nationalism, authoritarianism and growing protectionism (Abrahamsen et al. 2019), making it more difficult to tackle global challenges including protecting the environment (Schreurs 2016; Parker et al. 2017; WEF 2019).

Transnational alliances. Partly countering this trend, cities, businesses, a wide range of other non-state actors also have emerged with important international networks to foster mitigation. City-based examples include the Cities Alliance in addressing climate change, Carbon Neutral Cities Alliance, the Covenant of Mayors (chapter 8); there are numerous other alliances and networks such as those in finance (chapter 15), technology (chapter 16), amongst many others (chapters 13, 14).

Finally, under the Paris Agreement process, during 2020/21, many countries strengthened their Nationally Determined Contributions (NDCs). Including updates until October 2021, these would imply global GHG emissions declining by 2030 to between 1-4% below 2019 levels (unconditional NDCs), or 4-10% (for NDCs conditional on international support), See Table 4.3 in Chapter 4).This is a significant change but would still not be compatible with 1.5°C pathways, and even if delivered in full, to *likely* stay below 2°C, emissions would have to fall very rapidly after 2030 (Section 3.2.5).

Thus, developments since AR5 highlight the complexity of the mitigation challenge. There is no far-sighted, globally optimising decision-maker and indeed climate policymaking at all levels is subject to conflicting pressures in multiple ways. The next section overviews the drivers and constraints.

1.4 Drivers and Constraints of Climate Mitigation and System Transitions/Transformation

This section provides brief assessment of key factors and dynamics that drive, shape and or limit climate mitigation in (i) ***Economic factors***: which include sectors and services; trade and leakage; finance and investment; and technological innovation; (ii) ***Socio-political issues***; which include political economy; social innovation and equity and fairness; and (iii) ***Institutional factors***, which comprise policy, legal frameworks and international co-operation.

AR 5 introduced six "enabling conditions" for shifting development pathways which are presented in Chapter 4 of this report and some of which overlap with the drivers reviewed here. However, the terminology of drivers and constraints have been chosen here to reflect the fact that each of these factors can serve as an enabling condition or a constraint to ambitious climate action depending on the context and how they are deployed. Often one sees the factors exerting both push and pull forces at the same time in the same and across different scales. For example, finance and investments can serve as a barrier or an enabler to climate action (Battiston et al. 2021). Similarly, political economy factors can align in favour of ambitious climate action or act in ways that inhibit strong co-operation and low carbon transition. The other key insight from the assessment of the system drivers and constraints undertaken below is that none of the factors or conditions by themselves is more or less important than the others. In addition to being deeply intertwined all the factors matter in different measures with each exacting more or less force depending on prevailing social, economic, cultural and political context. Often achieving accelerated mitigation would require effort to bring several of the factors in alignment in and across multiple levels of political or governance scales.

1.4.1 Services, sectors and urbanisation

Human activities drive emissions primarily through the demand for a wide range of services such as food, shelter, heating/cooling, goods, travel, communication, and entertainment. This demand is fulfilled by various activities often grouped into sectors such as agriculture, industry and commerce. The literature uses a wide range of sectoral definitions to organize data and analysis (Chapter 2). Energy sectors are typically organised into primary energy producers, energy transformation processes (such as power generation, fuel refining), and major energy users such as buildings, industry, transport (Chapters 2, 5). Other research (Chapter 8) organizes data around interacting urban and rural human activities. Land-based activities can be organized into agriculture, forestry, and other land use (AFOLU), or land use, land use change and forestry (LULUCF) (Chapter 7). Each set of sectoral definitions and analysis offers its own insights.

Sectoral perspectives help to identify and understand the drivers of emissions, opportunities for emissions mitigation, and interactions with resources, other goals and other sectors, including the co-evolution of systems across scales (Moss et al. 2016; Kyle et al. 2016; Mori et al. 2017; IPBES 2019). Interactions between sectors and agents pursuing multiple goals is a major theme pervading this assessment.

The ‘nexus’ between energy, water, and land – all key contributors to human well-being – also helps to provide, regulate and support ecosystem and cultural services (Bazilian et al. 2011; Ringler et al. 2013; Smajgl et al. 2016; Albrecht et al. 2018; D’Odorico et al. 2018; Brouwer et al. 2018; Van Vuuren et al. 2019), with important implications for cities in managing new systems of transformation (Chapter 8; Thornbush et al. 2013; Wolfram et al. 2016) . Other important nexus’ shaping our planet’s future (Fajardy et al. 2018) include agriculture, forestry, land use and ecosystem services (Chazdon 2008; Keesstra et al. 2018; Nesshöver et al. 2017; Torralba et al. 2016; Settele et al. 2016).

Historically, energy-related GHG emissions were considered a by-product of the increasing scale of human activity, driven by population size, economic activity and technology. That simple notion has evolved greatly over time to become much more complex and diverse, with increasing focus on the provision of energy services (Garrett et al. 2020; Bardi et al. 2019; Cullen and Allwood 2010; Brockway et al. 2019)) The demand for agricultural products has historically driven conversion of natural lands (land use change). AFOLU along with food processing account for 21-37% of total net anthropogenic GHG emissions (SRCCL SPM A3).[5]

Continued growth in population and income are expected to continue driving up demand for goods and services (Chapters 2, 3 & 5), with an important role for urbanisation which is proceeding at an unprecedented speed and scale. In the last decade, the urban population grew by 70 million people each year, or about 1.3 million people per week, with urban area expanding by about 102 km^2 per day (Chapter 8). Urban areas account for most (45-87%) of the global carbon footprint (8.1) and the strong and positive correlation between urbanisation and incomes means higher consumption from urban lifestyles will continue driving direct and indirect GHG emissions. Cities provide conduit to many of the services such as transportation, housing, water, food, medical care, recreation and other services and urban carbon emissions are driven not only by population and income but also by form and structure of urban areas (8.1, 8.3, 8.4, 8.5, 8.6). This creates opportunities for decarbonization through urban planning and purposeful “experimentation” (Newman et al. 2017 Chapter 8).

Human needs and wants evolve over time making the transition toward climate and sustainable development goals either more or less difficult. For example, changes in the composition of goods consumed, such as, shifting diets toward a more vegetarian balance, can reduce land-use emissions without compromising the quality of life (Stehfest et al. 2009; van Vuuren et al. 2018; van den Berg et al. 2019; Hargreaves et al. 2021; Gough 2017; SRCCL SPM B2.3).

Human behavior and choices, including joint achievement of wider social goals, will play an important part in enabling or hindering climate mitigation and sustainable development (Shi et al. 2016), for example shifting passenger transportation preferences in ways that combine climate, health and sustainable development goals (Romanello et al. 2021).

1.4.2 Trade, consumption and leakage

Emissions associated with international trade account for 20-33 % of global emissions, as calculated using multi-regional input-output analysis (Wiedmann and Lenzen 2018). Whether international trade drives increase or decrease in global GHG emissions depends on emissions intensity of traded products as well as the influence of trade on relocation of production, with studies reaching diverse conclusions about the net effect of trade openness on CO_2 emissions (Section 2.4.5). Tariff reduction of low carbon technologies

FOOTNOTE[5] AFOLU accounted for about 13% of CO2, 44% of CH4 and 82% of N2O global anthropogenic GHG emissions in 2007-2016 (SRCCL SPM A3).

could facilitate effective mitigation (de Melo and Vijil 2014; WTO 2016; Ertugrul et al. 2016; Islam et al. 2016).

The magnitude of carbon leakage (Annex I) caused by unilateral mitigation in a fragmented climate policy world depends on trade and substitution patterns of fossil fuels and the design of policies (see Box 5.4. AR5), but its potential significance in trade-exposed energy-intensive sectors (Naegele and Zaklan 2019; Carbone and Rivers 2017; Bauer et al. 2013) can make it an important constraint on policy. See Section 13.6.6.1 in Chapter 13 for channels and evidence. Akimoto et al. (2018) argue that differences in marginal abatement cost of NDCs could cause carbon leakage in energy-intensive, trade-exposed sectors, and could weaken effective global mitigation.

Policy responses to cope with carbon leakage include border carbon adjustment (BCAs) and differentiated carbon taxes (Liu et al. 2020). Some BCA options focusing on levelling the cost of carbon paid by consumers on products could be designed in line with WTO (Ismer et al. 2016) while others may not be (Mehling et al. 2019). All proposals could involve difficulty of tracing and verifying the carbon content of inputs (Onder 2012; Denis-Ryan et al. 2016). An international consensus and certification practice on the carbon content would help to overcome WTO compatibility (Holzer 2014). See chapter 13, and (Mehling et al. 2019) on context of trade law and the PA.

Official inventories report territorial emissions, which do not consider the impacts embodied in imports of goods. Global supply chains undoubtedly lead to a growth in trade volumes (Federico and Tena-Junguito 2017), alternative methods have been suggested to account for emissions associated with international trade, such as shared responsibility (Lenzen et al. 2007), technology adjusted consumption based accounting (Kander et al. 2015), value added-based responsibility (Piñero et al. 2019) and exergy-based responsibility based on thermodynamics (Khajehpour et al. 2019). Consumption-based emissions (i.e. attribution of emissions related to domestic consumption and imports to final destination) are not officially reported in global emissions datasets but data has improved (Afionis et al. 2017; Tukker and Dietzenbacher 2013). This analysis have been used extensively for consumption-based accounting of emissions, and other environmental impacts (Malik et al. 2019; Wiedmann and Lenzen 2018). chapter 2.3).

Increasing international trade has resulted in a general shifting of fossil-fuel driven emissions-intensive production from developed to developing countries (Arto and Dietzenbacher 2014; Malik and Lan 2016), and between developing countries (Zhang et al. 2019). High-income developed countries thus tend to be net importers of emissions, whereas low/middle income developing countries net-exporters (Peters et al. 2011; Figure 1.2c, d).This trend is shifting, with a growth in trade between non-OECD countries (Meng et al. 2018; Zhang et al. 2019), and a decline in emissions intensity of traded goods (Wood et al. 2020b).

The Paris Agreement primarily deals with national commitments relating to domestic emissions and removals, hence emissions from international aviation and shipping are not covered. Aviation and shipping accounted for approximately 2.7% of greenhouse gas emissions in 2019 (before COVID-19); see Chapter 10.5.2 for discussion. In addition to CO_2 emissions, aircraft-produced contrail cirrus clouds and emissions of black carbon and short-lived aerosols (e.g. sulphates) from shipping are especially harmful for the Arctic (10.8, Box 10.6).

1.4.3 Technology

The rapid developments in technology over the past decade enhance potential for transformative changes, in particular to help deliver climate goals simultaneously with other SDGs.

The fall in renewable energy costs alongside rapid growth in capacity (Figure 1.3; Figure X in Chapter 2) has been accompanied by varied progress in many other technology areas such electric vehicles, fuel cells for both stationary and mobile applications (Dodds 2019), thermal energy (chapter 6) and battery and other storage technologies (Chapters 6, 9, 12; Freeman et al. 2017). Nuclear contributions may be enhanced by new generations of reactors, e.g., Generation III, and small modular reactors (Knapp and Pevec 2018; see also Chapter 6).

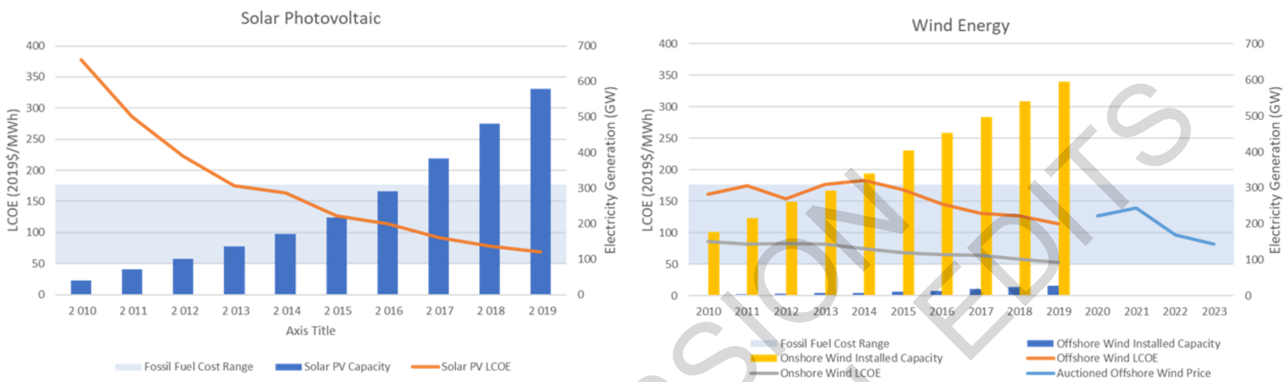

Figure 1.2: Cost reductions and adoption in solar PV and wind energy

Source: (IRENA 2020a,b), with fossil fuel LCOE indicated as shaded blue at USD 50-177/MWh (IRENA 2020b)

Large-scale hydrogen developments could provide a complementary energy channel with long-term storage. Like electricity, hydrogen (H_2) is an energy vector with multiple potential applications, including in industrial processes such as steel and non-metallic materials production (Chapter 11), for long-range transportation (Chapter 10), and low-temperature heating in buildings (Chapter 9). Emissions depend on how it is produced, and deploying H_2 delivery infrastructure economically is a challenge when the future scale of hydrogen demand is so uncertain (Chapter 6). H_2 from natural gas with CO_2 capture and storage (CCS) may help to kick-start the H_2 economy (Sunny et al. 2020).

CO_2-based fuels and feedstocks such as synthetic methane, methanol, diesel, jet fuel and other hydrocarbons, potentially from carbon capture and utilisation (CCU), represent drop-in solutions with limited new infrastructure needs (Artz et al. 2018; Bobeck et al. 2019; Yugo and Soler 2019); Chapter 10. Deployment and development of CCS technologies (with large-scale storage of captured CO_2) have been much slower than projected in previous Assessments (Page et al. 2019; IEA 2019b; see also Chapter 11).

Potential constraints on new energy technologies may include their material requirements, notably rare earth materials for electronics or lithium for batteries (Wanger 2011; Flexer et al. 2018), stressing the importance of recycling (Rosendahl and Rubiano 2019; IPCC 2011b). Innovation is enabling greater recycling and re-use of energy-intensive materials (Shemi et al. 2018) and introducing radically new and more environmentally friendly materials, however, still not all materials can be recycled (Allwood 2014).

By sequestering carbon in biomass and soils, soil carbon management, and other terrestrial strategies could offset hard-to-reduce emissions in other sectors. However, large-scale bioenergy deployment could increase risks of desertification, land degradation, and food insecurity (IPCC 2019a), and higher water withdrawals (Hasegawa et al. 2018; Fuhrman et al. 2020), though this may be at least partially offset by innovation in agriculture, diet shifts and plant-based proteins contributing to meeting demand for food, feed, fibre and, bioenergy (or BECCS with CCS) (Chapters 5, 7; Köberle et al. 2020; Havlik et al. 2014; Popp et al. 2017).

A broad class of more speculative technologies propose to counteract effects of climate change by removing CO_2 from the atmosphere (CDR), or directly modify the Earth's energy balance at a large scale (SRM). CDR technologies include ocean iron fertilisation, enhanced weathering and ocean alkalinisation (Council 2015a), along with Direct Air Capture with Carbon Storage (DACCS). They could potentially draw down atmospheric CO_2 much faster than the Earth's natural carbon cycle, and reduce reliance on biomass-based removal (Realmonte et al. 2019; Köberle 2019), but some present novel risks to the environment and DACCS is currently more expensive than most other forms of mitigation (Fuss et al. 2018; Cross-chapter box 8 in Chapter 12). Solar radiation modification (SRM) could potentially cool the planet rapidly at low estimated direct costs by reflecting incoming sunlight (Council 2015b), but entails uncertain side effects and thorny international equity and governance challenges (Netra et al. 2018; Florin et al. 2020; National Academies of Sciences 2021) (Chapter 14). Understanding the climate response to SRM remains subject to large uncertainties (AR6 WG1). Some literature uses the term "geoengineering" for both CDR or SRM when applied at a planetary scale (Shepherd 2009; GESAMP 2019). In this report, CDR and SRM are discussed separately reflecting their very different geophysical characteristics.

Large improvements in information storage, processing, and communication technologies, including artificial intelligence, will affect emissions. They can enhance energy-efficient control, reduce transaction cost for energy production and distribution, improve demand-side management (Raza and Khosravi 2015), and reduce the need for physical transport (Smidfelt Rosqvist and Winslott Hiselius 2016; see Chapters 5, 6, 9-11). However, data centres and related IT systems (including blockchain), are electricity-intensive and will raise demand for energy (Avgerinou et al. 2017) - cryptocurrencies may be a major global source of CO_2 if the electricity production is not decarbonised (Mora et al. 2018) – and there is also a concern that information technologies can compound and exacerbate current inequalities (Chapter 16; Box 2). IT may affect broader patterns of work and leisure (Boppart and Krusell 2020), and the emissions intensity of how people spend their leisure time will become more important (see Chapters 5, 9). Because higher efficiency tends to reduces costs, it often involves some 'rebound' offsetting at least some of the emission savings (Belkhir and Elmeligi 2018; Sudbury and Hutchinson 2016; Cohen and Cavoli 2019).

Technology can enable both emissions reductions and/or increased emissions (Chapter 16). Governments play an important role in most major innovations, in both 'technology-push' (Mazzucato 2013) and induced by 'demand-pull' (Grubb et al. 2021a), so policy is important in determining its pace, direction, and utilisation (Roberts and Geels 2019a; Sections 1.7.1, 1.7.3). Overall, the challenge will be to enhance the synergies and minimise the trade-offs and rebounds, including taking account of ethical and distributional dimensions (Gonella et al. 2019).

1.4.4 Finance and investment

Finance is both an enabler and constraint on mitigation, and since AR5, attention to the financial sector's role in mitigation has grown. This is partly in the context of the Paris Agreement finance articles and Green Climate Fund, the pledge to mobilise USD100bn/yr by 2020, and the Addis Abbaba Action Agenda (Section 1.3.1). However there is a persistent but uncertain gap in mitigation finance (Cui and Huang 2018); (Table 15.15.1), even though tracked climate finance overwhelmingly goes toward mitigation compared to adaptation (UNEP 2020; 15.3; Working Group II). Green bond issuance has increased recently in parallel with efforts to reform the international financial system by supporting development of local capital markets (15.6.4).

Climate finance is a multi-actor, multi-objective domain that includes central banks, commercial banks, asset managers, underwriters, development banks, and corporate planners. Climate change presents both risks and opportunities for the financial sector. The risks include physical risks related to the impacts of climate change itself; transition risks related to the exposure to policy, technology and behavioural changes in line with a low-carbon transition; and liability risks from litigation for climate-related damages (Box 15.2). These could potentially lead to stranded assets (the loss of economic value of existing assets before the end of their useful lifetimes (Bos and Gupta 2019; Section 6.7 in Chapter 6, Section 15.6.3 in Chapter 15). Such risks continue to be underestimated by financial institutions (Section 15.6.1 in Chapter 15). The continuing expansion of fossil fuel infrastructure and insufficient transparency on how these are valued raises concerns that systemic risk may be accumulating in the financial sector in relation to a potential low-carbon transition that may already be under way (Battiston et al. 2017; Section 15.6.3 in Chapter 15). The Financial Stability Board's TCFD recommendations on transparency aim to ensure that investors and companies consider climate change risks in their strategies and capital allocation (TCFD 2018). This is helping "investors to reassess core assumptions" and may lead to "significant" capital reallocation (Fink 2020). However, metrics and indicators of assets risk exposure are inadequate (Campiglio et al. 2018; Monasterolo 2017) and transparency alone is insufficient to drive the required asset reallocation in the absence of clear regulatory frameworks (Chenet et al. 2021; Ameli et al. 2020). A coalition of Central Banks have formed the Network for Greening the Financial Sector, to support and advance the transformation of the financial system (Allen et al. 2020; NGFS 2020), with some of them conducting Climate-related institutional stress tests

Governments cannot singlehandedly fund the transition (Section 15.6.7 in Chapter 15), least of all in low-income developing countries with large sovereign debt and poor access to global financial markets. Long-term sources of private capital are required to close the financing gap across sectors and geographies (Section 15.6.7 in Chapter 15). Future investment needs are greatest in emerging and developing economies (Section 15.5.2 In Chapter 15) which already face higher cost of capital, hindering capacity to finance a transition (Buhr et al. 2018; Ameli et al. 2020). Requisite North-South financial flows are impeded by both geographic and technological risk premiums (Iyer et al. 2015), and the Covid-19 pandemic has further compromised the ability of developing and emerging economies to finance development activities or attract additional climate finance from developed countries (Cross-Chapter Box 1 in this chapter; Section 15.6.3 in Chapter 15). Climate-related investments in developing countries also suffer from structural barriers such as sovereign risk and exchange rate volatility (Farooquee and Shrimali 2016; Guzman et al. 2018) which affect not only climate-related investment but investment in general (Yamahaki et al. 2020) including in needed infrastructure development (Gray and Irwin 2003). A GCF report notes the paradox that USD14 trillion of negative-yielding debt in OECD countries might be expected to flow to much larger low-carbon, climate-resilient investment opportunities in developing countries, but "this is not happening" (Hourcade et al. 2021b).

There is often a disconnect between stated national climate ambition and finance flows, and overseas direct investment (ODI) from donor countries may be at odds with national climate pledges such as NDCs. One report found funds supported by foreign State-Owned Enterprises into 56 recipient countries in Asia and Africa in 2014-2017 went mostly to fossil fuel-based projects not strongly aligned with low-carbon priorities of recipient countries' NDCs (Zhou et al. 2018). Similarly, Steffen and Schmidt (2019) found that even within Multilateral Development Banks, 'public- and private-sector branches differ considerably', with public-sector lending used mainly in non-renewable and hydropower projects. Political leadership is therefore essential to steer financial flows to support low carbon transition (15.6). Voituriez er al. (2019) identify significant mitigation potential if financing countries simply applied their own environmental standards to their overseas investments.

1.4.5 Political economy

The politics of interest (most especially economic interest) of key actors at subnational, national and global level can be important determinants of climate (in)action (O'Hara 2009; Lo 2010; Tanner and Allouche 2011; Sovacool et al. 2015; Clapp et al. 2018; Lohmann 2017; Newell and Taylor 2018; Lohmann 2019). Political economy approaches can be crudely divided into "economic approaches to politics", and those used by other social scientists (Paterson and P-Laberge 2018). The former shows how electoral concerns lead to weak treaties (Battaglini and Harstad 2016) and when policy negotiations cause status-quo biases and the use of inefficient policy instruments (Austen-Smith et al. 2019) or delays and excessive harmonization (Harstad 2007). The latter emphasises the central role of structures of power, production, and a commitment to economic growth and capital accumulation in relation to climate action, given the historically central role of fossil fuels to economic development and the deep embedding of fossil energy in daily life (Malm 2015; Huber 2012; Di Muzio 2015; Newell and Paterson 2010).

The economic centrality of fossil fuels raises obvious questions regarding the possibility of decarbonisation. Economically, this is well understood as a problem of decoupling. But the constraint is also political, in terms of the power of incumbent fossil fuel interests to block initiatives towards decarbonisation (Newell and Paterson 2010; Geels 2014; Jones and Levy 2009). The effects of climate policy are key considerations in deciding the level of policy ambition and direction and strategies of states (Alam et al. 2013; Ibikunle and Okereke 2014; Lo 2010), regions (Goldthau and Sitter 2015); and business actors (Wittneben et al. 2012) and there is a widespread cultural assumption that continued fossil fuel use is central to this (Strambo and Espinosa 2020). Decarbonisation strategies are often centred around projects to develop new sources of economic activity: carbon markets creating new commodities to trade profit from (Newell and Paterson 2010); the investment generated in new urban infrastructure (Whitehead 2013); innovations in a range of new energy technologies (Fankhauser et al. 2013; Lachapelle et al. 2017; Meckling and Nahm 2018).

One factor limiting the ambition of climate policy has been the ability of incumbent industries to shape government action on climate change (Newell and Paterson 1998; Breetz et al. 2018; Jones and Levy 2009; Geels 2014). Incumbent industries are often more concentrated than those benefiting from climate policy and lobby more effectively to prevent losses than those who would gain (Meng and Rode 2019). Drawing upon wider networks (Brulle 2014), campaigns by oil and coal companies against climate action in the US and Australia are perhaps the most well-known and largely successful of these (Brulle et al. 2020; Stokes 2020; Mildenberger 2020; Pearse 2017) although similar dynamics have been demonstrated for example in Brazil and South Africa (Hochstetler 2020), Canada (Harrison 2018), Norway , or Germany (Fitzgerald et al. 2019). In other contexts, resistance by incumbent companies is more subtle but nevertheless has weakened policy design on emissions trading systems (Rosembloom and Markard 2020), and limited the development of alternative fuelled automobiles (Wells and Nieuwenhuis 2012; Levy and Egan 2003).

The interaction of politics, power and economics is central in explaining why countries with higher per-capita emissions, which logically have more opportunities to reduce emissions, in practice often take the opposite stance, and conversely, why some low-emitting countries may find it easier to pursue climate action because they have fewer vested interests in high-carbon economies. These dynamics can arise from the vested interest of State-owned Enterprises (Polman 2015; Wright and Nyberg 2017; Wittneben et al. 2012), the alignment and coalitions of countries in climate negotiations (Gupta 2016; Okereke and Coventry 2016), and the patterns of opposition to or support for climate policy among citizens (Swilling et al. 2016; Ransan-Cooper et al. 2018; Turhan et al. 2019; Baker 2015; Heffron and McCauley 2018).

1.4.6 Equity and fairness

Equity and fairness can serve as both driver and barrier to climate mitigation at different scales of governance. Literature regularly highlights equity and justice issues as critical components in local politics and international diplomacy regarding all SDG, such as goals for no poverty, zero hunger, gender equality, affordable clean energy, reducing inequality, but also for climate action (Goal 13) (Marmot and Bell 2018; Spijkers 2018). Equity issues help explain why it has proved hard to reach more substantive global agreements, as it is hard to agree on a level of greenhouse gas mitigation (or emissions) and how to distribute mitigation efforts among countries (Kverndokk 2018) for several reasons. First, an optimal trade-off between mitigation costs and damage costs of climate change depends on ethical considerations, and simulations from integrated assessment models using different ethical parameters producing different optimal mitigation paths, see (IPCC 2018b and Section 3.6.1.2 in Chapter 3). Second, treaties that are considered unfair may be hard to implement (Liu et al. 2017; Klinsky et al. 2017). Lessons from experimental economics show that people may not accept a distribution that is considered unfair, even if there is a cost of not accepting (Gampfer 2014). As equity issues are important for reaching deep decarbonisation, the transition towards a sustainable development (Okereke 2018; Evans and Phelan 2016; Heffron and McCauley 2018) depends on taking equity seriously in climate policies and international negotiations (Martinez et al. 2019; Okereke and Coventry 2016; Klinsky et al. 2017).

Climate change and climate policies affect countries and people differently Low-income countries tend to be more dependent on primary industries (agriculture, fisheries, etc.) than richer countries, and their infrastructure may be less robust to tackle more severe weather conditions. Within a country, the burdens may not be equally distributed either, due to policy measures implemented and from differences in vulnerability and adaptive capacity following from e.g. income and wealth distribution, race and gender. For instance, unequal social structures can result in women being more vulnerable to the effects of climate change compared to men, especially in poor countries (Jost et al. 2016; Rao et al. 2019; Arora-Jonsson 2011). Costs of mitigation also differ across countries. Studies show there are large disparities of economic impacts of NDCs across regions, and also between relatively similar countries when it comes to the level of development, due to large differences in marginal abatement cost for the emission reduction goal of NDCs (Akimoto et al. 2018; Fujimori et al. 2016; Edmonds et al. 2019; Hof et al. 2017). Equalizing the burdens from climate policies may give more support for mitigation policies (Maestre-Andrés et al. 2019).

Taking equity into account in designing an international climate agreement is complicated as there is no single universally accepted equity criterion, and countries may strategically choose a criterion that favours them (Lange et al. 2007, 2010). Still, several studies analyse the consequences of different social preferences in designing climate agreements, such as for instance inequality aversion, sovereignty and altruism (Anthoff et al. 2010; Kverndokk et al. 2014).

International transfers from rich to poor countries to support mitigation and adaptation activities may help equalizing burdens, as agreed upon in the UNFCCC (1992; Chapters 14 and 15) such that they may be motivated by strategic as well as equity reasons (Kverndokk 2018; see also 1.4.4).

1.4.7 Social innovation and behaviour change

Social and psychological factors affect both perceptions and behaviour (Whitmarsh et al. 2021; Weber 2015). Religion, values, culture, gender, identity, social status and habits strongly influence individual behaviours and choices and therefore, sustainable consumption (Section 1.6.3.1 in this chapter and Section 5.2 in Chapter 5). Identities can provide powerful attachments to consumption activities and objects that inhibit shifts away from them (Stoll-Kleemann and Schmidt 2017; Ruby et al. 2020; Brekke et al. 2003;

Bénabou and Tirole 2011). Consumption is a habit-driven and social practice rather than simply a set of individual decisions, making shifts in consumption harder to pursue (Evans et al. 2012; Shove and Spurling 2013; Kurz et al. 2015; Warde 2017; Verplanken and Whitmarsh 2021). Finally, shifts towards low-carbon behaviour are also inhibited by social-psychological and political dynamics that cause individuals to ignore the connections from daily consumption practices to climate change impacts (Norgaard 2011; Brulle and Norgaard 2019).

As a notable example, plant-based alternatives to meat could reduce emissions from diets (Willett et al. 2019; Eshel et al. 2019) however, diets are deeply entrenched in cultures and identities and hard to change (Fresco 2015; Mylan 2018). Changing diets also raises cross-cultural ethical issues, in addition to meat's role in providing nutrition (Plumwood 2004). Henceforth, some behaviours that are harder to change will only be transformed by the transition itself: triggered by policies, the transition will bring about technologies that, in turn, will entrench new sustainable behaviours.

Behaviour can be influenced through a number of mechanisms besides economic policy and regulation, such as information campaigns, advertising and 'nudging'. Innovations and infrastructure also impact behaviour, as with bicycle lanes to reduce road traffic. Wider social innovations also have indirect impacts. Education is increasing across the world, and higher education will have impacts on fertility, consumption and the attitude towards the environment (Osili and Long 2008; McCrary and Royer 2011; Hamilton 2011). Reducing poverty and improvements in health and reproductive choice will also have implications for fertility, energy use and consumption globally. Finally, social capital and the ability to work collectively may have large consequences for mitigation and the ability to adapt to climate change (Adger 2009; Section 4.3.5 in IPCC 2014a).

1.4.8 Policy impacts

Transformation to different systems will hinge on conscious policy to change the direction in which energy, land-use, agriculture and other key sectors develop (Bataille et al. 2016; Chapters 13, 16). Policy plays a central role in in land-related systems (Chapter 7), urban development (Chapter 8), improving energy efficiency in buildings (Chapter 9) and transport / mobility (Chapter 10), and decarbonising industrial systems (Chapter 11).

Policy has been and will be central not only because greenhouse gas emissions are almost universally under-priced in market economies (Stern and Stiglitz 2017; World Bank 2019), and because of inadequate economic incentives to innovation (Jaffe et al. 2005) but also due to various delay mechanisms (Karlsson and Gilek 2020) and multiple sources of path-dependence and lock-in to existing systems (Section 1.8.2), including "Infrastructure developments and long-lived products that lock societies into GHG-intensive emissions pathways may be difficult or very costly to change, reinforcing the importance of early action for ambitious mitigation *(robust evidence, high agreement)*." (AR5 p.18).

Many hundreds of policies have been introduced explicitly to mitigate GHG emissions, improve energy efficiency or land use, or to foster low carbon industries and innovation, with demonstrable impact. The role of policy to date has been most evident in energy efficiency (Sections 5.4 and 5.6 in Chapter 5) and electricity (Chapter 6). The IPCC Special Report on Renewable Energy already found that "Government policies play a crucial role in accelerating the deployment of RE technologies", (IPCC 2011a, p. 24). Policy packages since then have driven rapid expansion in renewables capacity and cost reductions (eg. through the German *Energiewende*), and emission reductions from electricity (most dramatically with the halving of CO_2 emissions from UK power sector, driven by multiple policy instruments and regulatory changes), as detailed in Chapter 6 (Section 6.7.5).

Chapter 13 charts the international evolution of policies and many of the lessons drawn. Attributing the overall impact on emissions is complex, but an emerging literature of several hundred papers indicates impacts on multiple drivers of emissions. Collectively, policies are likely to have curtailed global emissions growth by several $GtCO_2e$ annually already by the mid-2010s (see Cross-Chapter Box 10 in Chapter 14). This suggests initial evidence that policy has driven some decoupling (e.g. Figure 1.1d) and started to 'bend the curve' of global emissions, but more specific attribution to observed trends is not as yet possible.[6]

However, some policies (e.g. subsidies to fossil fuel production or consumption), increase emissions; whilst others (e.g. investment protection) may constrain efforts at mitigation. Also, wider economic and developmental policies have important direct and indirect impacts on emissions. Policy is thus both a driver and a constraint on mitigation.

Synergies and trade-offs arise partly because of the nexus of GHG emissions with other adverse impacts (e.g. local air pollution) and critical resources (e.g. water and food) (Conway et al. 2015; Andrews-Speed and Dalin 2017), which also imply interacting policy domains.

The literature shows increasing emphasis on policy packages, including those spanning the different levels of niche/behaviour; existing regimes governing markets and public actors; and strategic and landscape levels (Section 1.7.3). Chapters 13, 16, and 17 appraise policies for transformation in the context of sustainable development, indicating the importance of policy as a driver at multiple levels and across many actors, with potential for benefits as well as costs at many levels.

National-level legislation may be particularly important to the credibility and long-term stability of policy to reduce the risks, and hence cost, of finance (Chapters 13, 15) and for encouraging private sector innovation at scale (Chapter 16), for example if it offers greater stability and mid-term predictability for carbon prices; Nash and Steurer (2019) find that seven national Climate Change Acts in European countries all act as 'living policy processes, though to varying extents'.

The importance of policy at multiple levels does not lessen the importance of international policy, for reasons including long-term stability, equity, and scope, but examples of effective implementation policy at international levels remain fewer and governance weaker (Chapter 14).

1.4.9 Legal framework and institutions

Institutions are rules and norms held in common by social actors that guide, constrain and shape human interaction (IPCC 2018b). Institutions can be formal, such as laws and policies, or informal, such as norms and conventions. Institutions can both facilitate or constrain climate policy-making and implementation in multiple ways. Institutions set the economic incentives for action or inaction on climate change at national, regional and individual levels (Dorsch and Flachsland 2017; Sullivan 2017).

FOOTNOTE [6] Linking estimated policy impacts to trends is complex, and as yet very tentative. An important factor is that many mitigation policies involve investments in low carbon or energy efficient technology, the savings from which persist. As a purely illustrative example: the annual increase in global emissions during 2000-2010 averaged around $1GtCO_2e\ yr^{-1}$, but with large fluctuations. If policies by 2010 reduced the *annual increase* in that year by $100MtCO_2e$ ($0.1GtC0_2e$) below what it would otherwise have been, this is hard to discern. But if these savings sustain, and in each subsequent year, policies cut another $100MtCO_2e$ off the annual increase compared to the previous year, global emissions after a decade would be around $5GtCO_2e\ yr^{-1}$ below what they would have been without any such policies, and on average close to stabilising. However each step would be difficult to discern in the noise of annual fluctuations.

Institutions entrench specific political decision-making processes, often empowering some interests over others, including powerful interest groups who have vested interest in maintaining the current high carbon economic structures (Engau et al. 2017; Okereke and Russel 2010; Wilhite 2016); see also 1.4.6 and Chapter 13 on the sub national and national governance challenges including coordination, mediating politics and strategy setting.

Some suggest that societal transformation towards low a carbon future requires new politics that involves thinking in intergenerational time horizons, as well as new forms of partnerships between private and public actors (Westman and Broto 2018), and associated institutions and social innovations to increase involvement of non-state actors in climate governance (Fuhr et al. 2018). However literature is divided as to how much democratisation of climate politics, with greater emphasis on equity and community participation, would advance societal transformation in the face of climate change (Stehr 2005), or may actually hinder radical climate action in some circumstances (Povitkina 2018).

Since 2016, the number of climate litigation cases has increased rapidly. UN Environment's "Global Climate Litigation Report: 2020 Status Review" (UNEP 2020) noted that between March 2017 and 1 July 2020, the number of cases nearly doubled with at least 1,550 climate cases filed in 8 countries. Several important cases such as Urgenda Foundation v. The State of the Netherlands ("Urgenda") and Juliana et al v. United States ("Juliana") have had ripple effects, inspiring other similar cases (Lin and Kysar 2020).

Numerous international climate governance initiatives engage national and subnational governments, NGOs and private corporations, constituting a "regime complex" (Keohane and Victor 2011; Raustiala and Victor 2004). They may have longer-run and second-order effects if commitments are more precise and binding (Kahler 2017). However, without targets, incentives, defined baseline or monitoring, reporting, and verification, they are not likely to fill the "mitigation gap" (Michaelowa and Michaelowa 2017).

1.4.10 International cooperation

Tackling climate change is often mentioned as an important reason for strong international co-operation in the 21st century (Bodansky et al. 2017; Cramton et al. 2017b; Keohane and Victor 2016; Falkner 2016). Mitigation costs are borne by countries taking action, while the benefits of reduced climate change are not limited to them, being in economic terms "global and non-excludable". Hence anthropogenic climate change is typically seen as a global commons problem (Wapner and Elver 2017; Falkner 2016). Moreover, the belief that mitigation will raise energy cost and may adversely affect competitiveness creates incentives for free riding, where states avoid taking their fair share of action (Barrett 2005; Keohane and Victor 2016). International cooperation has the potential to address these challenges through collective action (Tulkens, 2019) and international institutions offer opportunity for actors to engage in meaningful communication, and exchange of ideas about potential solutions (Cole 2015). International cooperation is also vital for the creation and diffusion of norms and the framework for stabilising expectations among actors (Pettenger 2016).

Some key roles of the UNFCCC have been detailed by its former heads (Kinley et al. 2021). In addition to specific agreements (most recently the PA) it has enhanced transparency through reporting and data, and generated or reinforced several important norms for global climate action including the principles of equity, common but differentiated responsibility and respective capabilities, and the precautionary principles for maintaining global cooperation among states with unevenly distributed emissions sources, climate impacts, and varying mitigation cost across countries (Keohane and Victor, 2016). In addition to formal negotiations, the annual Conference of Parties have increased awareness, and motivated more ambitious actions, sometimes through for example the formation of 'coalitions of the willing'. It provides a structure for measuring and monitoring action towards a global goal (Milkoreit and Haapala 2019). International cooperation (including the UNFCCC) can also promote technology development and transfer and capacity building; mobilise finance for mitigation and adaptation, and help address concerns on climate justice (Chan et al. 2018; Okereke and Coventry 2016; see Chapters 14-16).

A common criticism of international institutions is their limited (if any) powers to enforce compliance (Zahar 2017). As a global legal institution, the PA has little enforcement mechanism (Sindico 2015), but enforcement is not a necessary condition for an instrument to be legally binding (Bodansky 2016; Rajamani 2016). In reality implementation of specific commitments tends to be high once countries have ratified and a Treaty or an Agreement is in force (Bodansky 2016; Rajamani 2016). Often, the problem is not so much of 'power to enforce compliance or sanction non-compliance', but the level of ambition (Chapter 14).

However, whilst in most respects a driver, international cooperation has also been characterised as 'organised hypocrisy' where proclamations are not matched with corresponding action (Egnell 2010). Various reasons for inadequate progress after 30 years of climate negotiations, have been identified (Stoddard et al. 2021). International cooperation can also seem to be a barrier to ambitious action when negotiation is trapped in 'relative-gains' calculus, seek to game the regime or gain leverage over one another (Purdon 2017), or where states lower ambition to the 'least common dominator' to accommodate participation of the least ambitious states (Falkner 2016). Geden (2016) and Dubash (2020) offer more nuanced assessments.

International collaboration works best if an agreement can be made self-reinforcing with incentives for mutual gains and joint action (Keohane and Victor 2016; Barrett 2016), but the structure of the climate challenge makes this hard to achieve. The evidence from the Montreal Protocol on ozone depleting substances and from the Kyoto Protocol on GHGs, is that legally binding targets have been *effective* in that participating Parties complied with them (Albrecht and Parker 2019; Shishlov et al. 2016), and (for Kyoto) these account for most of the countries that have sustained emission reductions for at least the past 10-15 years (Section 1.3.2; Section 2.2 in Chapter 2). However, such binding commitments may deter *participation* if there are no clear incentives to sustain participation and especially if other growing emitters are omitted by design, as with the Kyoto Protocol. Consequently the US refused to ratify (and Canada withdrew), particularly on the grounds that developing countries had no targets; with participation in Kyoto's second period commitments declining further, the net result was limited global progress in emissions under Kyoto (Scavenius and Rayner 2018; Bodansky 2016; Okereke and Coventry 2016) despite full legal compliance in both commitment periods (chapter 14).

The negotiation of the Paris Agreement was thus done in the context of serious questions about how best to structure international climate cooperation to achieve better results. This new agreement is designed to side-step the fractious bargaining which characterised international climate cooperation (Marcu 2017). It contains a mix of hard, soft and non-obligations, the boundaries between which are blurred, but each of which plays a distinct and valuable role (Rajamani 2016). The provisions of the PA could encourage flexible responses to changing conditions, but limit assurances of ambitious national commitments and their fulfilment (Pickering et al. 2018). The extent to which this new arrangement will drive ambitious climate policy in the long run remains to be seen (Chapter 14).

Whilst the PA abandoned common accounting systems and timeframes, outside the UNFCCC many other platforms and metrics for comparing mitigation efforts have emerged (Aldy 2015). Countries may assess others' efforts in determining their actions through multiple platforms including Climate Change Cooperation Index (C3-I), Climate Change Performance Index (CCPI) 'Climate Laws, Institutions and

Measures Index' (CLIMI) (Bernauer and Böhmelt 2013) and Energy Transition Index (Singh et al. 2019). International cooperative initiatives between and among non-state (e.g., business, investors, civil society) and subnational (e.g., city, state) actors have also been emerging, taking the forms of public-private partnerships, private sector governance initiatives, NGO transnational initiatives, and subnational transnational initiatives (Bulkeley and Schroeder 2012; Hsu et al. 2018). Literature is mostly positive about the role of these transnational initiatives in facilitating climate action across scales although criticism and caution about their accountability and effectiveness remain (Chan et al. 2016; Roger et al. 2017; Widerberg and Pattberg 2017; Michaelowa and Michaelowa 2017; Chapter 14).

1.5 Emissions Scenarios and Illustrative Mitigation Pathways (IMPs)

Scenarios are a powerful tool for exploring an uncertain future world against the background of alternative choices and development. Scenarios can be constructed using both narrative and quantitative methods. When these two methods are combined they provide complementary information and insights. Quantitative and narrative models are frequently used to represent scenarios to explore choices and challenges. The IPCC has a long history of assessing scenarios (Nakicenovic et al. 2000; van Vuuren et al. 2011, 2014; see also section 1.6 of AR6 WGI for a history of scenarios within the IPCC). This WGIII assessment employs a wide range of qualitative and quantitative scenarios including quantitative scenarios developed through a wide and heterogeneous set of tools ranging from spreadsheets to complex computational models (Annex III provides further discussion and examples of computational models).

The concept of an **illustrative pathway (IP)** was introduced in IPCC Special Report on 1.5 (IPCC 2018b) to highlight a subset of the quantitative scenarios, drawn from a larger pool of published literature, with specific characteristics that would help represent some of the key findings emerging from the assessment in terms of different strategies, ambitions and options available to achieve the Paris goals.

Integrated Assessment Models (IAMs) are the primary tools for quantitatively evaluating the technological and macro-economic implications of decarbonisation, particularly for global long-term pathways. They broadly divide into 'stylized aggregate benefit-cost models', and more complex, 'detailed process' IAMs (Weyant 2017), often mirroring the benefit-cost and cost-effective approaches outlined in 1.7.1, with more detailed classification in eg. Nikas et al. (2019). IAMs embody a number of structural and socio-demographic assumptions and include multiple modelling approaches, ranging from economic optimising behaviour to simulation (See Annex III). Detailed process models can include energy system models used to analyse decarbonisation and 'net zero' scenarios by international agencies (eg. IEA 2020a).

Calculating cost-effective trajectories towards given goals typically involves detailed process IAMs. Often these calculate the dynamic portfolio of technologies consistent with a given climate target. Some track records of technology forecasting in IAMs are outlined in Chapters 2.5.4, and Box 16.1. Climate targets may be imposed in models in a variety of ways that include, but are not limited to, constraints on emissions or cumulated emissions (carbon budgets), and the pricing of emissions. The time-path of mitigation costs calculated through these models may be translated into 'shadow prices' that (like the social-cost-of-carbon) offer a benchmark to assess the cost-effectiveness of investments, as used by some governments and companies (1.8.2).

Scenarios in the IPCC and AR6. For AR6, WG III received submissions of more than 2500 model-based scenarios published in the scientific literature. Such scenarios, which explore different possible evolutions of future energy and land use (with or without climate policy) and associated emissions, are made available through an interactive AR6 scenario database. The main characteristics of pathways in relation to 'net zero' emissions and remaining 'carbon budgets' are summarised in Box 3.5 in Chapter 3. The warming contribution of CO_2 is very closely related to cumulative CO_2 emissions, but the remaining 'carbon budget' for a given warming depends strongly *inter alia* on emissions of other GHGs; for targets below 2°C this may affect the corresponding 'carbon budget' by c. +/- 220GtCO_2, compared to central estimates of around 500GtCO_2 (for 1.5°C) and 1350GtCO_2 (for 2°C) (AR6 WGI, Table SPM.2; Cross-Working Group Box 1 in Chapter 3).

Pathways and 'net zero'. The date at which the world needs aggregate emissions to reach net zero for Paris-consistent temperature goals depends both on progress in reducing non-CO_2 GHG emissions and near-term progress in reducing CO_2 emissions. Faster progress in the near term extends the date at which net zero must be reached, while conversely, slower near-term progress brings the date even closer to the present. Some of the modelled 1.5°C pathways with limited overshoot cut global CO_2 emissions in half until 2030, which allows for a more gradual decline thereafter, reaching net zero CO_2 after 2050; also, net zero GHGs occurs later, with remaining emissions of some non-CO_2 GHGs compensated by 'net negative' CO_2 (see Annex I and FAQ 1.3, and Cross-Chapter Box 3 in Chapter 3).

Drawing from the scenarios database, five **Illustrative Mitigation Pathways' (IMPs)** were defined for this report (Figure 3.5 in Chapter 3 and Table 1.1). These are introduced here, with a more complete description and discussion provided in Section 3.2.5 of Chapter 3. These IMPs were chosen to illustrate key themes with respect to mitigation strategies across the entire WG III assessment. The IMPs embody both a storyline, which describes in narrative form the key socio-economic characteristics of that scenario, and a quantitative illustration providing numerical values that are internally consistent and comparable across chapters of this report. Quantitative IMPs can be associated directly with specific human activities and provide a quantitative point of reference that links activities in different parts of socioeconomic systems. Some parts of the report draw on these quantitative scenarios, whilst others use only the narratives. No assessment of the likelihood of each IMP has been made (as they reflect both human choice and deep uncertainty).

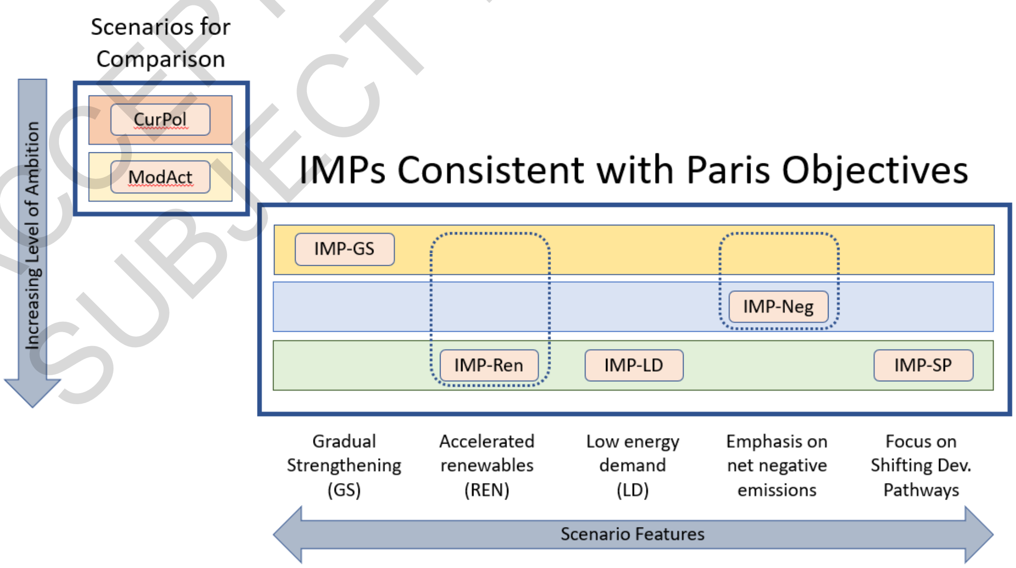

Figure 1.3 Illustrative Mitigation Pathways (IMPs) used in AR6 – illustration of key features and levels of ambition

The IMPs are organized around two dimensions: the *level of ambition* consistent with meeting Paris goals and the scenario features (Figure 1.4). The IMPs explore different pathways potentially consistent with meeting the long-term temperature goals of the Paris Agreement. As detailed in Section 3.2.5 of Chapter 3 and Chapter 4, a pathway of Gradual Strengthening of current policies (**IMP-*GS***) to 2030, if followed by very fast reductions, may stay below 2C. The **IMP-*NEG*** pathway, with somewhat deeper emission cutbacks to 2030, might enable 1.5C to be reached but only after significant overshoot, through the subsequent extensive use of CDR in the energy and the industry sectors to achieve net negative global emissions, as discussed in Chapters 3, 12, 7, 6, and 10.

Three other IMPs illustrate different features of technology scenarios with more short term rapid emission reductions, which could deliver outcomes compatible with the temperature range in the Paris agreement without large overshoot. Based on the assessment in Section 5.3.3 of Chapter 5, one key mitigation strategy would be to rely on the opportunities for reducing demand (**IMP-*LD***). Chapter 6 and the Chapter 7-11 show how energy systems based on accelerated deep renewable energy penetration and electrification can also provide a pathway to deep mitigation (**IMP-*REN***). Chapter 4, 17 and 3 provide insights how shifting development pathways can lead to deep emission reductions and achieve sustainable development goals (**IMP-*SP*)**.

These pathways can be implemented with different levels of ambition, that can be measured through the classes (C) of temperature levels from the scenarios database, see Chapter 3 (Table 3.2). In the IMP framework, Section 3.2.5 in Chapter 3 presents and explores quantitative scenarios that can limit warming to 1.5 °C (with a probability of 50% or greater, i.e., C1 for the illustrated quantification of LD, SP and REN, and C2 for NEG scenario), along with others GS pathway which keeps warming below 2°C with a probability of 67% or greater (C3). In addition to these primary IMPs, the full scenario database contains sensitivity cases that explore alternative warming levels.

In addition to the IMPs two additional scenarios were selected, which illustrate the consequences of current policies and pledges. Current Policies (***CurPol***) explores the consequences of continuing along the path of implemented climate policies in 2020 and only a gradual strengthening after that, drawing on numerous such scenarios in the literature. Moderate Action (***ModAct***) explores the impact of implementing NDCs to 2030, but without further strengthening; both results in global mean temperature above 2°C. They provide benchmarks against which to compare the IMPs.

Table 1.1 summarises the main storyline elements of the reference scenarios and each IMP.

Table 1.1 Illustrative Mitigation Pathways used in AR6

Scenarios			Full Name	Main Policy Characteristics
CurPol			Current Policies	Implementation of current climate *policies* (mostly as reported in NDCs), neglecting stated subsequent goals and objectives (e.g. for 2030); only gradual strengthening after 2030; Grey Covid recovery.
ModAct			Moderate Action	Implementation of current policies *and* achievement of 2030 NDCs, with further strengthening post-2030. Similarly to the situation implied by the diversity of NDCs (both policies and pledge), a fragmented policy landscape remains; mixed Covid recovery.
IMPs	**1.5/<2**	**GS**	Gradual Strengthening	Until 2030, primarily current NDCs are implemented; after that a strong, universal regime leads to coordinated and rapid decarbonisation actions.
		Neg	Net Negative Emissions	Successful international climate policy regime reduces emissions below ModAct or GS to 2030, but with a focus on the long-term temperature goal, negative emissions kick in at growing scales thereafter, so that mitigation in all sectors also includes a growing and ultimately large reliance on negative emissions, with large 'net global negative' after 2050 to meet 1.5C after significant overshoot
		Ren	Renewables	Successful international climate policy regime with immediate action particularly policies and incentives (including international finance) favouring renewable energy; Less emphasis on negative-emission technologies. Rapid deployment and innovation of renewables and systems; electrification of all end-use.
		LD	Low Demand	Successful international climate policy regime with immediate action on the demand side; policies and financial incentives favouring reduced demand that in turn leads to early emission reductions; this reduces the decarbonisation effort on the supply side.
		SP	Shifting Pathways	Successful international climate policy regime with a focus on additional SDG policies aiming, for example, at poverty reduction and broader environmental protection. Major transformations shift development towards sustainability and reduced inequality, including deep GHG emissions reduction.

What the IMPs do and don't do. The IMPs are, as their name implies, a set of scenarios meant to illustrate some important themes that run through the entire WGIII assessment. They illustrate that the climate outcomes that the individuals and society will face in the century ahead depend on individual and societal choices In addition, they illustrate that there are multiple ways to successful achievement of Paris long-term temperature goals.

IMPs are not intended to be comprehensive. They are not intended to illustrate all possible themes in this report. They do not, for example attempt to illustrate the range of alternative socioeconomic pathways against which efforts to implement Paris goals may be set, or to reflect variations in potential regional development pathways. They do not explore issues around income distribution or environmental justice, but assume implicitly that *where* and *how* action occurs can be separated from who pays, in ways to adequately address such issues. They are essentially pathways of technological evolution and demand shifts reflecting broad global trends in social choice. The IMPs do not directly assess issues of realization linked to the "drivers and constraints" summarized in our previous section, and the quantifications use, for the most part, models that are grounded mainly in the Aggregate Economics Frameworks (section 7.1). As such they reflect primarily the geophysical, economic and technological Dimensions of Assessment, but can be assessed in relation to the full set of Feasibility criteria (section 1.8.1).

Together the IMPs provide illustrations of potential future developments that can be shaped by human choices, including: Where are current policies and pledges leading? What is needed to reach specific temperature goals under varying assumptions? What are the consequences of different strategies to meet climate targets (i.e. demand-side strategy, a renewable energy strategy or a strategy with a role for net negative emissions)? What are the consequences of delay? What are the implications for other SDGs of various climate mitigation pathways?

1.6 Achieving mitigation in the context of sustainable development

This chapter now sets out approaches to understanding the mitigation challenge, working from its broad location in the context of wider aspirations for sustainable development, then identifying specific analytic approaches, before summarising the corresponding main dimensions used for assessment of options and pathways in much of the report.

1.6.1 The Climate Change and Development Connection

Climate change mitigation is one of many goals that societies pursue in the context of sustainable development, as evidenced by the wide range of the Sustainable Development Goals (SDGs). Climate change and sustainable development as well as development more broadly, are interwoven along multiple and complex lines of relationship (Fankhauser 2016; Gomez-Echeverri 2018a; Okereke and Massaquoi 2017; Okereke et al. 2009), as highlighted in several previous IPCC reports (IPCC 2007, 2019a, 2018b, 2011a, 2014a). With its significant negative impact on natural systems, food security and infrastructure, loss of lives and territories, species extinction, conflict health, among several other risks, climate change poses a serious threat to development and wellbeing in both rich and poor countries (IPCC 2019b, 2018b, 2007, 2011a, 2014a). Without serious efforts at mitigation and adaptation, climate change could push millions further into poverty and limit the opportunities for economic development (Chapter 4 and 17). It follows that ambitious climate mitigation is necessary to secure a safe climate within which development and wellbeing can be pursued and sustained.

At the same time, rapid and largescale economic development (which has in the past driven climate change through land use change and dependence on fossil fuels), is widely seen as needed to improve global wellbeing and lift millions especially in low- and middle-income countries out of poverty (Baarsch et al. 2020; Lu et al. 2019; Mugambiwa and Tirivangasi 2017; Chen et al. 2017; See Figure

1.6). This strand of literature emphasises the importance of economic growth including for tackling climate change itself, pointing to the relationship between economic development and climate resilience as well as the role of industry-powered technologies such as electric vehicles in reducing GHG levels and promoting wellbeing (Heinrichs et al. 2014; Kasztelan 2017). Yet, others argue that the character of social and economic development produced by the nature of capitalist society (Pelling and Manuel-Navarrete 2011; Koch 2012; Malm 2016) is ultimately unsustainable.

There are at least two major implications of the very close link between climate change and development as outlined above. The first is that the choice of development paths made by countries and regions have significant consequences for GHG emissions and efforts to combat climate change (see Chapters 2, 3, 4, 5, and 14). The second is that climate mitigation at local, national and global level cannot be effectively achieved by a narrow focus on 'climate-specific' sectors, actors and policies; but rather through a much broader attention to the mix of development choices and the resulting development paths and trajectories (see Chapter 4, 6, 10; O'Neill et al. 2014).

As a key staple of IPCC reports and global climate policy landscape (Gidden et al. 2019; Quilcaille et al. 2019; van Vuuren et al. 2017; IPCC 2014b, 2007; see also Chapter 2), integrated assessment models and global scenarios (such as the "Shared Socio-Economic Pathways" – SSPs) highlight the interaction between development paths, climate change and emission stabilisation (see Section 3.6 in Chapter 3). The close links are also recognised in the PA (section 1.3.1).

The impact of climate change in limiting wellbeing is most acutely felt by the world's poorest people, communities, and nations, who have the smallest carbon footprint, constrained capacity to respond and limited voice in important decision-making circles (Okereke and Ehresman 2015; Tosam and Mbih 2015; Mugambiwa and Tirivangasi 2017). The wide variation in the contribution to, and impact of climate change within and across countries makes equity, inequality, justice, and poverty eradication, inescapable aspects of the relationship between sustainable development and climate change (Reckien et al. 2017; Okereke and Coventry 2016; Bos and Gupta 2019; Klinsky et al. 2017; Baarsch et al. 2020; Kayal et al. 2019; Diffenbaugh and Burke 2019). This underpins the conclusion as commonly expressed that climate action needs to be pursued in the context of sustainable development, equity and poverty eradication (Burton et al. 2001; Smit et al. 2001; Klinsky and Winkler 2014; Tschakert and Olsson 2005; IPCC 2014a, 2018b).

1.6.2 Concepts and frameworks for integrating climate mitigation and development:

At one level, sustainable development can be seen as a meta framework for integrating climate action with other global sustainability goals (Antal and Van Den Bergh 2016; Casadio Tarabusi and Guarini 2013). Fundamentally, the concept of sustainable development underscores the interlinkages and interdependence of human and natural systems and the need to balance economic, social, and environmental (including climate pollution) aspects in development planning and processes (Nunan 2017; Gomez-Echeverri 2018b; Zhenmin and Espinosa 2019).

Despite the appeal of the concept, tensions remain over the interpretation and practical application, with acute disagreements regarding what the balancing entails in real life, how to measure wellbeing, which goals to set, and the means through which such goals might be pursued (Michelsen et al. 2016; Shang et al. 2019; Okereke and Massaquoi 2017; UNEP 2018b; Arrow et al. 2011; Dasgupta et al. 2015; Sugiawan et al. 2019; Haberl et al. 2019).

Moreover, countries differ enormously in their respective situation regarding their development path – a condition which affects their capability, goals, priorities and approach to the pursuit of sustainability (Ramos-Mejía et al. 2018; Okereke et al. 2019; Shi et al. 2016). Most of the literature recognises that despite its limitations, sustainable development with its emphasis on integrating social, economic and environmental goals, provides a more comprehensive approach to the pursuit of planetary health and human wellbeing. Sustainable development is then not a static objective but a dynamic framework for measuring human progress (Costanza et al. 2016; Fotis and Polemis 2018), relevant for all countries even if different groups of nations experience the challenge of sustainability in different ways.

Much like sustainable development, concepts like low-carbon development (Mulugetta and Urban 2010; Yuan et al. 2011; Wang et al. 2017; Tian et al. 2019), climate-compatible development (CCD) (Mitchell and Maxwell 2010; Tompkins et al. 2013; Stringer et al. 2014; Bickersteth et al. 2017) and more recently climate-resilient development (CRD) (Fankhauser and McDermott 2015; Henly-Shepard et al. 2018) (see IPCC SR 1.5 2018b) have all emerged as ideas, tools and frameworks, intended to bring together the goals of climate mitigation and the SDGs, as well as development more broadly. Figure 1.5 suggests that the prospects for realizing a climate-resilient and equitable world is enhanced by a process of transformation and development trajectories that seek to limit global warming while also achieving the SDGS. The SDGs represent medium-term goals, and long-term sustainability requires continued effort to keep the world along a climate resilient development path. A key feature of development or transformation pathways that achieve a climate resilient world is that they maximise the synergies and minimise the trade-offs between climate mitigation and other sustainable development goals (Dagnachew et al. 2018; Fuso Nerini et al. 2018; Thornton and Comberti 2017; Wüstemann et al. 2017; Mainali et al. 2018; Klausbruckner et al. 2016). Crucially, the nature of trade-offs and timing of related decisions will vary across countries depending on circumstances including the level of development, capability and access to resources (see Cross-chapter Box 5, Shifting Development Paths to increase Sustainability, in Chapter 4).

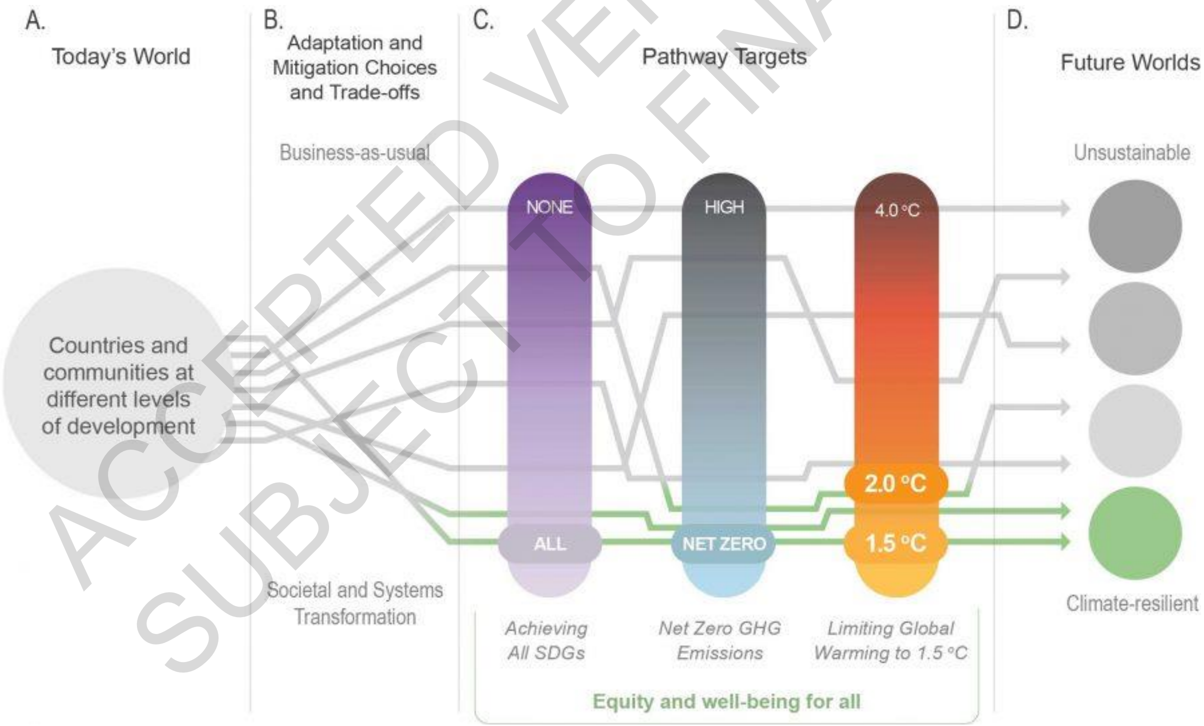

Figure 1.4: A climate-resilient and equitable world requires limiting global warming while achieving the SDGS.

Source: IPCC 2018b

Other concepts such as "Doughnut Economics" (Raworth 2018), ecological modernisation, and mainstreaming are also used to convey ideals of development pathways that take sustainability, climate mitigation, and environmental limits seriously (Dale et al. 2015a). Mainstreaming focuses on incorporating climate change into national development activities, such as the building of infrastructure (Wamsler and Pauleit 2016; Runhaar et al. 2018). The 'green economy' and green growth – growth without undermining ecological systems, partly by gaining economic value from cleaner technologies and systems and is inclusive and equitable in its outcomes - has gained popularity in both developed and developing countries as an approach for harnessing economic growth to address environmental issues (Bina 2013; Georgeson et al. 2017; Capasso et al. 2019; Song et al. 2020; Hao et al. 2021). Critics however argue that green economy ultimately emphasises economic growth to the detriment of other important aspects of human welfare such as social justice (Adelman 2015; Death 2014; Kamuti 2015), and challenge the central idea that it is possible to decouple economic activity and growth (measured as GDP increment) from increasing use of biophysical resources (raw materials, energy) (Jackson and Victor 2019; Parrique et al. 2019; Hickel and Kallis 2020; Haberl et al. 2020; Vadén et al. 2020).

Literature on degrowth, post growth, and post development questions the sustainability and imperative of more growth especially in already industrialised countries and argues that prosperity and the 'Good Life' are not immutably tied to economic growth (Escobar 2015; Asara et al. 2015; Kallis 2019; Latouche 2018; see also Section 5.2.1 in Chapter 5). The concept of 'just transition' also stresses the need to integrate justice concerns so as to not impose hardship on already marginalised populations within and between countries (Goddard and Farrelly 2018; Smith, Jackie and Patterson 2018; McCauley and Heffron 2018; Evans and Phelan 2016; Heffron and McCauley 2018; see section 1.7.2). The key insight is that pursuing climate goals in the context of sustainable development requires holistic thinking including on how to measure well-being, serious consideration of the notion of ecological limits, at least some level of decoupling and certainly choices and decision-making approaches that exploit and maximise the synergy and minimises the trade-off between climate mitigation and other sustainable development goals. It also requires consideration of equity and justice within and between countries. However, ideas of a synergistic relationship between development and climate mitigation can sometimes offer limited practical guidelines for reconciling the tensions that are often present in practical policy making (Dale et al. 2015b; Ferguson et al. 2014; Kasztelan 2017; Kotzé 2018).

1.6.3 Climate Mitigation, Equity and the Sustainable Development Goals (SDGs)

Climate action can be conceptualised as both a stand-alone and cross-cutting issue in the 2030 SDGs (Makomere and Liti Mbeva 2018), given that several of the other goals such as ending poverty (Goal 1), zero hunger (Goal 2), good health and wellbeing (Goal 3), affordable and clean energy (Goal 7) among many others are related to climate change (see Figure 3.39 in Chapter 3).

In addition to galvanising global collective action, the SDGs provide concrete themes, targets and indicators for measuring human progress to sustainability (Kanie and Biermann 2017). The SDGs also provide a basis for exploring the synergies and trade-offs between sustainable development and climate change mitigation (Makomere and Liti Mbeva 2018; Mainali et al. 2018; Fuso Nerini et al. 2018; Pradhan et al. 2017). Progress to date (Sachs et al. 2016) shows fulfilling SDGs is a challenge for all groups of countries – developed and developing – even though the challenge differs between countries and regions (Pradhan et al. 2017).

Historically, the industrialisation associated with economic development has involved a strong relationship with GHG emissions (see Section 5.2.1 in Chapter 5). Figure 1.6 shows per capita GHG emissions on the vertical axis and Historical Index of Human Development (HIHD) levels (Prados de la Escosura 2015) on the horizontal axis.[7] The grey line shows historic global average GHG emissions

FOOTNOTE[7] The Historical Index of Human Development (HIHD) emulates the widely used Human Development Index (HDI) as they both summarise in indexes, key human development dimensions consisting of a healthy life, knowledge and a decent standard of living. HDI is based on: life expectancy, expected years of per capita and levels of human development over time, from 1870 to 2014. The current position of different regions are shown by bubbles, with sizes representing total GHG emissions. Figure 1.6 also shows the estimated position of the SDGs zone for the year 2030, and a "sustainable development corridor" as countries reach towards higher HDI and lower emissions. To fulfil the SDGs, including SDG 13 climate action, the historic relationship needs to change.

The top of the SDG zone is situated around the global per capita GHG emissions level of 5 tonnes CO_2eq required for the world to be path towards fulfilling the Paris Agreement.[8] The horizontal position of the SDG zone is estimated based on the HIHD levels (Prados de la Escosura 2015) of countries that have been shown to either have achieved, or have some challenges, when it comes to SDG 3, SDG 4 and SDG 8 (Sachs et al. 2016); as these SDGs are related to the constituent parts of the HIHD. Beyond 2030, the sustainable development corridor allows for increasing levels of human development while lowering per capita GHG emissions.

Figure 1.6 shows that at present, regions with HIHD levels of around 0.5 all have emissions at or above about 5tCO_2eq per-capita (even more so on a consumption footprint basis, see Figure 1.1c,d), but there are wide variations within this. Indeed, there are regions with HIHD levels above 0.8 which have GHG per-capita emissions lower than several with HIHD levels of around 0.5. The mitigation challenge involves countries at many different stages of development seeking paths towards higher welfare with low emissions.

From Figure 1.6, there are two distinct dimensions to sustainable development pathways for fulfilling the SDGs. In terms of per-capita GHG emissions (the vertical), some regions have such low levels that they could increase and still be below the global average required in 2030 for the world to be on path to fulfil the Paris Agreement. Meanwhile other regions with high per capita GHG emissions would require a rapid transformation in technologies and practices. It is against this background that Dubash (2019) emphasises placing the need for urgent action on climate change in the context of domestic political priorities and the institutions within which national frameworks are crystallised.

Concerns over equity in the context of growing global inequality and very tight remaining global carbon budgets have motivated an emphasis on equitable access to sustainable development (Peters et al. 2015; Kartha et al. 2018b; Matthews et al. 2019; van den Berg et al. 2019). This literature emphasises the need for less developed countries to have sufficient room for development while addressing climate change (Pan et al. 2014; Winkler et al. 2013; Gajevic Sayegh 2017; Warlenius 2018; Robinson and Shine 2018). Meanwhile, many countries reliant on fossil fuels, related technologies and economic activities are eager to ensure tax revenues are maintained, workers and industries have income and justice is embedded in the economic transformations required to limit GHG emissions (Cronin et al. 2021).

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schooling of children, the mean years of schooling of the adult population, and GNI per capita adjusted for purchasing power; the HIHD is based on: life expectancy at birth, adult literacy rates, educational enrolment rates, and GDP per capita, and is used in Figure 1.6 because it is available for a longer time series (Prados de la Escosura 2015).

FOOTNOTE[8] Based on global population projections of between 8 and 8.5 billion people in 2030, and GHG emissions levels from the C1, C2 and C3 categories of scenarios in Table 3.2 and Box 3.7 in Chapter 3.

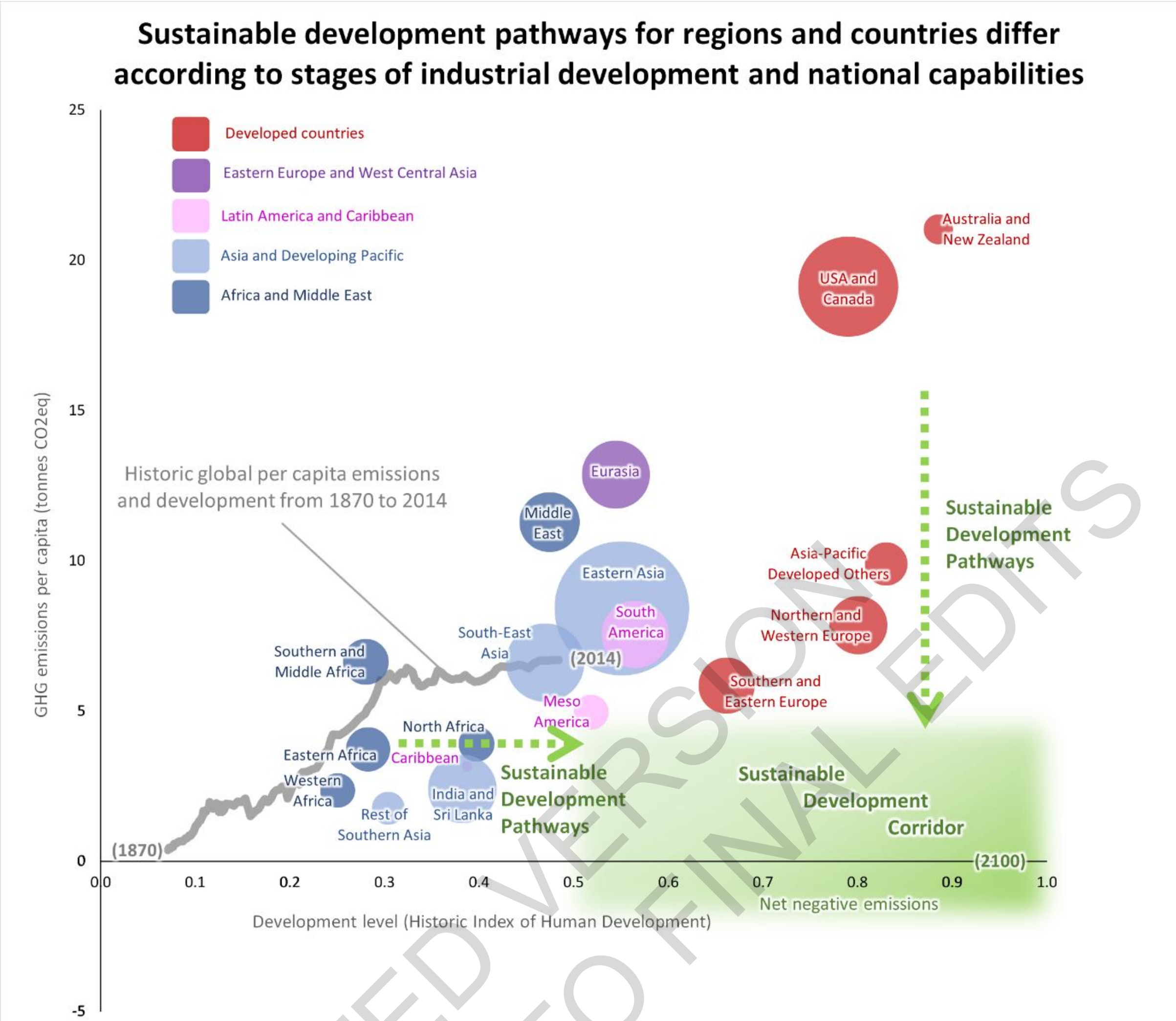

Figure 1.5: Sustainable development pathways towards fulfilling the SDGs.

The graph shows global average per capita GHG emissions (vertical axis) and relative "Historic Index of Human Development" (HIHD) levels (horizonal) have increased globally since the industrial revolution (grey line). The bubbles on the graph show regional per capita GHG emissions and human development levels in the year 2015, illustrating large disparities. Pathways towards fulfilling the Paris Agreement (and SDG 13) involve global average per capita GHG emissions below about 5 tCO_2e by 2030. Likewise, to fulfil SDGs 3, 4 and 8, HIHD levels (see footnote 7) need to be at least 0.5 or greater. This suggests a 'sustainable development zone' for year 2030 (in green); the in-figure text also suggests a sustainable development corridor, where countries limit per capita GHG emissions while improving levels of human development over time. The emphasis of pathways into the sustainable development zone differ (green arrows) but in each case transformations are needed in how human development is attained while limiting GHG emissions.

Correlation between CO_2 emission intensity, or absolute emission and gross domestic product growth, is not rigid, unambiguous and deterministic (Ojekunle et al. 2015), but the extent to which SDGs and economic growth expectations can be fulfilled while decoupling GHG emissions remains a concern (Hickel and Kallis 2020; Haberl et al. 2020). Below some thresholds of absolute poverty, more consumption is necessary for development to lead to well-being (see Section 5.2.1.1 in Chapter 5), which may not be the case at higher levels of consumption (Steinberger et al. 2020; Lamb and Steinberger 2017; Section 1.7.2).

In conclusion, achieving climate stabilisation in the context of sustainable development and efforts to eradicate poverty requires collective action and exploiting synergies between climate action and sustainable development, while minimising the impact of trade-offs (Najam 2005; Makomere and Liti Mbeva 2018; Okereke and Massaquoi 2017; Dooley et al. 2021). It also requires a focus on equity considerations to avoid climate induced harm, as well as unfairness that can result from urgent actions to cut emissions (Kartha et al. 2018a; Robiou du Pont et al. 2017; Pan et al. 2014). This is ever more important as the diminishing carbon budget has intensified debates on which countries should have the greatest claim to the 'remaining space' for emissions (Raupach et al. 2014) or production (McGlade and Ekins 2015),amplified by persistent concerns over the insufficiency of support for means of implementation, to support ambitious mitigation efforts (Pickering et al. 2015; Weikmans and Roberts 2019).

1.7 Four Analytic Frameworks for understanding mitigation response strategies

Climate change is unprecedented in its scope (sectors, actors and countries), depth (major transformations) and timescales (over generations). As such, it creates unique challenges for analysis. It has been called "the greatest market failure in history" (Stern 2007); the Perfect Moral Storm (Gardiner 2006) and a "super wicked problem" (Lazarus 2009; Levin et al. 2012) - one which appears difficult to solve through the traditional tools and assumptions of social organisation and analysis.

To complement the extensive literature on risks and decision-making under uncertainty reviewed in AR6-WGII (notably, Chapter 19), this section summarises insights and developments in key analytic frameworks and tools particularly relevant to understanding specific mitigation strategies, policies and other actions, including explaining the observed if limited progress to date. Organised partly as reflected in the quotes above, these include *aggregated* (principally, economic) frameworks to evaluate system-level choices; *ethical* perspectives on values and equity including stages of development and distributional concerns; and *transition* frameworks which focus on the processes and actors involved in major technological and social transitions. These need to be complemented by a fourth set of approaches which shine more light on *psychological/behavioural and political* factors. All these frameworks are relevant, and together they point to the multiple perspectives and actions required if the positive drivers of emission reduction summarised in section 4 are to outweigh the barriers and overcome the constraints.

1.7.1 Aggregated approaches: economic efficiency and global dynamics of mitigation

Some of the most established and influential approaches to understand *aggregate* causes and consequences of climate change and mitigation across societies, draw upon economic theories and modelling to generate global emission pathways in the absence of climate policies (a reference) and to study alternative mitigation pathways (described in detail in Section 3.2.5 in Chapter 3). The underlying economic concepts aggregate wealth or other measures of welfare based on utilitarian ethical foundations, and in most applications, a number of additional assumptions detailed in AR5 (Chapters 2 and 3).

1.7.1.1 Cost-benefit and cost-effectiveness analysis

Such global aggregate economic studies coalesce around two main questions. One, as pioneered by Nordhaus (1992; 2008) attempts to monetize overall climate damages and mitigation costs so as to strike a 'cost-benefit optimum' pathway. More detailed and empirically-grounded 'cost-effectiveness analysis' explores pathways that would minimise mitigation costs (IPCC 2014a section 2.5; Ekholm 2014; Weyant 2017) for given targets (e.g. as agreed in international negotiations, see Section 3.2 in Chapter 3). Both approaches recognise that resources are limited, and climate change competes with other priorities in government policymaking, and are generally examined with some form of Integrated Assessment Model (IAMs: see 1.5, and Appendix C). Depending on the regional disaggregation of the modelling tools used and on the scope of the analyses, these studies may or may not address distributional aspects within and across nations associated with climate policies (Bauer et al. 2020).

For at least 10-15 years after the first computed global cost-benefit estimate (Nordhaus 1992), the dominant conclusions from these different approaches seemed to yield very different recommendations, with cost-benefit studies suggesting lenient mitigation compared to the climate targets typically recommended from scientific risk assessments (Weyant 2017). Over the past 10-15 years, literature has made important strides towards reconciling these two approaches, both in the analytic methods and the conclusions arising.

Damages and risks Incorporating impacts which may be extremely severe but are uncertain (known as "fat tails" (Weitzman 2009, 2011), strengthens the economic case for ambitious action to avoid risks of extreme climate impacts (Ackerman et al. 2010; Dietz and Stern 2015; Fankhauser et al. 2013). The salience of risks has also been amplified by improved understanding of climate 'tipping points' (Lontzek et al. 2015; Lenton et al. 2019); valuations should reflect that cutting emissions reduces not only average expected damages, but also the risk of catastrophic events (IWG 2021).

Discounting. The role of time-discounting, in weighting future climate change impacts against today's costs of mitigating emissions, has been long recognised (Weitzman 1994, 2001; Nordhaus 2007; Dasgupta 2008; Stern 2007). Its importance is underlined in analytical Integrated Assessment Models (IAMs) (Golosov et al. 2014; van der Ploeg and Rezai 2019; van den Bijgaart et al. 2016); also Annex III. Economic literature suggests applying risk-free, public, and long-term interest rates when evaluating overall climate strategy (Arrow et al. 2013; Groom and Hepburn 2017; Weitzman 2001; Dasgupta 2008). Expert elicitations indicate values around 2% (majority) to 3% (Drupp et al. 2018). This is lower than in many of the studies reviewed in earlier IPCC Assessments, and many IAM studies since, and by increasing the weight accorded to the future would increase current 'optimal effort'. The U.S. Interagency Working Group on the Social Cost of Carbon used 3% as its central value (IAWG 2016; Li and Pizer 2018; Adler et al. 2017). Individual projects may require specific risk adjustments.

Distribution of impacts. The economic damages from climate change at the nationally aggregated and subnational level are very diverse (Moore et al. 2017; Ricke et al. 2018; Carleton et al. 2020). A 'global damage function' necessarily implies aggregating impacts across people and countries with different levels of income, and over generations, a process which obscures the strategic considerations that drive climate policy making (Keohane and Oppenheimer 2016). Economics acknowledges there is no single, objectively-defined such 'social welfare function' (IPCC 1995, 2014a). This applies also to distribution of responses; both underline the relevance of equity (next section) and global negotiations to determine national and collective objectives.

Obvious limitations arise from these multiple difficulties in assessing an objective, globally-acceptable single estimate of climate change damages (e.g. Pindyck 2013; Arrow et al. 2013; Auffhammer 2018; Stern et al. 2021), with some arguing that agreement on a specific value can never be expected (Rosen and Guenther 2015; Pezzey 2018). A new generation of cost-benefits analysis, based on projections of actual observed damages, result in stronger mitigation efforts as optimal (Glanemann et al. 2020; Hänsel et al. 2020). Overall the combination of improved damage functions with the wider consensus on low discount rates (as well as lower mitigation costs due to innovation) has increasingly yielded 'optimal' results from benefit-cost studies in line with the range established in the Paris Agreement (see Cross-Working-Group Box 1 in Chapter 3).

Hybrid cost-benefit approaches that extend the objective of the optimisation beyond traditional welfare, adding some form of temperature targets as in (Llavador et al. 2015; Held 2019) also represent a step in bridging the gap between the two approaches and result in proposed strategies much more in line with those coming from the cost-effectiveness literature. Approaching from the opposite side, cost-effectiveness studies have looked into incorporating benefits from avoided climate damages, to improve the assessment of net costs (Drouet et al. 2021).

Cost-benefit IAMs utilise damage functions to derive a social cost of CO_2 emissions' (SCC - the additional cost to society of a pulse of CO_2 emissions). One review considered "the best estimate" of the optimal [near-term] level "still ranges from a few tens to a few hundreds of dollars per ton of carbon (Tol 2018)", with various recent studies in the hundreds, taking account of risks (Taconet et al. 2019), learning (Ekholm 2018) and distribution (Ricke et al. 2018). In addition to the importance of uncertainty/risk, aggregation, and realistic damage functions as noted, on which some progress has been made, some reviews additionally critique how IAMs represent abatement costs in terms of energy efficiency and innovation (e.g. Rosen and Guenther 2015; Farmer et al. 2015; Keen 2021); see also 1.7.3 and 1.7.4. IAMs may better reflect associated 'rebound' at system level (Saunders et al. 2021), and *inefficient implementation* would raise mitigation costs (Homma et al. 2019); conversely, ***co-benefits*** – most extensively estimated for air-quality, valued at a few tens of USD/tCO_2 across sixteen studies (Karlsson et al. 2020) - complement global with additional local benefits (see alsoTable 1.2).

Whereas many of these factors affect primarily cost-benefit evaluation, discounting also determines the cost-effective trajectory: Emmerling et al. (2019) find that, for a remaining budget of 1000$GtCO_2$, reducing the discount rate from 5% to 2% would more than double current efforts, limit 'overshoot', greatly reduce a late rush to negative emissions, and improve intergenerational justice by more evenly distributing policy costs across the 21st century.

1.7.1.2 Dynamic efficiency and uncertainty

Care is required to clarify what is optimised (Dietz and Venmans 2019). Optimising a path towards a given temperature goal *by a fixed date* (e.g. 2100) gives time-inconsistent results backloaded to large, last-minute investment in carbon dioxide removal. 'Cost-effective' optimisations generate less initial effort than *equivalent* cost-benefit models (Gollier 2021; Dietz and Venmans 2019) as they do not incorporate benefits of reducing impacts earlier.

'Efficient pathways' are affected by inertia and innovation. Inertia implies amplifying action on long-lived investments and infrastructure that could otherwise lock in emissions for many decades (Vogt-Schilb et al. 2018; Baldwin et al. 2020). Chapter 3 (section 3.5) discusses interactions between near, medium and long-term actions in global pathways, particularly *vis-à-vis* inertia. Also, to the extent that early action induces low carbon innovation, it 'multiplies' the optimal effort (for given damage assumptions), because it facilitates subsequent cheaper abatement. For example, a 'learning-by-doing' analysis concludes that early deployment of expensive PV was of net global economic benefit, due to induced innovation (Newbery 2018).

Research thus increasingly emphasises the need to understand climate transformation in terms of dynamic, rather than static, efficiency (Gillingham and Stock 2018). This means taking account of inertia, learning and various additional sources of 'path-dependence'. Including induced innovation in stylised IAMs can radically change the outlook (Acemoglu et al. 2012, 2016), albeit with limitations (Pottier et al. 2014); many more detailed-process IAMs now do include endogenous technical change (as reviewed in Yang et al. (2018) and Grubb et al. (2021b); also Annex III).

These dynamic and uncertainty effects typically justify greater up-front effort (Kalkuhl et al. 2012; Bertram et al. 2015), including accelerated international diffusion (Schultes et al. 2018), and strengthen optimal initial effort in cost-benefit models (Grubb et al. 2021b; Baldwin et al. 2020). Approaches to risk premia common in finance would similarly amplify the initial mitigation effort, declining as uncertainties reduce (Daniel et al. 2019).

1.7.1.3 Disequilibrium, complex systems and evolutionary approaches

Other approaches to aggregate evaluation draw on various branches of intrinsically non-equilibrium theories (e.g. Chang 2014). These including long-standing theories from the 1930s (e.g. Schumpeter 1934a; Keynes 1936) to understand situations of structurally under-employed resources, potential financial instabilities (Minsky 1986), and related economic approaches which emphasise time dimensions (e.g. recent reviews in Legrand and Hagemann 2017; Stern 2018). More recently developing have been formal economic theories of endogenous growth building on eg. Romer (1986), and developments of Schumpeterian creative destruction (Aghion et al. 2021) and evolutionary economic theories which abandon any notion of full or stable resource utilisation even as a reference concept (Nelson and Winter 1982; Freeman and Perez 1988; Carlsson and Stankiewicz 1991; Perez 2001; Freeman and Louçã 2001).

The latter especially are technically grounded in complex system theories (e.g. Arthur 1989, 1999; Beinhocker 2007; Hidalgo and Hausmann 2009). These take inherently dynamic views of economies as continually evolving systems with continuously unfolding and path-dependent properties, and emphasise uncertainty in contrast to any predictable or default optimality. Such approaches have been variously applied in policy evaluation (Walton 2014; Moore et al. 2018), and specifically for global decarbonisation (e.g. Barker and Crawford-Brown 2014) using global simulation models. Because these have no natural reference 'least lost' trajectory, they illustrate varied and divergent pathways and tend to emphasise the diversity of possibilities and relevant policies, particularly linked to innovation and potentially 'sensitive intervention points' (Farmer et al. 2019; see also section 1.7.3). They also illustrate that different representations of innovation and financial markets together can explain why estimated impacts of mitigation on GDP can differ very widely (potentially even in sign), between different model types (Chapter 15, Section 15.6.3 and Box 15.7).

1.7.2 Ethical approaches

Gardiner's (2011) description of climate change as "The Perfect Moral Storm" identified three 'tempests'. Its *global* dimension, in a world of sovereign states which have only fragmentary responsibility and control, makes it 'difficult to generate the moral consideration and necessary political will'. Its impacts are *intergenerational* but future generations have no voice in contemporary affairs, the usual mechanism for addressing distributional injustices, amplified by the intrinsic inequity of wealthy big emitters impacting particularly poorer victims. He argues that these are exacerbated by a third, *theoretical* failure to acknowledge a central need for 'moral sensitivity, compassion, transnational and transgenerational care, and other forms of ethical concern to rise to the surface' to help guide effective climate action. As noted in section 1.4.6, however, equity and ethics are both a driver of and constraint on mitigation.

1.7.2.1 Ethics and values

A large body of literature examines the critical role of values, ethics, attitudes, and behaviours as foundational frames for understanding and assessing climate action, sustainable development and societal transformation (IPCC WGIII IPCC 2014a chapter 3). Most of this work is offered as a counter point or critique to mainstream literature's focus on safe-guarding of economic growth of nations, corporations and individuals (Castree 2017; Gunster 2017). These perspectives highlight the dominance of economic utilitarianism in western philosophical thought as a key driver for unsustainable consumption and global environmental change (Hoeing et al. 2015; Popescu 2016).

Entrenching alternative values that promote deep decarbonisation, environmental conservation and protection across all levels of society is then viewed as foundational component of climate resilient and sustainable development and for achieving human rights, and a safe climate world (Jolly et al. 2015; Evensen 2015; Popescu 2016; Tàbara et al. 2019). The UN Human Rights Office of the High Commissioner has highlighted the potentially crucial role of human rights in relation to climate change (UNHCR 2018). While acknowledging the role of policy, technology, and finance, the 'managerialist' approaches that emphasise 'technical governance' and fail to challenge the deeper values that underpin societies may not secure the deep change required to avert dangerous climate change and other environmental challenges (Hartzell-Nichols 2014; Steinberger et al. 2020).

Social justice perspectives emphasise the distribution of responsibilities, rights, and mutual obligations between nations in navigating societal transformations (Patterson et al. 2018; Gawel and Kuhlicke 2017; Leach et al. 2018). Current approaches to climate action may fail to match what is required by science because they tend to circumvent constraints on human behaviour, especially constraints on economic interest and activity. Related literature explores governance models that are centred on environmental limits, planetary boundaries and the moral imperative to prioritise the poor in earth systems governance (Carley and Konisky 2020; Kashwan et al. 2020), with emphasis on trust and solidarity as foundations for global co-operation on climate change (Jolly et al. 2015). A key obstacle is that the economic interests of states tend to be stronger than the drivers for urgent climate action (Bain 2017).

Short-term interests of stakeholders is acknowledged to impede the reflection and deliberation needed for climate mitigation and adaptation planning (Hackmann 2016; Herrick 2018; Sussman et al. 2016; Schlosberg et al. 2017). Situationally appropriate mitigation and adaptation policies at both national and international level may require more ethical self-reflection (Herrick 2018), including self-transcendent values such as universalism and benevolence, and moderation which are positively related to pro-environmental behaviours (Howell and Allen 2017; Jonsson and Nilsson 2014; Katz-Gerro et al. 2015; Braito et al. 2017).

Another strong theme in the literature concerns recognition of interdependence including the intimate relationship between humans and the non-human world (Hannis 2016; Gupta and Racherla 2018; Howell and Allen 2017), with such ecological interdependence offered as an organising principle for enduring transformation to sustainability. A key policy implication of this is moving away from valuing nature only in market and monetary terms to strongly incorporating existential and non-material value of nature in natural resource accounting (Neuteleers and Engelen 2015; Himes-Cornell et al. 2018; Shackleton et al. 2017). There has been increasing attention on ways to design climate policy frameworks to help reconcile ecological virtue (with its emphasis on the collective) with and individual freedoms and personal autonomy (Kasperbauer 2016; Nash et al. 2017; Xiang et al. 2019). In such a framework, moderation, fairness, and stewardship are all understood and promoted as directly contributing to the 'Good Life'. Such approaches are deemed vital to counteract tendencies to 'free ride', and to achieve behavioural changes often associated with tackling climate change (Section 5.2.1 in Chapter 5).

Some literature suggests that attention to emotions, especially with regards to climate communication, could help societies and individuals act in ways that focus less on monetary gain and more on climate and environmental sustainability (Bryck and Ellis 2016; Chapman et al. 2017; Nabi et al. 2018; Zummo et al. 2020).

1.7.2.2 Equity and representation: international public choice across time and space

Equity perspectives highlight three asymmetries relevant for climate change (Okereke 2017; Okereke and Coventry 2016; 1.4.6). *Asymmetry in contribution* highlights different contributions to climate change both in historical and current terms, and apply both within and between states as well as between generations (Caney 2016; Heyward and Roser 2016). *Asymmetry in impacts* highlight the fact that the damages will be borne disproportionately across countries, regions, communities, individuals and gender; moreover, it is often those that have contributed the least that stand to bear the greatest impact of climate change (Shi et al. 2016; IPCC 2014a). *Asymmetry in capacity* highlights differences of power between groups and nations to participate in climate decision and governance, including capacity to implement mitigation and adaptation measures.

If attention is not paid to equity, efforts designed to tackle climate change may end up exacerbating inequities among communities and between countries (Heffron and McCauley 2018). The implication is that to be sustainable in the long run, mitigation involves a central place for consideration of justice, both within and between countries (Chapters 4, 14). Arguments that the injustices following from climate change are symptomatic of a more fundamental structural injustice in social relations, are taken to imply a need to address the deeper inequities within societies (Routledge et al. 2018).

Climate change and climate policies affect countries and people differently, with the poor likely to be more affected (1.6.1). Ideas of 'just transition' (outlined in 1.8.2.) often have a national focus in the literature, but also imply that mitigation should not increase the asymmetries between rich and poor countries, implying a desire for transitions which seek reduce (or at least avoid adverse) distributional affects. Thus, it comes into play in the timing of zero emissions (chapter 3 and 14). International climate finance in which rich countries finance mitigation and adaptation in poor countries is also essential for reducing the asymmetries between rich and poor countries (1.6.3 and chapter 15).

Equity across generations also matters, i.e., the distribution between the present and future generations. One aspect is discounting (1.7.1). Another approach has been to study the burdens on each generation following from the transition to low-carbon economies (IPCC 2014a chapter 3, Cross Working Group Box 3 in Chapter 12). Suggestions include shifting more investments into 'natural capital', so that future generations will inherit less physical capital but a better environment, or financing mitigation efforts today using governmental debt redeemed by future generations (Broome 2012; Heijdra et al. 2006; Karp and Rezai 2014; Hoel et al. 2019).

1.7.3 Transition and transformation processes

This report uses the term *transition* as the process, and *transformation* as the overall change or outcome, of large-scale shifts in technological, economic and social systems, called socio-technical systems in the innovation literature. Typically, new technologies, ideas and associated systems initially grow slowly in absolute terms, but may then 'take-off' in a phase of exponential growth as they emerge from a position of niche into mainstream diffusion, as indicated by the 'S-curve' growth in Figure 1.7 (lower panel). These dynamics arise from interactions between innovation (in technologies, companies and other organisations), markets, infrastructure and institutions, at multiple levels (Geels et al. 2017; Kramer 2018). Consequently, interdisciplinary perspectives are needed (Turnheim et al. 2015; Geels et al. 2016; Hof et al. 2020). Beyond aggregated economic perspectives on dynamics (1.7.1.2), these emphasise the multiple actors and processes involved.

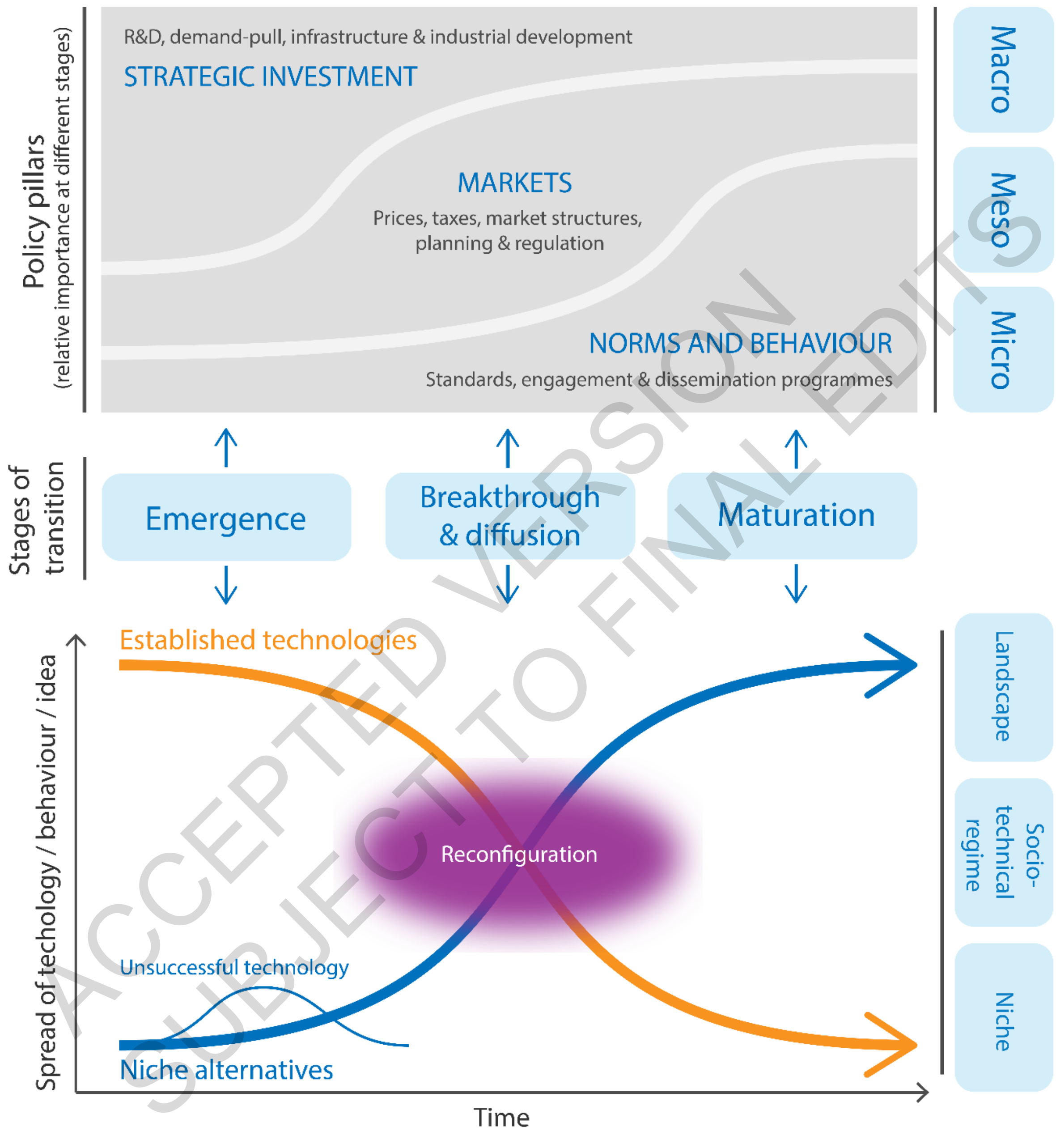

Figure 1.6: Transition dynamics: levels, policies and processes

Note: The lower panel illustrates growth of innovative technologies or practices, which if successful emerge from niches into an S-shape dynamic of exponential growth. The diffusion stage often involves new infrastructure and reconfiguration of existing market and regulatory structures (known in the literature as the "socio-technical regime"). During the phase of more widespread diffusion; growth levels off to linear, then slows as the industry and market matures. The processes displace incumbent technologies/practices which decline, initially slowly but then at an accelerating pace. Many related

literatures identify three main levels with different characteristics, most generally termed micro, meso and macro. Transitions can be accelerated by policies appropriately targeted, which may be similarly grouped and sequenced (upper panel) in terms of corresponding three pillars of policy (Section 1.7.3); generally all are relevant, but their relative importance differs according to stage of the transition.

Technological Innovation Systems (TIS) frameworks (chapter 16.4) focus on processes and policies of early innovation and 'emergence', which combine experimentation and commercialisation, involving *Strategic Niche Management* (Rip and Kemp 1998; Geels and Raven 2006). Literatures on the wider processes of transition highlight different stages (eg. Cross-Chapter box 12 in Chapter 16) and scales across three main levels, most generally termed *micro, meso and macro* (Rotmans et al. 2001).

The widely-used '*Multi-Level Perspective'* or MLP (Geels 2002) identifies the meso-level as the established 'socio-technical (ST) regime', an set of interrelated sub-systems which define rules and regulatory structures around existing technologies and practices. The micro level is an ecosystem of varied niche alternatives, and overlaying the ST regime is a macro 'landscape' level. Transitions often start with niche alternatives (Köhler et al. 2019; Grin et al. 2010), which may break through to wider diffusion (second stage in Figure 1.8), especially if external landscape developments 'create pressures on the regime that lead to cracks, tensions and windows of opportunity' (Geels 2010; Rotmans et al. 2001); an example is climate change putting sustained pressure on current regimes of energy production and consumption (Kuzemko et al. 2016). There are continual interactions between landscape, regime and niches, with varied implications for *Transition Management* (Loorbach 2010; Rotmans et al. 2001).

In contrast to standard economic metrics of marginal or smooth change (e.g. elasticities), transition theories emphasise interdisciplinary approaches and the non-linear dynamics, social, economic and environmental aspects of transitions to sustainability (Köhler et al. 2018; Cherp et al. 2018). This may explain persistent tendencies to underestimate the exponential pace of change now being observed in renewable electricity (Chapters 2, 6) and emerging in mobility (Chapter 10).

Recent decades have seen parallel broadening of economic perspectives and theories. Building also on the New Institutional Economics literatures (Williamson 2000), Grubb et al. (2015) classify these into three 'domains of economic decision-making' associated with different branches of economic theory, respectively (1) *behavioural and organisational*; (2) *neoclassical and welfare*, and (3) *evolutionary and institutional*. Like MLP, these are related to different social and temporal scales, as applied also in studying the 'adaptive finance' in UK electricity transition (Hall et al. 2017). There are significant differences but these approaches all point to understanding the characteristics of different actors, notably, individuals/local actors; larger corporate organisations (public or private); and (mainly) public authorities, each with different decision-making characteristics.

Sustainability may require purposeful actions at the different levels to foster the growth of sustainable technologies and practices, including support for niche alternatives (Grin et al. 2010). The middle level (established 'socio-technical regime') tends to resist major change, reforms generally involve pressures from the other two levels. Thus, transitions can be accelerated by policies appropriately targeting relevant actors at the different levels (Köhler et al. 2019), the foundations for "three pillars of policy" (Grubb et al. 2014), which logically evolve in the course of transition (Figure 2.6a). Incumbent industries have to adapt if they are to thrive within the growth of new systems. Policy may need to balance existing socio-technical systems with strategic investment and institutional development of the emerging niches (e.g. the maintenance of energy provision and energy security with the development of renewables), and help manage declining industries (Koasidis et al. 2020).

There is usually a social dimension to such transitions. Key elements include capacity to transform (Folke et al. 2010), planning, and interdisciplinarity (Woiwode 2013). The Second World War demonstrated the extent to which crises can motivate (sometimes positive) change across complex social and technical systems, including industry, and agriculture which then doubled its productivity over 15 years (Roberts and Geels 2019b). In practice, climate change may involve a combination of (reactive) transformational adaptation, and (proactive) societal transformation (Feola 2015), the latter seen as reorientation (including values and norms) in a sustainable direction (Section 5.4 in Chapter 5), including eg. 'democratisation' in energy systems (Sorman et al. 2020). Business change management principles could be relevant to support positive social change (Stephan et al. 2016). Overall, effective transitions rest on appropriate enabling conditions, which can also link socio-technical transitions to broader development pathways (Cross-Chapter Box 12 in Chapter 16).

Transition theories tend to come from very different disciplines and approaches compared to either economics or other social sciences, with less quantification, notwithstanding evolutionary and complex system models (1.7.1.3). However, a few distinct types of quantitative models of 'socio-technical energy transition' (Li et al. 2015) have emerged. For policy evaluation, transitions can be viewed as processes in which dynamic efficiency (1.7.2) dominates over static allocative efficiency, with potential 'positive intervention points' (Farmer et al. 2019). Given inherent uncertainties, there are obvious risks (e.g. Alic and Sarewitz 2016). All this may make an evaluation framework of *risks and opportunities* more appropriate than traditional cost-benefit (Mercure et al. 2021), and (drawing on lessons from renewables and electric vehicles), create foundations for sector-based international 'positive sum cooperation' in climate mitigation (Sharpe and Lenton 2021).

1.7.4 Approaches from psychology and politics of changing course

The continued increase in global emissions to 2019, despite three decades of scientific warnings of ever-greater clarity and urgency, motivates growing attention in the literature to the psychological 'faults of our rationality' (Bryck and Ellis 2016), and the political nature of climate mitigation.

1.7.4.1 Psychological and behavioural dimensions

AR5 emphasised that decision processes often include both deliberate ('calculate the costs and benefits') and intuitive thinking, the latter utilising emotion- and rule-based responses that are conditioned by personal past experience, social context, and cultural factors (e.g. Kahneman 2003), and that laypersons tend to judge risks differently than experts - for example, 'intuitive' reactions are often characterised by biases to status quo and aversion to perceived risks and ambiguity (Kahneman and Tversky 1979). Many of these features of human reasoning create 'psychological distance' from climate change (Spence et al. 2012; Marshall 2014). These can impede adequate personal responses, in addition to the collective nature of the problem, where such problems can take the form of 'uncomfortable knowledge', neglected and so becoming 'Unknown knowns' (Sarewitz 2020).These decision processes, and the perceptions that shape them, have been studied through different lenses from psychology (Weber 2016) to sociology (Guilbeault et al. 2018), and media studies (Boykoff 2011). Karlsson and Gilek (2020) identify science denialism and 'decision thresholds' as key mechanisms of delay.

Experimental economics (Allcott 2011) also helps explain why cost-effective energy efficiency measures or other mitigation technologies are not taken up as fast or as widely as the benefits might suggest, including procrastination and inattention, as "we often resist actions with clear long-term benefits if they are unpleasant in the short run." (Allcott and Mullainathan 2010). Incorporating behavioural and social dynamics in models is required particularly to better represent the demand side (Nikas et al. 2020), eg. Safarzyńska (2018) demonstrates how behavioural factors change responses to carbon pricing relative to other instruments. A key perspective is to eschew 'either/or' between economic and behavioural frameworks, as the greatest effects often involve combining behavioural dimensions (e.g. norms, social influence networks, convenience and quality assurance) with financial incentives and information (Stern et al. 2010). Randomised, controlled field trials can help predict the effects of behavioural interventions (Levitt and List 2009; McRae and Meeks 2016; Gillan 2017). Chapter 5 explores both positive and negative dimensions of behaivour in more depth, including the development of norms and interactions with the wider social context, with emphasis upon the services associated with human wellbeing, rather than the economic activities per se.

1.7.4.2 Socio-political and institutional approaches

Political and institutional dynamics shape climate change responses in important ways, not least because incumbent actors have frequently blocked climate policy (1.4.5). Institutional perspectives probe networks of opposition (Brulle 2019) and emphasise that their ability to block - as well as the ability of others to foster low carbon transitions - are structured by specific institutional forms across countries (Lamb and Minx 2020). National institutions have widely been developed to promote traditionally fossil-fuel based sectors like electricity and transport as key to economic development, contributing to carbon lock-in (Seto et al. 2016) and inertia (Rosenschöld et al. 2014).

The influence of interest groups on policy-making varies across countries. Comparative political economy approaches tend to find that countries where interests are closely coordinated by governments ('coordinated market economies') have been able to generate transformative change more than those with a more arms-length, even combative relationship between interest groups and governments ('liberal market economies') (Lachapelle and Paterson 2013; Meckling 2018; Ćetković and Buzogány 2016; Zou et al. 2016). 'Developmental states' often have the capacity for strong intervention but any low-carbon interventions may be overwhelmed by other pressures and very rapid economic growth (Wood et al. 2020a).

Institutional features affecting climate policy include levels and types of democracy (Povitkina 2018), electoral systems, or levels of institutional centralisation (federal vs unitary states, presidential vs parliamentary systems) (Steurer and Clar 2018; Clulow 2019; Lachapelle and Paterson 2013). Countries that have constructed an overarching architecture of climate governance institutions (e.g. cross-department and multilevel coordination, and semi-autonomous climate agencies), are more able to develop strategic approaches to climate governance needed to foster transformative change (Dubash 2021).

Access of non-governmental organisations (NGOs) to policy processes enables new ideas to be adopted, but too close an NGO-government relation may stifle innovation and transformative action (Dryzek et al. 2003). NGO campaigns on fracking (Neville et al. 2019) or divestment (Mangat et al. 2018) have raised attention to ideas such as 'stranded assets' in policy arenas (Piggot 2018; Newell et al. 2020; Paterson 2021; Green 2018). Attempts to depoliticise climate change may narrow the space for democratic participation and contestation, thus impacting policy responses (Swyngedouw 2010, 2011; Kenis and Lievens 2014). Some institutional innovations have more directly targeted enhanced public deliberation and participation, notably in citizens' climate assemblies (Howarth et al. 2020) and in the use of legal institutions to litigate against those opposing climate action (Peel and Osofksy 2020). This literature shows that transformative pathways are possible within a variety of institutional settings, although institutional innovation will be necessary everywhere to pursue zero carbon transitions; see also Chapters 4 (Section 4) and 13.

Balancing the forces outlined in Section 4.6 in Chapter 4 typically involves building coalitions of actors who benefit economically from climate policy (Levin et al. 2012). Policy stability is critical to enabling long-term investments in decarbonisation (Rietig and Laing 2017; Rosenbloom et al. 2018). Policy design can encourage coalitions to form, that sustain momentum by supporting further policy development to accelerate decarbonisation (Roberts et al. 2018), for example by generating concentrated benefits to coalition members (Millar et al. 2020; Bernstein and Hoffmann 2018; Meckling 2019), as with renewable feed-in-tariffs (FiTs) in Germany (Michaelowa et al. 2018). Coalitions may also be sustained by overarching framings, especially to involve actors (e.g. NGOs) for whom the benefits of climate policy are not narrowly economic. However policy design can also provoke coalitions to oppose climate policy, as in the FiT programme in Ontario (Stokes 2013; Raymond 2020) or the yellow vest protests against carbon taxation in France (Berry and Laurent 2019). The 'just transitions' frame can thus also be understood in terms of coalition-building, as well as ethics, as the pursuit of low carbon transitions which spread the economic benefits broadly, through 'green jobs', and the redistributive policies embedded in them both nationally and globally (Healy and Barry 2017; Winkler 2020). Appropriate policy design will be different at different stages of the transition process (Meckling et al. 2017; Breetz et al. 2018).

Integration. Politics is ultimately the way in which societies make decisions – which in turn, reflect diverse forces and assumed frameworks. Effective policy requires understandings which combine economic efficiency, ethics and equity, the dynamics and processes of large-scale transitions, and the role of psychology and politics. No one framework is adequate to such a broad-ranging goal, nor are single tools. Chapter 13 (Figure 13.6) presents a 'framing' table for policy instruments depending on the extent to which they focus on mitigation *per se* or wider socio-economic development, and whether they aim to shift marginal incentives or drive larger transitions. Holistic analysis needs to bridge modelling, qualitative transition theories illuminated by case studies, and practice-based action research (Geels et al. 2016).

These analytic frameworks also point to arenas of potential synergies and trade-offs (when broadly known), and opportunities and risks (when uncertainties are greater), associated with mitigation. This offers theoretical foundations for mitigation strategies which can also generate co-benefits. Climate policy may help to motivate policies with beneficial synergies (such as the consumer cost savings from energy efficiency, better forest management, transitions to cleaner vehicles) and opportunities (such as stimulating innovation), by focusing on options for which the positives outweigh the negatives, or can be made to through smart policy (e.g. Karlsson et al. 2020). More broadly, climate concerns may help to attract international investment, and help overcoming bureaucratic or political obstacles to better policy, to support synergies between mitigation, adaptation, and other SDGs, a foundation for shifting development pathways towards sustainability (Section 1.6.1; Chapter 17)

Table 1.2: Potential for net co-benefits arising from synergies and trade-offs, opportunities and risks

	Positives	**Negatives**
Broadly known (e.g. air pollution, distributional)	Synergies	Trade-offs
Deep uncertainties (e.g. radical innovations)	Opportunities	Risks
	Select options with maximum synergies, and foster and exploit opportunities	Ameliorate trade-offs (e.g. revenue redistribution), and minimize or allocate risks appropriately
	↑ ↑ ↑ ↑ ↑ ↑	↑ ↑ ↑ ↑ ↑
	Net co-benefits from appropriate mitigation choices	

1.8 Feasibility and multi-dimensional assessment of mitigation

1.8.1 Building on the SR1.5 assessment framework: feasibility and enabling conditions

While previous ARs dealt with the definition of alternative mitigation pathways mostly exploring the technological potentials, latest research focused on what kind of mitigation pathways are feasible in a broader sense, underlining the multi-dimensional nature of the mitigation challenge. Building on frameworks introduced by Majone (1975) and Gilabert and Lawford-Smith (2012), SR1.5 introduced multi-dimensional approaches to analysing 'feasibility' and 'enabling conditions', which AR6 develops and applies broadly in relation to six 'dimensions of feasibility assessment' (**Figure 1.7**). Two reflect the physical environment:

- *Geophysical*, not only the global risks from climate change but also, for technology assessment, the global availability of critical resources;
- *Environmental & ecological*, including local environmental constraints and co-benefits of different technologies and pathways

The other four dimensions correspond broadly to the four Analytic Frameworks outlined in Section 1.7:

- *Economic*, particularly aggregate economic and financial indicators, and SDGs reflecting different stages and goals of economic development;
- *Socio-cultural*, including particularly ethical and justice dimensions, and social and cultural norms;
- *Technological*, including innovation needs and transitional dynamics associated with new and emergent technologies and associated systems; and
- *Institutional & political*, including political acceptability, legal and administrative feasibility, and the capacity and governance requirements at different levels to deliver sustained mitigation in the wider context of sustainable development.

AR6 emphasises that all pathways involve different challenges and require choices to be made. Continuing 'business as usual' is still a choice, which in addition to the obvious geophysical risks, involves not making best use of new technologies, risks of future stranded assets, greater local pollution, and multiple other environmental threats.

The dimensions as listed provide a basis for this assessment both in the sectoral chapters (6-11), providing a common framework for cross-sectoral assessment detailed further in chapter 12, and in the evaluation of global pathways (Section 3.2 in Chapter 3). More specific indicators under each of these dimensions offer consistency in assessing the challenges, choices, and enabling requirements facing different aspects of mitigating climate change.

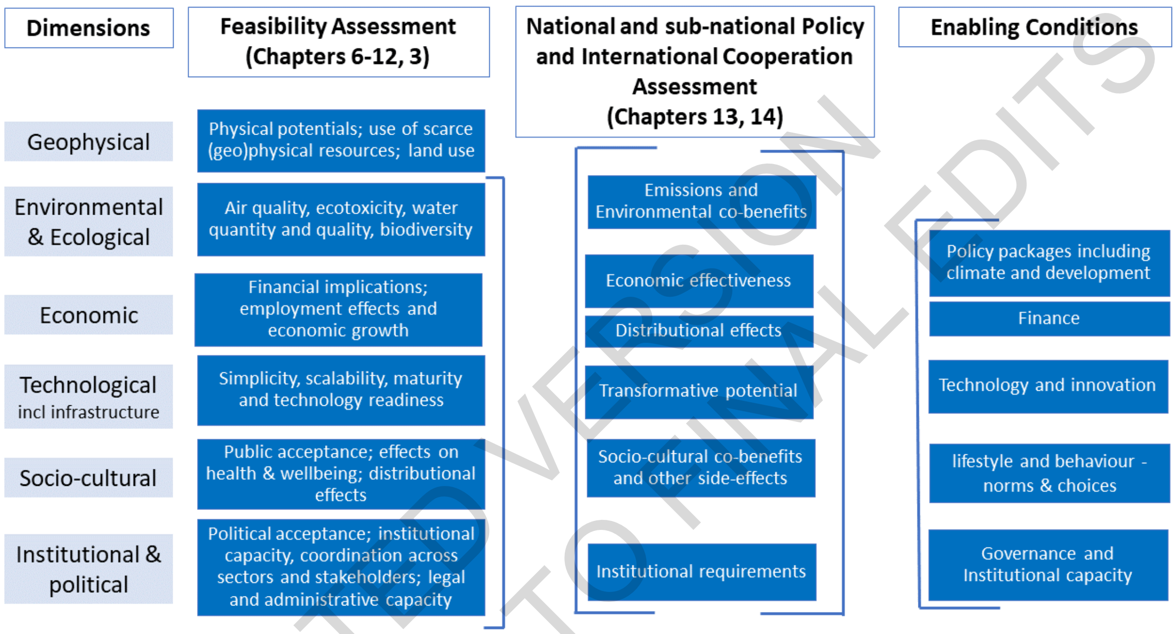

Figure 1.7: Feasibility and related dimensions of assessment

Figure 1.7 also illustrates variants on these dimensions appropriate for evaluating domestic and international policies (Chapters 13 and 14). The SR1.5 (Section 4.4 in Chapter 4) also introduced a framework of '*Enabling Conditions for systemic change'*, which as illustrated also has key dimensions in common with those of our feasibility assessment. In AR6 these enabling conditions are applied particularly in the context of shifting developments pathways (Chapter 4.4).

Some fundamental criteria may span across several dimensions. Most obviously, issues of ethics and equity are intrinsic to the economic, socio-cultural (values, including intergenerational justice) and institutional (e.g., procedural justice) dimensions. Geopolitical issues could also clearly involve several dimensions, e.g., concerning the politics of international trade, finance and resource distribution (economic dimension); international vs nationalistic identity (socio-cultural); and multilateral governance (institutional).

In this report, chapters with a strong demand-side dimension also suggest a simple policy hierarchy, reflecting that avoiding wastage – demands superfluous to human needs and wants – can carry benefits across multiple indicators. Consequently, chapters 5 and 10 organise key actions in a hierarchy of **Avoid** (unnecessary demand) – **Shift** (to less resource-intensive modes) **- Improve** (technologies for existing modes), with a closely-related policy hierarchy in Chapter 9 (buildings).

1.8.2 Illustrations of multi-dimensional assessment: lock-in, policies and 'just transition'

The rest of this section illustrates briefly how such multi-dimensional assessment, utilising the associated analytic frameworks, can shed light on a few key issues which arise across many chapters of this assessment.

'Carbon Lock-in'. The continued rise of global emissions reflects in part the strongly *path-dependent* nature of socio-economic systems, which implies a historic tendency to 'carbon lock-in' (Unruh 2000). An interdisciplinary review (Seto et al. 2016) identifies a dozen main components organised into four types, across the relevant Dimensions of Assessment as summarised in Table 1.3.

Table 1.3: Carbon lock-in – types and key characteristics

Source: Adapted from (Seto et al. 2016)

Lock-in type	Key characteristics
Economic	- Large investments with long lead-times and sunk costs, made on basis of anticipated use of resources, capital, and equipment to pay back the investment and generate profits - Initial choices account for private but not social costs and benefits
Socio-cultural, equity and behaviour	- Lock-in through social structure (e.g., norms and social processes) - Lock-in through individual decision making (e.g., psychological processes) - Single, calculated choices become a long string of non-calculated and self-reinforcing habits which are- Interrupting habits is difficult but possible (e.g., family size, thermostat setting) to change - Individuals and communities become dependent on fossil-fuel economy, meaning that change may have adverse distributional impacts
Technology and infrastructure	- Learning-by-doing and scale effects, including cumulative nature of innovation, reinforces established technologies - Interaction of technologies and networks (physical, organisational, financial) on which they depend - Random, unintentional events including network and learning effect final outcomes (e.g., Lock-in to the QWERTY keyboard)
Institutional & political	- Powerful economic, social, and political actors seek to reinforce status quo that favours their interests - Laws and Institutions, including regulatory structures, are designed to stabilise and lock -in also to provide long-term predictability (socio-technical regimes in transition theories) - Beneficial and intended outcomes for some actors - Not random chance but intentional choice (e.g., support for renewable electricity in Germany) can develop political consistencies that reinforce a direction of travel

Along with the long lifetime of various physical assets detailed in AR5, AR6 underlines the exceptional degree of path-dependence in urban systems (Chapter 8) and associated buildings (9) and transport (10) sectors, but it is a feature across almost all the major emitting sectors. The (typically -expected) operating lifetimes of existing carbon-emitting assets would involve anticipated emissions (often but inaccurately called 'committed' emissions in the literature), substantially exceeding the remaining carbon budgets associated with 1.5C pathways (Chapter 2.7). Ongoing GHG-intensive investments, including those from basic industrialisation in poorer countries, are adding to this.

The fact that investors anticipate a level of fossil fuel use that is not compatible with severe climate constraints creates a clear risk of '*stranded assets'* facing these investors (Box 6.2), and others who depend on them, which itself raises issues of equity. A multi-dimensional / multi-framework assessment helps to explain why such investments have continued, even in rich countries, and the consequent risks, and the complexity of shifting such investments in all countries. It may also inform approaches that could exploit path-dependence in clean energy systems, if there is sufficient investment in building up the low-GHG industries, infrastructures and networks required.

Carbon pricing. Appraisal of policy instruments also requires such multi-dimensional assessment. Stern's (2007) reference to climate change as "the greatest market failure in history" highlights that damages inflicted by climate change are not properly costed in most economic decision-making. Economic perspectives emphasise the value of removing fossil-fuel subsidies, and pricing emissions to 'internalise' in economic decision-making the 'external' damages imposed by GHG emissions, and/or to meet agreed goals. Aggregate economic frameworks generally indicate carbon pricing (on principles which extend to other gases) as the most cost-effective way to reduce emissions, notwithstanding various market failures which complicate this logic.[9] The High Level Commission on carbon pricing (Stern and Stiglitz 2017) estimated an appropriate range as USD40-80/tCO_2 in 2020, rising steadily thereafter. In practice the extent and level of carbon pricing implemented to date is far lower than this or than most economic analyses now recommend (Section 3.6.1 in Chapter 3), and nowhere is carbon pricing the only instrument deployed.

A socio-cultural and equity perspective emphasises that the faith in and role of markets varies widely between countries – many energy systems do no in fact operate on a basis of competitive markets – and that because market-based carbon pricing involves large revenues transfers, it must also contend with major distributional effects and political viability (Klenert et al. 2018; Prinn et al. 2017), both domestic (Chapter 13) and international (Chapter14). A major review (Maestre-Andrés et al. 2019) finds persistent distributional concerns (rich incumbents have also been vocal in using arguments about impacts on the poor (Rennkamp 2019), but suggests these may be addressed by combining redistribution of revenues with support for low carbon innovation. Measures could include redistributing the tax revenue to favour of low-income groups or differentiated carbon taxes (Metcalf 2009; Klenert and Mattauch 2016; Stiglitz 2019), including 'dual track' approaches (van den Bergh et al. 2020). To an extent though, all these depend on levels of trust, and institutional capacity.

Technological and transitions perspectives in turn find carbon pricing incentives may only stimulate incremental improvements, but other instruments may be much more effective for driving deeper innovation and transitions (Chapters 14, 15, 16), whilst psychological and behavioural studies emphasise many factors beyond only pricing (Sections 5.4.1 and 5.4.2 in Chapter 5). In practice, a wide range of policy instruments are used (Chapter 13).

Finally, in economic theory, negotiations on a common carbon price (or other common policies) may have large benefits (less subject to 'free riding') compared to a focus on negotiating national targets (Cramton et al. 2017a). The fact that this has never even been seriously considered (outside some efforts in the EU) may reflect the exceptional sovereignty sensitivities around taxation and cultural differences around the role of markets. However, carbon pricing concepts can be important outside of the traditional

FOOTNOTE[9] Beyond GHG externalities, Stern (2015) lists such market failures as; inadequate R&D; failures in risk/capital markets; network effects creating coordination failures; wider information failures; and co-benefits.

market ('tax or trading') applications. A 'social cost of carbon' can be used to evaluate government and regulatory decisions, to compensate for inadequate carbon prices in actual markets, and by companies to reflect the external damage of their emissions and strategic risks of future carbon controls (Zhou and Wen 2020). An agreed 'social value of mitigation activities' could form a basic index for underwriting risks in low carbon investments internationally (Hourcade et al. 2021a).

Thus, practical assessment of carbon pricing inherently needs multi-dimensional analysis. The realities of political economy and lobbying have to date severely limited the implementation of carbon pricing (Mildenberger 2020), leading some social scientists to ask '*Can* we price carbon?' (Rabe 2018). Slowly growing adoption (World Bank 2019) suggests "yes", but only through complex evolution of efforts: a study of 66 implemented carbon pricing policies show important effects of regional clustering, international processes, and seizing political windows of opportunity (Skovgaard et al. 2019).

Just Transitions. Finally, whilst 'transition' frameworks may explain potential dynamics that could transform systems, a multi-dimensional/multi-framework assessment underlines the motivation for 'just transitions' (see subsection 1.6.2.3 in this chapter and section 4.5 in Chapter 4). This can be defined as a transition from a high-carbon to a low-carbon economy which is considered sufficiently equitable for the affected individuals, workers, communities, sectors, regions and countries (Jasanoff 2018; Newell and Mulvaney 2013). As noted, sufficient equity is not only an ethical issue but an enabler of deeper ambition for accelerated mitigation (Hoegh-Guldberg et al. 2019; Klinsky and Winkler 2018; Urpelainen and Van de Graaf 2018). Perception of fairness influences the effectiveness of cooperative action (Winkler et al. 2018), and this can apply to affected individuals, workers, communities, sectors, regions and countries (Newell and Mulvaney 2013; Jasanoff 2018).

A 'just transitions' framing can also enable coalitions which integrate low carbon transformations with concerns for climate adaptation (Patterson et al. 2018). All this explains the emergence of 'just transition Commissions' in several of the more ambitious developed countries and complex social packages for coal phase-out in Europe (Section 4.5 in Chapter 4; Sovacool et al. 2019; Green and Gambhir 2020), as well as reference to the concept in the PA and its emphasis in the Talanoa dialogue and Silesia declaration (1.2.2).

Whilst the broad concepts of 'just transition' have roots going back decades, its specific realisation in relation to climate change is of course complex: Section 5 in Chapter 4 identifies at least eight distinct elements proposed in the literature, even before considering the international dimensions.

1.9 Governing climate change

Previous sections have highlighted the multiple factors that drive and constrain climate action, the complex interconnection between climate mitigation and other societal objectives, and the diversity of analytical frames for interpreting these connections. Despite the complexities, there are signs of progress including increased societal awareness, change in social attitudes, policy commitments by a broad range of actors and sustained emission reductions in some jurisdictions. Nevertheless, emission trends at the global level remains incompatible with the goals agreed in the Paris Agreement. Fundamentally, the challenge of how best to urgently scale up and speed-up the climate mitigation effort at all scales –from local to global – to the pace needed to address the climate challenge is that of governance understood as 'modes and mechanisms to steer society' (Jordan et al. 2015). The concept of governance encompasses the ability to plan and create the organisations needed to achieve a desired goal (Güney 2017) and the process of interaction among actors involved in a common problem for making and implementing decisions (Hufty 2012; Kooiman 2003).

Climate change governance has been projected as conscious transformation at unprecedented scale and speed involving a contest of ideas and experimentation across scales of authority and jurisdiction (Hildén et al. 2017; Laakso et al. 2017; Gordon 2018; van der Heijden 2018; Kivimaa et al. 2017). Yet, there remains a sense that achieving the urgent transition to a low carbon, climate resilient and sustainable world requires significant innovation in governance (Hoffmann 2011; Stevenson and Dryzek 2013; Aykut 2016).

Starting from an initial focus on multilateral agreements, climate change governance has long evolved into a complex polycentric structure that spans from the global to national and sub-national levels, with "multiple parallel initiatives involving a range of actors at different levels of governance" (Okereke et al. 2009) and relying on both formal and informal networks and policy channels channels (Bulkeley et al. 2014; Jordan et al. 2015). At the international level, implementation of the Paris Agreement and the UNFCCC more broadly is proceeding in parallel with other activities in an increasingly diverse landscape of loosely coordinated institutions, constituting 'regime complex' (Keohane and Victor 2011), and new cooperative efforts demonstrate an evolution in the shifting authority given to actors at different level of governance (Chan et al. 2018).

Multi-level governance has been used to highlight the notion that the processes involved in making and implementing decisions on climate change is no longer the exclusive preserve of government actors but rather involve a range of non-nation state actors such as cities, businesses, and civil society organisations (Bäckstrand et al. 2017; Jordan et al. 2018; IPCC 2014a Chapter 13, 13.3.1 and 13.5.2). Increased multi-level participation of subnational actors, along with a diversity of other transnational and non-state actors have helped to facilitate increased awareness, experimentation, innovation, learning and achieving benefits at multiple scales. Multi-level participation in governance systems can help to build coalitions to support climate change mitigation policies (Roberts et al. 2018) and fragmentation has the potential to take cooperative and even synergistic forms (Biermann et al. 2009)

However, there is no guarantee that multilevel governance can successfully deal with complex human-ecological systems (Biermann et al. 2017; York et al. 2005; Di Gregorio et al. 2019). Multi-level governance can contribute to an extremely polarised discussion and policy blockage rather than enabling policy innovation (Fisher and Leifeld 2019). Fragmented governance landscape may lead to coordination and legitimacy gaps undermining the regime (Nasiritousi and Bäckstrand 2019). Nevertheless, the realities of the 'drivers and constraints' detailed in Section 4 the "glocal" nature of climate change, the divided authority in world politics, diverse preferences of public and private entities across the spectrum, and pervasive suspicions of free riding, implying the challenge as how to incrementally deepen cooperation in a polycentric global system, rather than seeking a single, integrated governance (Keohane and Victor 2016).

Crucially, climate governance takes place in the context of embedded power relations, operating at global, national and local context. Effective rules and institutions to govern climate change are more likely to emerge when where power structures and interests favour action. However widespread and enduring co-operation can only be expected to when the benefits outweigh the cost of cooperation and when the interest of key actors are sufficiently aligned (Barrett 1994; Victor 2011; Finus and Rübbelke 2008; Tulkens 2019; Mainali et al. 2018). Investigating the distribution and role of hard and soft power resources, capacities and power relations within and across different jurisdictional levels is therefore important to uncover hindrances to effective climate governance (Marquardt 2017). Institutions at international and national levels as also critical as they have the ability to mediate power and interest of actors and sustain cooperation based on equity and fair rules and outcomes. Governance, in fact, helps to align and moderate the interests of actors as well as to shift perceptions, including the negative, burden-sharing narratives that often accompany discussion about climate action especially in international negotiations. It is also useful for engaging the wider public and international networks in imagining low carbon societies (e.g. Levy and Spicer 2013; Milkoreit 2017; Nikoleris et al. 2017; Wapner and Elver 2017; Bengtsson Sonesson et al. 2019; Fatemi et al. 2020). Experimentation also represents an important source of governance innovation and capability-formation, linked to global knowledge and technology flows, which could reshape emergent socio-technical regimes and so contribute to alternative development pathways (Berkhout et al. 2010; Roberts et al. 2018; Turnheim et al. 2018; Lo and Castán Broto 2019).

1.10 Conclusions

Global conditions have changed substantially since the IPCCs Fifth Assessment in 2014. The Paris Agreement and the SDGs provided a new international context, but global intergovernmental cooperation has been under intense stress. Growing direct impacts of climate change are unambiguous and movements of protest and activism – in countries and transnational organisations at many levels – have grown. Global emissions growth had slowed but not stopped up to 2018/19, albeit with more diverse national trends. Growing numbers of countries have adopted 'net zero' CO_2 and/or GHG emission goals and decarbonisation or low carbon growth strategies, but the current NDCs to 2030 collectively would barely reduce global emissions below present levels (1.3.3).. An unfolding technology revolution is making significant contributions in some countries, but as yet its global impact is limited. Global climate change can only be tackled within, and if integrated with, the wider context of sustainable development, and related social goals including equity concerns. Countries and their populations have many conflicting priorities. Developing countries in particular have multiple urgent needs associated with earlier stages of sustainable development as reflected in the non-climate SDGs. Developed countries are amongst the most unsustainable in terms of overall consumption, but also face social constraints particularly arising from distributional impacts of climate policies.

The assessment of the key drivers for, and barriers against mitigation undertaken in this chapter underscore the complexity and multidimensional nature of climate mitigation. Historically, much of the academic analysis of mitigating climate change, particularly global approaches, has focused on modelling costs and pathways, and discussion about 'optimal' policy instruments. Developments since AR5 have continued to highlight the role of a wide range of factors intersecting the political, economic, social and institutional domains. Yet despite such complexities, there are signs of progress emerging from years of policy effort in terms of technology, social attitudes, emission reductions in some countries, with tentative signs of impact on the trajectory of global emissions. The challenge remains how best to urgently scale up and speed-up the climate mitigation effort at all scales –from local to global – to achieve the level of mitigation needed to address the problem as indicated by climate science. A related challenge is how to ensure that mitigation effort and any associated benefits of action are distributed fairly within and between countries and aligned to the overarching objective of global sustainable development. Lastly, globally effective and efficient mitigation will require international co-operation especially in the realms of finance, and technology.

Multiple frameworks of analytic assessment, adapted to the realities of climate change mitigation, are therefore required. We identified four main groups. *Aggregate economic* frameworks – including environmental costs or goals, and with due attention to implied behavioural, distributional and dynamic assumptions - can provide insights about trade-offs, cost-effectiveness and policies for delivering agreed goals. *Ethical frameworks* are equally essential to inform both international and domestic discourse and decisions, including the relationship with international (and intergenerational) responsibilities, related financial systems, and domestic policy design in all countries. Explicit frameworks for analysing *transition and transformation* across multiple sectors need to draw on both socio-technical transition literatures, and those on social transformation. Finally, literatures on *psychology, behaviour and political sciences* can illuminate obstacles that have impeded progress to date, and suggest ways to overcome them.

No single analytical framework, or single discipline, on its own can offer a comprehensive assessment of climate change mitigation. Together they point to the relevance of growing literatures and discourses on 'just transitions', and the role of governance at multiple levels. Ultimately all these frameworks are needed to inform the decisions required to deepen and connect the scattered elements of progress to date, and hence accelerate progress towards agreed goals and multiple dimensions of climate change mitigation in the context of sustainable development.

1.11 Knowledge gaps

Despite huge expansion in the literature (Callaghan et al. 2020), knowledge gaps remain. Modeling still struggles to bring together detailed physical and economic climate impacts and mitigation, with limited representation of financial and distributional dynamics. There are few interdisciplinary tools which apply theories of transition and transformation to questions of economic and social impacts, compounded by remaining uncertainties concerning the role of new technological sets, international instruments, policy and political evaluation.

One scan of future research needs suggests three priority areas (Roberts et al. 2020); 1. Human welfare focused development (e.g. reducing inequality), 2. How the historic position of states within international power relations conditions their ability to respond to climate change, 3. Transition dynamics and the flexibility of institutions to drive towards low carbon development pathways. There remain gaps in understanding how international dynamics and agreements filter down to affect constituencies and local implementation. Literature on the potential for supply side agreements, in which producers agree to restrict the supply of fossil fuels (e.g. Asheim et al. 2019) is limited but gaining increasing academic attention.

Nature is under pressure both at land and at sea as demonstrated by declining biodiversity (IPBES 2019). Climate policies could increase the pressure on land and oceans (see IPCC 2019c,b), with insufficient attention to relationships between biodiversity and climate agreements and associated policies. IPBES aims to coordinate with the IPCC more directly, but literature will be required to support these reports.

Compounding these gaps is the fact that socially oriented, agriculture-related options, where human and non-human systems intersect most obviously, remain under-researched (e.g. Balasubramanya and Stifel 2020). Efforts to engage with policies here, especially framed around ecosystem services, have often neglected their "practical fitness" in favor of focusing on their "institutional fitness", which needs to be addressed in future research (Stevenson et al. 2021).

The relative roles of short-term mitigation policies and long-term investments, including government and financial decision-making tools, remains inadequately explored. Strategic investments may include city planning, public transport, EV charging networks, and CCU/CCS. Understanding how international treaties can increase incentives to make such investments is all the more salient in the aftermath of COVID-19, on which research is necessarily young but rapidly growing. Finally, the economic, institutional and political strategies to close the gap between NDCs, actual implementation, and mitigation goals– informed by the PA and the UNFCCC Global Stocktake – require much further research.

1.12 Roadmap to the Report

This Sixth Assessment Report covers Mitigation in five main parts (**Figure 1.8**), namely: introduction and frameworks; emission trends, scenarios and pathways; sectors; institutional dimensions including national and international policy, financial and technological mitigation drivers; and conclusions.

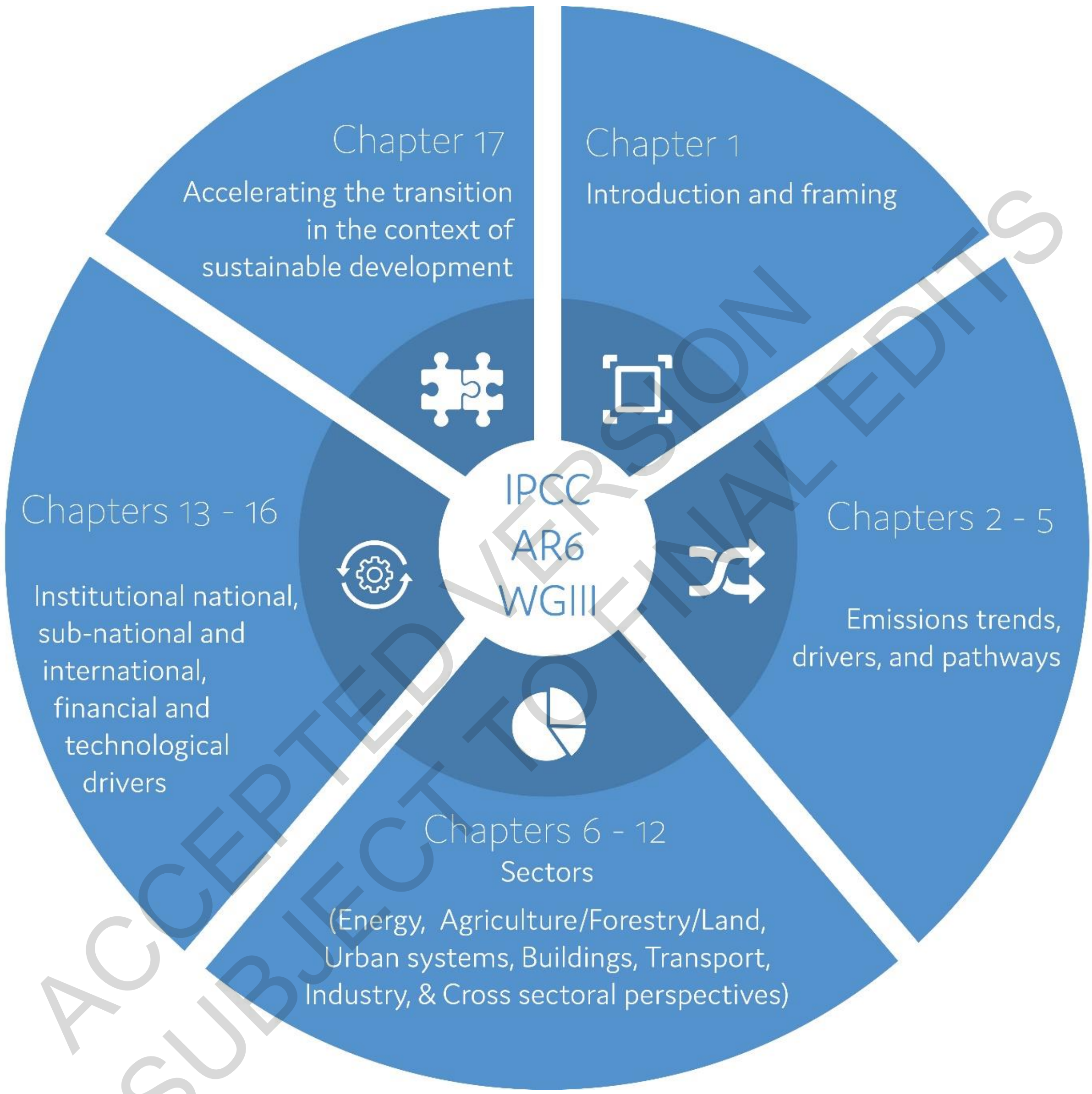

Figure 1.8: The Structure of AR6 Mitigation Report

Chapters 2-5 cover the big picture trends, drivers and projections at national and global levels. (2) analyses emission trends and drivers to date. (3) presents long-term global scenarios, including the projected economic and other characteristics of mitigation through to balancing of sources and sinks through the second half this century, and the implications for global temperature change and risks. (4) explores the shorter-term prospects including NDCs, and the possibilities for accelerating mitigation out to 2050 in the context of sustainable development at the national, regional and international scales.

(5), a new chapter for IPCC Assessments, focuses upon the role of services and derived demand for energy and land use, and the social dimensions.

Chapters 6-12 examine sectoral contributions and possibilities for mitigation. (6) summarises characteristics and trends in the energy sector, specifically supply, including the remarkable changes in the cost of some key technologies since AR5; (7) examines the roles of AFOLU, drawing upon and updating the recent Special Report, including the potential tensions between the multiple uses of land; (8) presents a holistic view of the trends and pressures of urban systems, as both a challenge and an opportunity for mitigation; Chapters 9 and 10 then examine two sectors which entwine with, but go well beyond, urban systems: buildings (9) including construction materials and zero carbon buildings; and transport (10), including shipping and aviation and a wider look at mobility as a general service; (11) explores the contribution of industry, including supply chain developments, resource efficiency/circular economy, and the cross-system implications of decarbonisation for industrial systems; finally (12) takes a cross-sectoral perspective and explores cross-cutting issues like the interactions of biomass energy, food and land, and carbon dioxide removal.

Four chapters then review thematic issues in implementation and governance of mitigation. (13) explores national and sub-national policies and institutions, bringing together lessons of policies examined in the sectoral chapters, as well as insights from service and demand-side perspectives (5), along with governance approaches and capacity-building, and the role and relationships of sub-national actors. (14) then considers the roles and status of international cooperation, including the UNFCCC agreements and international institutions, sectoral agreements and multiple forms of international partnerships, and the ethics and governance challenges of Solar Radiation Modification. (15) explores investment and finance, including current trends, the investment needs for deep decarbonisation, and the complementary roles of public and private finance. This includes climate-related investment opportunities and risks (e.g. 'stranded assets'), linkages between finance and investments in adaptation and mitigation; and the impact of COVID-19. A new chapter on innovation (16) looks at technology development, accelerated deployment and global diffusion as systemic issues that hold potential for transformative changes, and the challenges of managing such changes at multiple levels including the role of international cooperation.

Finally, (17) considers Accelerating the transition in the context of sustainable development, including practical pathways for joint responses to climate change and sustainable development challenges. This includes major regional perspectives, mitigation-adaptation interlinkages, and enabling conditions including the roles of technology, finance and cooperation for sustainable development.

Frequently Asked Questions (FAQs)

FAQ 1.1 What is climate change mitigation?

Climate change mitigation refers to actions or activities that limit emissions of GHGs from entering the atmosphere and/or reduce their levels in the atmosphere. Mitigation includes reducing the GHGs emitted from energy production and use (eg. that reduces use of fossil fuels) and land use, and methods to mitigate warming eg. by carbon sinks which remove emissions from the atmosphere through land use or other (including artificial) mechanisms (See section 12.3, 14.4.5; see WGI for physical science, and Chapter 7 for AFOLU mitigation).

The ultimate goal of mitigation is to preserve a biosphere which can sustain human civilisation and the complex of ecosystem services which surround and support it. This means reducing anthropogenic GHGs emissions towards net zero to limit the warming, with global goals agreed in the Paris

Agreement. Effective mitigation strategies require an understanding of mechanisms that underpin release of emissions, and the technical, policy and societal options for influencing these

FAQ 1.2 Which Greenhouse Gasses (GHGs) are relevant to which sectors?

Anthropogenic GHGs such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases (e.g. hydrofluorocarbons, perfluorocarbons, Sulphur hexafluoride) are released from various sources. CO_2 makes the largest contribution to global GHG emissions; but some have extremely long atmospheric lifetimes extending to tens of thousands of years, such as F gases (Chapter 2).

Different combinations of gases are emitted from different activities. The largest source of CO_2 is combustion of fossil fuels in energy conversion systems like boilers in electric power plants, engines in aircraft and automobiles, and in cooking and heating within homes and businesses (approximately 64% of emissions, Figure SPM.2). Fossil fuels are also a major source of methane (CH_4), the second biggest contributor to global warming. While most GHGs come from fossil fuel combustion, about one quarter comes from land-related activities like agriculture (mainly CH_4 and N_2O) and deforestation (mainly CO_2), with additional emissions from industrial processes (mainly CO_2, N_2O and F-gases), and municipal waste and wastewater (mainly CH_4) (2). In addition to these emissions, black carbon – an aerosol that is, for example, emitted during incomplete combustion of fossil fuels – contributes to warming of the Earth's atmosphere, whilst some other short-lived pollutants temporarily cool the surface (IPCC WG1 Chapter 6.5.4.3).

FAQ 1.3 What is the difference between "net zero emissions" and "carbon neutrality"?

Annex I states that "carbon neutrality and net zero CO2 emissions are overlapping concepts" which "can be applied at the global or sub-global scales (e.g., regional, national and sub-national)". At the global scale the terms are equivalent. At sub-global scales, net-zero CO2 typically applies to emissions under direct control or territorial responsibility of the entity reporting them (e.g. a country, district or sector); while carbon neutrality is also applied to firms, commodities and activities (e.g. a service or an event) and generally includes emissions and removals beyond the entity's direct control or territorial responsibility, termed 'Scope 3' or 'value chain emissions' (Bhatia et al. 2011).

This means the emissions and removals that should be included are wider for 'neutrality' than for net-zero goals, but also that offset mechanisms could be employed to help achieve neutrality through abatement beyond what is possible under the direct control of the entity. Rules and environmental integrity criteria are intended to ensure additionality and avoid double counting of offsets consistent with "neutrality" claims (see Annex I definitions of "Carbon neutrality" and "Offset" for detail and a list of criteria).

While the term 'carbon' neutrality in this report is defined as referring specifically to CO_2 neutrality, use of this term in practice can be ambiguous, as some users apply it to neutrality of all GHG emissions. GHG neutrality means an entity's gross emissions of all GHG must be balanced by the removal of an equivalent amount of CO2 from the atmosphere. This requires the selection of a suitable metric that aggregates emissions from non-CO2 gases, such as the commonly used GWP100 metric (for a discussion of GHG metrics, see AR6 WG1 Box 1.3 and Cross-Chapter Box 2 in Chapter 2 of this report).

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Chapter 2: Emissions Trends and Drivers

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Date of Draft: 27/11/2021

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Executive Summary

Global net anthropogenic Greenhouse Gas (GHG) emissions during the last decade (2010-2019) were higher than at any previous time in human history *(high confidence)*. Since 2010**,** GHG emissions have continued to grow reaching 59±6.6 $GtCO_2eq$ in 2019[1], but the average annual growth in the last decade (1.3%, 2010-2019) was lower than in the previous decade (2.1%, 2000-2009) (*high confidence*). Average annual GHG emissions were 56 $GtCO_2eqyr^{-1}$ for the decade 2010-2019 growing by about 9.1 $GtCO_2eqyr^{-1}$ from the previous decade (2000-2009) – the highest decadal average on record (*high confidence*). {2.2.2, Table 2.1, Figure 2.5}

Emissions growth has varied, but persisted across all groups of greenhouse gases *(high confidence)*. The average annual emission levels of the last decade (2010-2019) were higher than in any previous decade for each group of greenhouse gases (*high confidence*). In 2019, CO_2 emissions were 45±5.5 $GtCO_2$,[2] CH_4 11±3.2 $GtCO_2eq$, N_2O 2.7±1.6 $GtCO_2eq$ and fluorinated gases (F-gases: HFCs, PFCs, SF_6, NF_3) 1.4±0.41 $GtCO_2eq$. Compared to 1990, the magnitude and speed of these increases differed across gases: CO_2 from fossil fuel and industry (FFI) grew by 15 $GtCO_2eqyr^{-1}$ (67%), CH_4 by 2.4 $GtCO_2eqyr^{-1}$ (29%), F-gases by 0.97 $GtCO_2eqyr^{-1}$ (250%), N_2O by 0.65 $GtCO_2eqyr^{-1}$ (33%). CO_2 emissions from net land use, land-use change and forestry (LULUCF) have shown little long-term change, with large uncertainties preventing the detection of statistically significant trends. F-gases excluded from GHG emissions inventories such as *chlorofluorocarbons* and *hydrochlorofluorocarbons* are about the same size as those included (*high confidence*). {2.2.1, 2.2.2, Table 2.1, Figure 2.2, Figure 2.3, Figure 2.5}

Globally, GDP per capita and population growth remained the strongest drivers of CO_2 emissions from fossil fuel combustion in the last decade *(robust evidence, high agreement)*. Trends since 1990 continued in the years 2010 to 2019 with GDP per capita and population growth increasing emissions by 2.3% and 1.2% yr^{-1}, respectively. This growth outpaced the reduction in the use of energy per unit of GDP (-2% yr^{-1}, globally) as well as improvements in the carbon intensity of energy (-0.3%yr^{-1}). {2.4.1, Figure 2.19}

The global COVID-19 pandemic led to a steep drop in CO_2 emissions from fossil fuel and industry (*high confidence*). Global CO_2-FFI emissions dropped in 2020 by about 5.8% (5.1% – 6.3%) or about 2.2 (1.9-2.4) $GtCO_2$ compared to 2019. Emissions, however, have rebounded globally by the end of December 2020 (*medium confidence*). {2.2.2, Figure 2.6}

Cumulative net CO_2 emissions of the last decade (2010-2019) are about the same size as the remaining carbon budget for keeping warming to 1.5°C *(medium confidence)*. Cumulative net CO_2 emissions since 1850 are increasing at an accelerating rate. 62% of total cumulative CO_2 emissions from 1850 to 2019 occurred since 1970 (1500±140 $GtCO_2$), about 43% since 1990 (1000±90 $GtCO_2$), and about 17% since 2010 (410±30 $GtCO_2$). For comparison, the remaining carbon budget for keeping warming to 1.5°C with a 67% (50%) probability is about 400(500)±220 $GtCO_2$. {2.2.2, Figure 2.7; WG1 5.5; WG1 Table 5.8}

A growing number of countries have achieved GHG emission reductions longer than 10 years – a few at rates that are broadly consistent with climate change mitigation scenarios that limit

FOOTNOTE [1] Emissions of GHGs are weighed by Global Warming Potentials with a 100-year time horizon (GWP100) from the Sixth Assessment Report (Forster et al., 2021). GWP-100 is commonly used in wide parts of the literature on climate change mitigation and is required for reporting emissions under the United Nations Framework Convention on Climate Change (UNFCCC). All metrics have limitations and uncertainties. (Cross-Chapter Box 2, Annex II, Part II, Section 8)

FOOTNOTE [2] In 2019, CO_2 from fossil fuel and industry (FFI) were 38±3.0 Gt, CO_2 from net land use, land-use change and forestry (LULUCF) 6.6±4.6 Gt

warming to well below 2°C *(high confidence)*. There are about 24 countries that have reduced CO_2 and GHG emissions for longer than 10 years. Reduction rates in a few countries have reached 4% in some years, in line with rates observed in pathways that *likely* limit warming to 2°C. However, the total reduction in annual GHG emissions of these countries is small (about 3.2 $GtCO_2eqyr^{-1}$) compared to global emissions growth observed over the last decades. Complementary evidence suggests that countries have decoupled territorial CO_2 emissions from Gross Domestic Product (GDP), but fewer have decoupled consumption-based emissions from GDP. This decoupling has mostly occurred in countries with high per capita GDP and high per capita CO_2 emissions. {2.2.3, 2.3.3, Figure 2.11, Table 2.3, Table 2.4}

Consumption-based CO_2 emissions in developed countries and the Asia and Developing Pacific region are higher than in other regions (*high confidence*). In developed countries, consumption-based CO_2 emissions peaked at 15 $GtCO_2$ in 2007, declining to about 13 $GtCO_2$ in 2018. The Asia and Developing Pacific region, with 52% of current global population, has become a major contributor to consumption-based CO_2 emission growth since 2000 (5.5% yr^{-1} for 2000-2018); it exceeded the developed countries region, which accounts for 16% of current global population, as the largest emitter of consumption-based CO_2. {2.3.2, Figure 2.14}

Carbon intensity improvements in the production of traded products have led to a net reduction in CO_2 emissions embodied in international trade (*robust evidence, high agreement*). A decrease in the carbon intensity of traded products has offset increased trade volumes between 2006 and 2016. Emissions embodied in internationally traded products depend on the composition of the global supply chain across sectors and countries and the respective carbon intensity of production processes (emissions per unit of economic output). {2.3, 2.4}

Developed countries tend to be net CO_2 emission importers, whereas developing countries tend to be net emission exporters (*robust evidence, high agreement*). Net CO_2 emission transfers from developing to developed countries via global supply chains have decreased between 2006 and 2016**.** Between 2004 and 2011, CO_2 emission embodied in trade between developing countries have more than doubled (from 0.47 to 1.1 Gt) with the centre of trade activities shifting from Europe to Asia. {2.3.4, Figure 2.15}

Emissions from developing countries have continued to grow, starting from a low base of per capita emissions and with a lower contribution to cumulative emissions than developed countries *(robust evidence, high agreement)*. Average 2019 per capita CO_2-FFI emissions in three developing regions - Africa (1.2 tCO_2/cap), Asia and developing Pacific (4.4 tCO_2/cap), and Latin America and Caribbean (2.7 tCO_2/cap) - remained less than half that of developed countries (9.5 tCO_2/cap) in 2019. CO_2-FFI emissions in the three developing regions together grew by 26% between 2010 and 2019, compared to 260% between 1990 and 2010, while in Developed Countries emissions contracted by 9.9% between 2010-2019 and by 9.6% between 1990-2010. Historically, the three developing regions together contributed 28% to cumulative CO_2-FFI emissions between 1850 and 2019, whereas Developed Countries contributed 57% and least developed countries contributed 0.4%. {2.2.3, Figure 2.9, Figure 2.10}

Globally, GHG emissions continued to rise across all sectors and subsectors; most rapidly in transport and industry (*high confidence***)**. In 2019, 34% (20 $GtCO_2eq$) of global GHG emissions came from the energy sector, 24% (14 $GtCO_2eq$) from industry, 22% (13 $GtCO_2eq$) from AFOLU, 15% (8.7 $GtCO_2eq$) from transport and 5.6% (3.3 $GtCO_2eq$) from buildings. Once indirect emissions from energy use are considered, the relative shares of industry and buildings emissions rise to 34% and 17%, respectively. Average annual GHG emissions growth during 2010-2019 slowed compared to the previous decade in energy supply (from 2.3% to 1.0%) and industry (from 3.4% to 1.4%, direct emissions only), but remained roughly constant at about 2% per year in the transport sector *(high* *confidence).* Emission growth in AFOLU is more uncertain due to the high share of CO_2-LULUCF emissions. {2.4.2, Figure 2.13, Figures 2.16 to 2.21}.

Average annual growth in GHG emissions from energy supply decreased from 2.3% for 2000–2009 to 1.0% for 2010–2019 *(high confidence)*. This slowing of growth is attributable to further improvements in energy efficiency (annually, 1.9% less energy per unit of GDP was used globally between 2010 and 2019). Reductions in global carbon intensity by -0.2% yr^{-1} contributed further - reversing the trend during 2000-2009 (+0.2% yr^{-1}) (*medium confidence*). These carbon intensity improvement were driven by fuel switching from coal to gas, reduced expansion of coal capacity particularly in Eastern Asia, and the increased use of renewables. {2.2.4, 2.4.2.1, Figure 2.17}

GHG emissions in the industry, buildings and transport sectors continue to grow, driven by an increase in the global demand for products and services (*high confidence*). These final demand sectors make up 44% of global GHG emissions, or 66% when the emissions from electricity and heat production are reallocated as indirect emissions to related sectors, mainly to industry and buildings. Emissions are driven by the large rise in demand for basic materials and manufactured products, a global trend of increasing floor space per capita, building energy service use, travel distances, and vehicle size and weight. Between 2010-2019, domestic and international aviation were particularly fast growing at average annual rates of +3.3% and +3.4%. Global energy efficiencies have improved in all three demand sectors, but carbon intensities have not. {2.2.4; Figure 2.18; Figure 2.19; Figure 2.20}.

Providing access to modern energy services universally would increase global GHG emissions by at most a few percent (*high confidence*). The additional energy demand needed to support decent living standards[3] for all is estimated to be well below current average energy consumption (*medium evidence, high agreement*). More equitable income distributions can reduce carbon emissions, but the nature of this relationship can vary by level of income and development (*limited evidence, medium agreement*). {2.4.3}

Evidence of rapid energy transitions exists, but only at sub-global scales *(medium evidence, medium agreement)*. Emerging evidence since AR5 on past energy transitions identifies a growing number of cases of accelerated technology diffusion at sub-global scales and describes mechanisms by which future energy transitions may occur more quickly than those in the past. Important drivers include technology transfer and cooperation, intentional policy and financial support, and harnessing synergies among technologies within a sustainable energy system perspective *(medium evidence, medium agreement)*. A fast global low-carbon energy transition enabled by finance to facilitate low-carbon technology adoption in developing and particularly in least developed countries can facilitate achieving climate stabilisation targets (*robust evidence, high agreement*). {2.5.2, Table 2.5}

Multiple low-carbon technologies have shown rapid progress since AR5 – in cost, performance, and adoption – enhancing the feasibility of rapid energy transitions (*robust evidence, high agreement*). The rapid deployment and cost decrease of modular technologies like solar, wind, and batteries have occurred much faster than anticipated by experts and modelled in previous mitigation scenarios (*robust evidence*, *high agreement*). The political, economic, social, and technical feasibility of solar energy, wind energy and electricity storage technologies has improved dramatically over the past few years. In contrast, the adoption of nuclear energy and CO_2 capture and storage in the electricity sector has been slower than the growth rates anticipated in stabilisation scenarios. Emerging evidence since AR5 indicates that small-scale technologies (e.g. solar, batteries) tend to improve faster and be adopted more quickly than large-scale technologies (nuclear, CCS) *(medium evidence, medium agreement*). {2.5.3, 2.5.4, Figures 2.22 and 2.23}

FOOTNOTE [3] Decent Living Standards (DLS) – a benchmark of material conditions for human well-being – overlaps with many Sustainable Development Goals (SDGs). Minimum requirements of energy use consistent with enabling well-being for all is between 20 and 50 GJ cap-1 yr-1 23 depending on the context.{5.2.2, 5.2.2, Box 5.3, Figure 5.6}

Robust incentives for investment in innovation, especially incentives reinforced by national policy and international agreements, are central to accelerating low-carbon technological change *(robust evidence, medium agreement)*. Policies have driven innovation, including instruments for technology push (e.g., scientific training, R&D) and demand pull (e.g., carbon pricing, adoption subsidies), as well as those promoting knowledge flows and especially technology transfer. The magnitude of the scale-up challenge elevates the importance of rapid technology development and adoption. This includes ensuring participation of developing countries in an enhanced global flow of knowledge, skills, experience, equipment, and technology itself requires strong financial, institutional, and capacity building support (*robust evidence, high agreement*). {2.5.4, 2.5, 2.8}

The global wealthiest 10% contribute about 36-45% of global GHG emissions *(robust evidence, high agreement)*. The global 10% wealthiest consumers live in all continents, with two thirds in high-income regions and one third in emerging economies *(robust evidence, medium agreement)*. The lifestyle consumption emissions of the middle income and poorest citizens in emerging economies are between 5-50 times below their counterparts in high-income countries *(medium evidence, medium agreement)*. Increasing inequality within a country can exacerbate dilemmas of redistribution and social cohesion, and affect the willingness of rich and poor to accept lifestyle changes for mitigation and policies to protect the environment *(medium evidence, medium agreement)* {2.6.1, 2.6.2, Figure 2.25}

Estimates of future CO_2 emissions from existing fossil fuel infrastructures already exceed remaining cumulative net CO_2 emissions in pathways limiting warming to 1.5°C with no or limited overshoot (*high confidence*)**.** Assuming variations in historic patterns of use and decommissioning, estimated future CO_2 emissions from existing fossil fuel infrastructure alone are 660 (460-890) $GtCO_2$ and from existing and currently planned infrastructure 850 (600-1100) $GtCO_2$. This compares to overall cumulative net CO_2 emissions until reaching net zero CO_2 of 510 (330-710) Gt in pathways that limit warming to 1.5°C with no or limited overshoot, and 880 (640-1160) Gt in pathways that limit *likely* warming to 2°C (*high confidence*). While most future CO_2 emissions from existing and currently planned fossil fuel infrastructure are situated in the power sector, most remaining fossil fuel CO_2 emissions in pathways that limit likely warming to 2°C and below are from non-electric energy – most importantly from the industry and transportation sectors (*high confidence*). Decommissioning and reduced utilization of existing fossil fuel installations in the power sector as well as cancellation of new installations are required to align future CO_2 emissions from the power sector with projections in these pathways (*high confidence*). {2.7.2, 2.7.3, Figure 2.26, Table 2.6, Table 2.7}

A broad range of climate policies, including instruments like carbon pricing, play an increasing role in GHG emissions reductions. The literature is in broad agreement, but the magnitude of the reduction rate varies by the data and methodology used, country, and sector (*robust evidence, high agreement*). Countries with a lower carbon pricing gap (higher carbon price) tend to be less carbon intensive (*medium confidence*). {2.8.2, 2.8.3}

Climate-related policies have also contributed to decreasing GHG emissions. Policies such as taxes and subsidies for clean and public transportation, and renewable policies have reduced GHG emissions in some contexts (*robust evidence, high agreement*). Pollution control policies and legislations that go beyond end-of-pipe controls have also had climate co-benefits, particularly if complementarities with GHG emissions are considered in policy design (*medium evidence, medium agreement*). Policies on agriculture, forestry and other land use (AFOLU) and AFOLU sector-related policies such as afforestation policies can have important impacts on GHG emissions (*medium evidence, medium agreement*). {2.8.4}

2.1 Introduction

As demonstrated by the contribution of Working Group I to the Sixth Assessment Report (IPCC, 2021a), greenhouse gas[4] (GHG) concentrations in the atmosphere and annual anthropogenic GHG emissions continue to grow and have reached a historic high driven mainly by continued fossil fuels use (Peters et al., 2020; Jackson et al., 2019; Friedlingstein et al., 2020). Unsurprisingly, a large volume of new literature has emerged since the AR5 on the trends and underlying drivers of anthropogenic GHG emissions. This chapter provides a structured assessment of this new literature and establishes the most important thematic links to other chapters in this report.

While AR5 has mostly assessed GHG emissions trends and drivers between 1970 and 2010, this assessment focusses on the period 1990–2019 with the main emphasis on changes since 2010. Compared to Chapter 5 in the contribution of WG III to the AR5 (Blanco et al., 2014), the scope of the present chapter is broader. It presents the historical background of global progress in climate change mitigation for the rest of the report and serves as a starting point for the assessment of long-term as well as near- and medium-term mitigation pathways in Chapters 3 and 4, respectively. It also provides a systemic perspective on past emission trends in different sectors of the economy (Chapters 6–12), and relates GHG emissions trends to past policies (Chapter 13) and observed technological development (Chapter 16). There is also a greater thrust into the analysis of consumption-based sectoral emissions trends, empirical evidence of emissions consequences of behavioural choices and lifestyles, and the social aspects of mitigation (Chapter 5). Finally, a completely new section discusses the mitigation implications of existing and planned long-lived infrastructure and carbon lock-in.

Figure 2.1 presents the road map of this chapter. It is a simplified illustration of the causal chain driving emissions along the black arrows. It also highlights the most important linkages to other chapters in this volume (blue lines). The logic of the figure is the following: the main topic of this chapter is trends of GHG emissions (discussed only in this chapter at such level of detail), hence they are at the top of the figure in yellow-shaded boxes. The secondary theme is the drivers behind these trends, depicted in the second line of yellow-shaded boxes. Four categories of drivers highlight key issues and guide readers to chapters in which more details are presented. Finally, in addition to their own motivations and objectives, climate and non-climate policies and measures shape the aspirations and activities of actors in the main driver categories, hence shown in the yellow-shaded box below.

FOOTNOTE[4] Greenhouse gases are gaseous constituents of the atmosphere that absorb and emit radiation at specific wavelengths within the spectrum of radiation emitted by the Earth's surface, by the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and ozone (O_3) are the primary GHGs in the Earth's atmosphere. Human-made GHGs include sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs), chlorofluorocarbons (CFCs), and perfluorocarbons (PFCs); see Annex I.

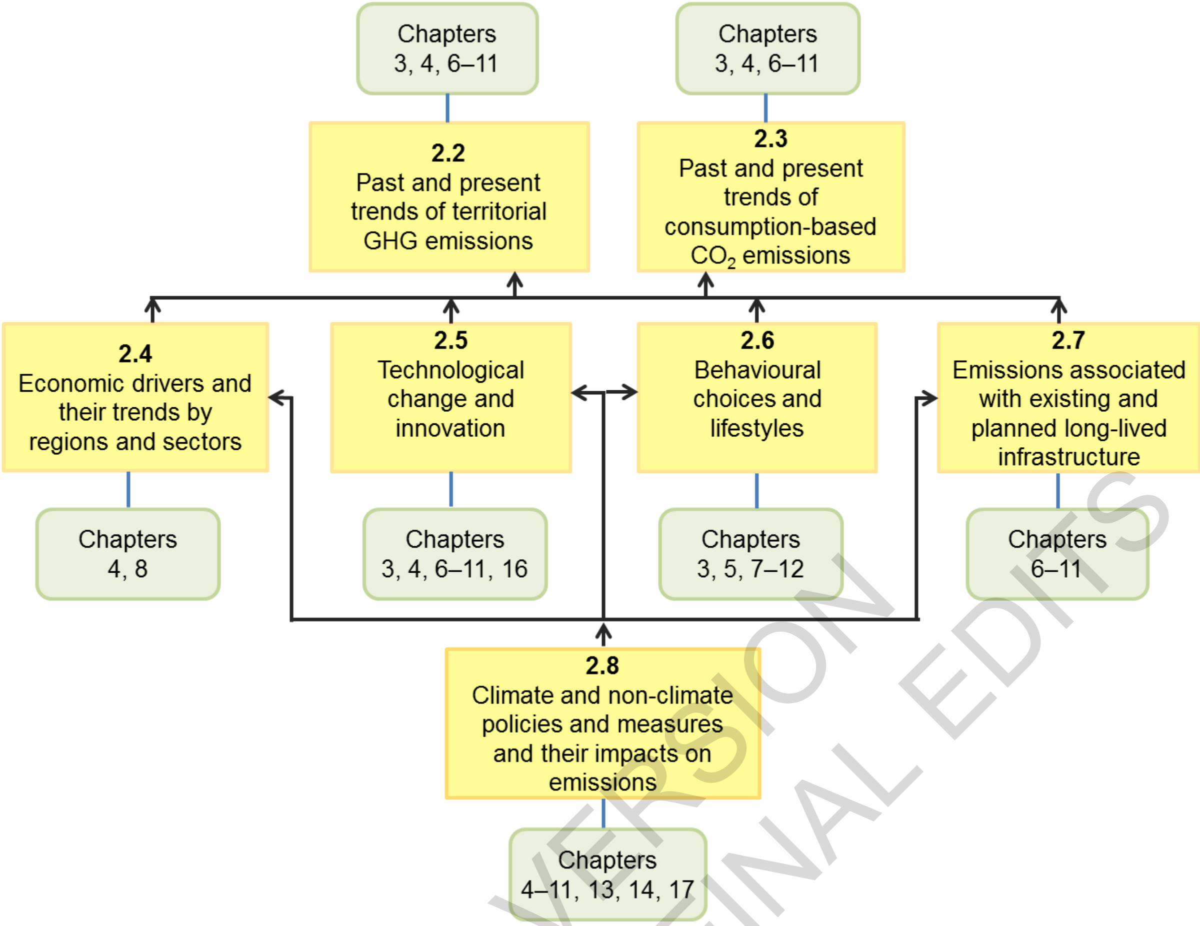

Figure 2.1 Chapter 2 road map and linkages to other chapters

Black arrows show the causal chain driving emissions, blue lines indicate key linkages to other chapters in this report.

Accordingly, the yellow-shaded boxes at the top of Figure 2.1 show that the first part of the chapter presents GHG emissions from two main perspectives: their geographical locations and the places where goods are consumed and services are utilised. A complicated chain of factors called drivers underlie these emissions. They are linked across time, space, and various segments of the economy and society in complex non-linear relationships. Sections shown in the second row of yellow-shaded boxes assess the latest literature and improve the understanding of the relative importance of these drivers in mitigating GHG emissions. A huge mass of physical capital embodying immense financial assets and potentially operating over a long lifetime produces vast GHG emissions. This long-lived infrastructure can be a significant hindrance to fast and deep reductions of emissions, it is therefore also shown as an important driver. A large range of economic, social, environmental, and other policies has been shaping these drivers of GHG emissions in the past and are anticipated to influence them in the future, as indicated by the yellow-shaded policies box and its manifold linkages. As noted, blue lines show linkages of sections to other chapters discussing these drivers and their operating mechanisms in detail.

2.2 Past and present trends of territorial GHG emissions

Total anthropogenic greenhouse gas (GHG) emissions as discussed in this chapter comprise CO_2 emissions from fossil fuel combustion and industrial processes[5] (FFI), net CO_2 emissions from land use,

FOOTNOTE[5] Industrial processes relate to CO_2 releases from fossil fuel oxidation and carbonate decomposition.

land-use change, and forestry (CO_2-LULUCF) (in previous IPCC reports often named FOLU: forestry and other land-use), methane (CH_4), nitrous oxide (N_2O) and fluorinated gases (F-gases) comprising hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF6) as well as nitrogen trifluoride (NF_3). There are other major sources of F-gas emissions that are regulated under the Montreal Protocol such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) that also have considerable warming impacts (see Figure 2.4), however they are not considered here. Other substances including ozone and aerosols that further contribute climate forcing are only treated very briefly, but a full chapter is devoted to it in the Working Group I contribution to AR6 (Naik et al., 2021a; b).

A growing number of global GHG emissions inventories have become available since AR5 (Minx et al., 2021). However, only a few are comprehensive in their coverage of sectors, countries and gases – namely EDGAR (Emissions Database for Global Atmospheric Research) (Crippa et al., 2021), PRIMAP (Potsdam Real-time Integrated Model for probabilistic Assessment of emissions Paths) (Gütschow et al., 2021a), CAIT (Climate Analysis Indicators Tool) (WRI, 2019) and CEDS (A Community *Emissions* Data System for Historical *Emissions)* (Hoesly et al., 2018). None of these inventories presently cover CO_2-LULUCF, while CEDS excludes F-gases. For individual gases and sectors, additional GHG inventories are available, as shown in Figure 2.2, but each has varying system boundaries leading to important differences between their respective estimates (Section 2.2.1). Some inventories are compiled bottom-up, while others are produced synthetically and are dependent on other inventories. A more comprehensive list and discussion of different datasets is provided in the Chapter 2 Supplementary Material (SM2.1) and in Minx et al. (2021).

Across this report version 6 of EDGAR (Crippa et al., 2021) provided by the Joint Research Centre of the European Commission is used for a consistent assessment of GHG emission trends and drivers. It covers anthropogenic releases of CO_2-FFI, CH_4, N_2O, and F-gas (HFCs, PFCs, SF_6, NF_3) emissions by 228 countries and territories and across 5 sectors and 27 subsectors. EDGAR is chosen, because it provides the most comprehensive global dataset in its coverage of sources, sectors and gases. For transparency and as part of the uncertainty assessment EDGAR is compared to other global datasets in Section 2.2.1 as well as in the Chapter 2 Supplementary Material (SM2.1). For individual country estimates of GHG emissions, it may be more appropriate to use inventory data submitted to the UNFCCC under the common reporting format (CRF) (UNFCCC, 2021). However, these inventories are only up to date for Annex I countries and cannot be used to estimate global or regional totals. As part of the regional analysis, a comparison of EDGAR and CRF estimates at the country-level is provided, where the latter is available (Figure 2.9).

Net CO_2-LULUCF estimates are added to the dataset as the average of estimates from three bookkeeping models of land-use emissions (Houghton and Nassikas, 2017; Hansis et al., 2015; Gasser et al., 2020) following the Global Carbon Project (Friedlingstein et al., 2020). This is different to AR5, where land-based CO_2 emissions from forest fires, peat fires, and peat decay, were used as an approximation of the net-flux of CO_2-LULUCF (Blanco et al., 2014). Note that the definition of CO_2-LULUCF emissions by global carbon cycle models, as used here, differs from IPCC definitions (IPCC, 2006) applied in national greenhouse gas inventories (NGHGI) for reporting under the climate convention (Grassi et al., 2018, 2021) and, similarly, from FAO estimates of carbon fluxes on forest land (Tubiello et al., 2021). The conceptual difference in approaches reflects different scopes. We use the global carbon cycle models' approach for consistency with Working Group I (Canadell et al., 2021) and to comprehensively distinguish natural from anthropogenic drivers, while NGHGI generally report as anthropogenic all CO_2 fluxes from lands considered managed (see Section 7.2.2 in Chapter 7). Finally, note that the CO_2-LULUCF estimate from bookkeeping models as provided in this chapter is indistinguishable to the CO_2 from Agriculture, Forestry and other Land Use (AFOLU) as reported in Chapter 7, because the CO_2 emissions component from agriculture is negligible.

The resulting synthetic dataset used here has undergone additional peer-review and is publicly available (https://doi.org/10.5281/zenodo.5566761). Comprehensive information about the dataset as well as underlying uncertainties (including a comparison with other datasets) can be found in the Supplementary Material to this chapter and in Minx et al. (2021).

In this chapter and the report as a whole, different greenhouse gases are frequently converted into common units of CO_2 equivalent (CO_2eq) emissions using 100-year Global Warming Potentials (GWP100) from WGI of IPCCs Sixth Assessment Report (AR6) (Forster et al., 2021a). This reflects the dominant use in the scientific literature and is consistent with decisions made by Parties to the Paris Agreement for reporting and accounting of emissions and removals (UNFCCC, 2019). Other GHG emissions metrics exist, all of which, like GWP100, are designed for specific purposes and have limitations and uncertainties. The appropriate choice of GHG emissions metrics depends on policy objective and context (Myhre et al., 2013; Kolstad et al., 2015). A discussion of GHG metrics is provided in a Cross-Chapter Box later in the chapter (see Cross-Chapter Box 2) and, at length, in the Chapter 2 Supplementary Material. Throughout the chapter GHG emissions are reported (in GtCO_2eq) at two significant digits to reflect prevailing uncertainties in emissions estimates. Estimates are subject to uncertainty, which we report for a 90% confidence interval.

2.2.1 Uncertainties in GHG emissions

Estimates of historical GHG emissions – CO_2, CH_4, N_2O and F-gases – are uncertain to different degrees. Assessing and reporting uncertainties is crucial in order to understand whether available estimates are sufficiently robust to answer policy questions; for example, if GHG emissions are still rising, or if a country has achieved an emission reduction goal (Marland, 2008). These uncertainties can be of scientific nature, such as when a process is not sufficiently understood. They also arise from incomplete or unknown parameter information (e.g. activity data, or emission factors), as well as estimation uncertainties from imperfect modelling techniques. There are at least three major ways to examine uncertainties in emission estimates (Marland et al., 2009): 1) by comparing estimates made by independent methods and observations (e.g. comparing atmospheric measurements with bottom-up emissions inventory estimates) (Saunois et al., 2020; Petrescu et al., 2020b; a; Tian et al., 2020); 2) by comparing estimates from multiple sources and understanding sources of variation (Andrew, 2020; Macknick, 2011; Ciais et al., 2021; Andres et al., 2012); 3) by evaluating estimates from a single source (Hoesly and Smith, 2018), for instance via statistical sampling across parameter values (e.g. Robert J. Andres et al., 2014; Monni et al., 2007; Solazzo et al., 2021; Tian et al., 2019).

Uncertainty estimates can be rather different depending on the method chosen. For example, the range of estimates from multiple sources is bounded by their interdependency; they can be lower than true structural plus parameter uncertainty or than estimates made by independent methods. In particular, it is important to account for potential bias in estimates, which can result from using common methodological or parameter assumptions, or from missing sources (systemic bias). It is further crucial to account for differences in system boundaries, i.e. which emissions sources are included in a dataset and which are not, otherwise direct comparisons can exaggerate uncertainties (Macknick, 2011; Andrew, 2020). Independent top-down observational constraints are, therefore, particularly useful to bound total emission estimates, but are not yet capable of verifying emission levels or trends (Petrescu et al., 2021a; b). Similarly, uncertainties estimates are influenced by specific modelling choices. For example, uncertainty estimates from studies on the propagation of uncertainties associated with key input parameters (activity data, emissions factors) following the IPCC Guidelines (IPCC, 2006) are strongly determined by assumptions on how these parameters are correlated between sectors, countries, and regions (Solazzo et al., 2021; Janssens-Maenhout et al., 2019). Assuming (full) covariance between source categories, and therefore dependence between them, increases uncertainty estimates. Estimates allowing for some covariance as in Sollazo et al. (2021) also tend to yield higher estimates than the range of values from ensemble of dependent inventories (Saunois et al., 2016, 2020).

For this report, a comprehensive assessment of uncertainties is provided in the Supplementary Material (SM2.2) to this chapter based on Minx et al. (2021). The uncertainties reported here combine statistical analysis, comparisons of global emissions inventories and an expert judgement of the likelihood of results lying outside a defined confidence interval, rooted in an understanding gained from the relevant literature. This literature has improved considerably since AR5 with a growing number of studies that assess uncertainties based on multiple lines of evidence (Petrescu et al., 2021a; b; Tian et al., 2020; Saunois et al., 2016, 2020).

To report the uncertainties in GHG emissions estimates, a 90% confidence interval (5^{th}-95^{th} percentile) is adopted, i.e., there is a 90 % likelihood that the true value will be within the provided range if the errors have a Gaussian distribution, and no bias is assumed. This is in line with previous reporting in IPCC AR5 (Ciais et al., 2014; Blanco et al., 2014). Note that national emissions inventory submissions to the UNFCCC are requested to report uncertainty using a 95% confidence interval. The use of this broader uncertainty interval implies, however, a relatively high degree of knowledge about the uncertainty structure of the associated data, particularly regarding the distribution of uncertainty in the tails of the probability distributions. Such a high degree of knowledge is not present over all regions, emission sectors and species considered here.

Based on this assessment of relevant uncertainties above, a constant, relative, global uncertainty estimates for GHGs is applied at a 90% confidence interval that range from relatively low values for CO_2-FFI (±8%), to intermediate values for CH_4 and F-gases (±30%), to higher values for N_2O (±60%) and CO_2-LULUCF (±70%). Uncertainties for aggregated total GHG emissions in terms of CO_2eq emissions are calculated as the square root of the squared sums of absolute uncertainties for individual gases (taking F-gases together), using 100-year Global Warming Potentials (GWP100) to weight emissions of non-CO_2 gases but excluding uncertainties in the metric itself.

This assessment of uncertainties is broadly in line with WGIII AR5 (Blanco et al., 2014), but revises individual uncertainty judgements in line with the more recent literature (Friedlingstein et al., 2020; Janssens-Maenhout et al., 2019; Solazzo et al., 2021; Tian et al., 2020; Saunois et al., 2016, 2020) as well as the underlying synthetic analysis provided here (e.g. Figure 2.2, Figure 2.3, Minx et al. (2021)). As such, reported changes in these estimates do not reflect changes in the underlying uncertainties, but rather a change in expert judgement based on an improved evidence base in the scientific literature. Uncertainty estimates for CO_2-FFI and N_2O remain unchanged compared to AR5. The change in the uncertainty estimates for CH_4 from 20% to 30% is justified by larger uncertainties reported for EDGAR emissions (Solazzo et al., 2021; Janssens-Maenhout et al., 2019) as well as the wider literature (Tubiello et al., 2015; Kirschke et al., 2013; Saunois et al., 2020, 2016). As AR6 – in contrast to AR5 - uses CO_2-LULUCF data from global bookkeeping models, the respective uncertainty estimate is based on the reporting in the underlying literature (Friedlingstein et al., 2020) as well as Working Group I (Canadell et al., 2021). The 70% uncertainty value is at the higher end of the range considered in AR5 (Blanco et al., 2014).

Finally, for F-gas emissions top-down atmospheric measurements from the 2018 World Meteorological Organisation's (WMO) Scientific Assessment of Ozone Depletion (see Engel and Rigby, 2018; Montzka and Velders, 2018) are compared to the data used in this report (Minx et al., 2021; Crippa et al., 2021) as shown in Figure 2.3. Due to the general absence of natural F-gas fluxes, there is a sound understanding of global and regional F-gas emissions from top-down estimates of atmospheric measurements with small and well-understood measurement, lifetime and transport model uncertainties (see Engel and Rigby, 2018; Montzka and Velders, 2018). However, when species are aggregated into total F-gas emissions, EDGARv6 emissions are around 10% lower than the WMO 2018 values throughout, with larger differences for individual f-gas species, and further discrepancies when comparing to older EDGAR versions. Based on this, the overall uncertainties for aggregate F-gas emissions is judged conservatively at 30% - 10 percentage points higher than in AR5 (Blanco et al., 2014).

Aggregate uncertainty across all greenhouse gases is approximately ±11% depending on the composition of gases in a particular year. AR5 applied a constant uncertainty estimates of ±10% for total GHG emissions. The upwards revision applied to the uncertainties of CO_2-LULUCF, CH_4 and F-gas emissions therefore has a limited overall effect on the assessment of GHG emissions.

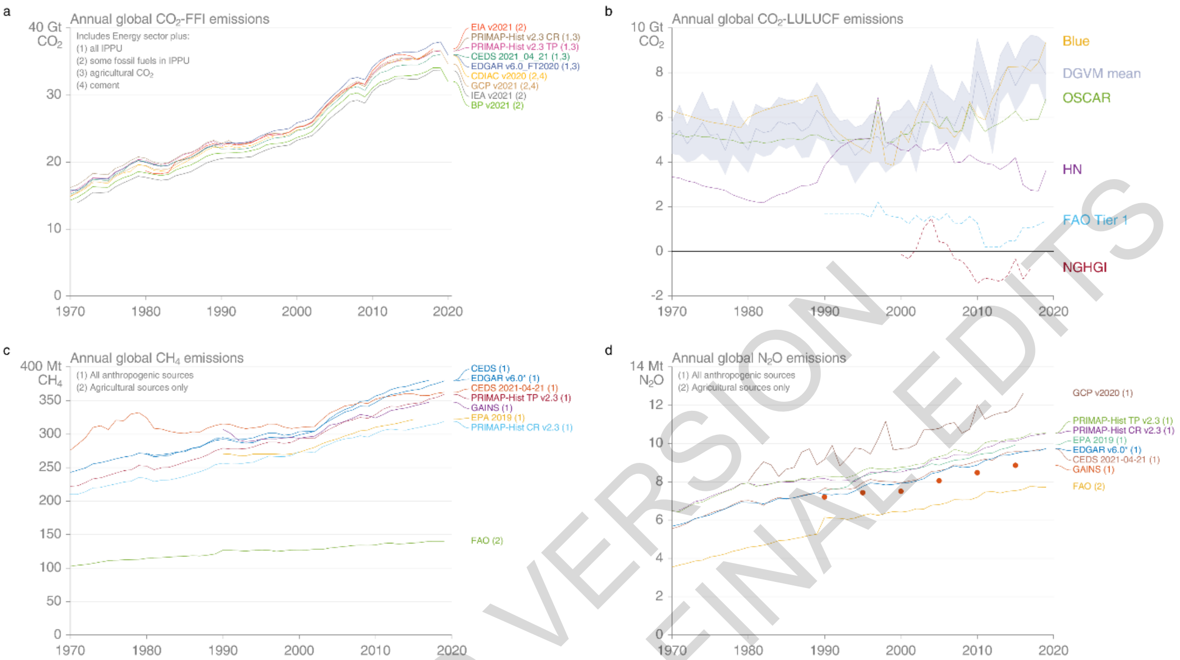

Figure 2.2 Estimates of global anthropogenic greenhouse gas emissions from different data sources 1970-2019.

Top-left panel: CO_2 FFI emissions from: EDGAR - Emissions Database for Global Atmospheric Research (this dataset) (Crippa et al., 2021); GCP – Global Carbon Project (Friedlingstein et al., 2020; Andrew and Peters, 2021); CEDS - Community Emissions Data System (Hoesly et al., 2018; O'Rourke et al., 2021); CDIAC Global, Regional, and National Fossil-Fuel CO_2 Emissions (Gilfillan et al., 2020); PRIMAP-hist - Potsdam Real-time Integrated Model for probabilistic Assessment of emissions Paths (Gütschow et al., 2016, 2021b); EIA - Energy Information Administration International Energy Statistics (EIA, 2021); BP - BP Statistical Review of World Energy (BP, 2021); IEA - International Energy Agency (IEA, 2021a; b); IPPU refers to emissions from industrial processes and product use. Top-right panel: Net anthropogenic CO_2-LULUCF emissions from: BLUE – Bookkeeping of land-use emissions (Hansis et al., 2015; Friedlingstein et al., 2020); DGVM-mean – Multi-model mean of CO_2-LULUCF emissions from dynamic global vegetation models (Friedlingstein et al., 2020); OSCAR – an earth system compact model (Gasser et al., 2020; Friedlingstein et al., 2020); HN – Houghton and Nassikas Bookkeeping Model (Houghton and Nassikas, 2017; Friedlingstein et al., 2020); for comparison, the net CO_2 flux from FAOSTAT (FAO Tier 1) is plotted, which comprises net emissions and removals on forest land and from net forest conversion (Tubiello et al., 2021; FAOSTAT, 2021), emissions from drained organic soils under cropland/grassland (Conchedda and Tubiello, 2020), and fires in organic soils (Prosperi et al., 2020), as well as a net CO_2 flux estimate from National Greenhouse Gas Inventories (NGHGI) based on country reports to the UNFCCC, which include land use change, and fluxes in managed lands (Grassi et al., 2021). Bottom-left panel: Anthropogenic CH_4 emissions from: EDGAR (above); CEDS (above); PRIMAP-hist (above); GAINS - The Greenhouse gas – Air pollution Interactions and Synergies Model (Höglund-Isaksson et al., 2020); EPA-2019: Greenhouse gas emission inventory (US-EPA, 2019); FAO –FAOSTAT inventory emissions (Tubiello et al., 2013; Tubiello, 2018; FAOSTAT, 2021); Bottom-right panel: Anthropogenic N_2O emissions from: GCP – global nitrous oxide budget (Tian et al., 2020); CEDS (above); EDGAR (above);

PRIMAP-hist (above); GAINS (Winiwarter et al., 2018); EPA-2019 (above); FAO (above). Differences in emissions across different versions of the EDGAR dataset are shown in the Supplementary Material (Fig. SM2.2).

Source: Minx et al. (2021)

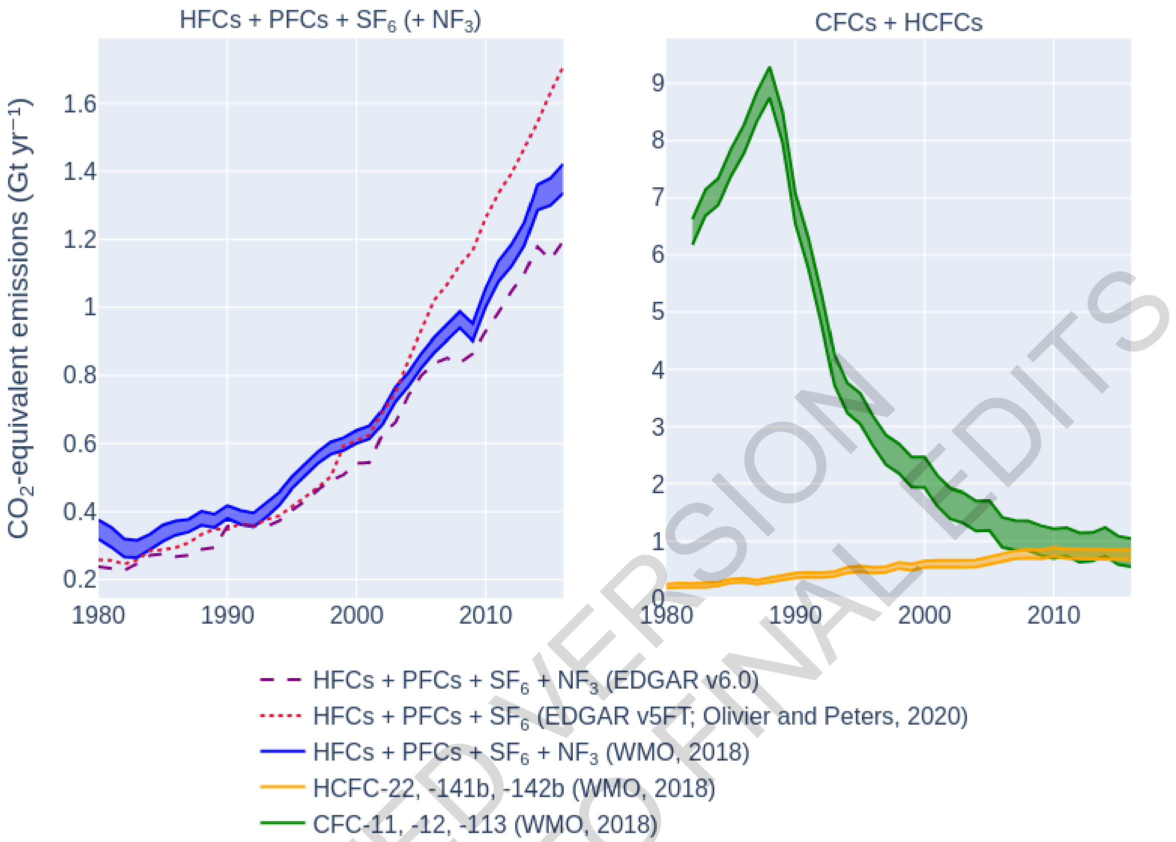

Figure 2.3 Comparison between top-down estimates and bottom-up EDGAR inventory data on GHG emissions for 1980-2016

Left panel: Total GWP-100-weighted emissions based on IPCC AR6 (Forster et al., 2021a) of F-gases in Olivier & Peters (2020) [EDGARv5FT] (red dashed line, excluding C_4F_{10}, C_5F_{12}, C_6F_{14} and C_7F_{16}) and EDGARv6 (purple dashed line) compared to top-down estimates based on AGAGE and NOAA data from WMO (2018) (blue lines; Engel and Rigby (2018); Montzka and Velders (2018)). Right panel: Top-down aggregated emissions for the three most abundant CFCs (-11, -12 and -113) and HCFCs (-22, -141b, -142b) not covered in bottom-up emissions inventories are shown in green and orange. For top-down estimates the shaded areas between two respective lines represent 1σ uncertainties.

Source: Minx et al. (2021).

GHG emissions metrics such as GWP-100 have themselves uncertainties, which has been largely neglected in the literature so far. Minx et al. (2021) report the uncertainty in GWP-100 metric values as ±50% for methane and other SLCFs, and ±40% for non-CO_2 gases with longer atmospheric lifetimes (specifically, those with lifetimes longer than 20 years). If uncertainties in GHG metrics are considered, and are assumed independent (which may lead to an underestimate) the overall uncertainty of total GHG emissions in 2019 increases from ±11% to ±13%. Metric uncertainties are not further considered in this chapter (but see Cross-chapter Box 2 and Chapter 2 Supplementary Material on GHG metrics (SM2.3)).

The most appropriate metric to aggregate GHG emissions depends on the objective (see Cross-chapter Box 2). One such objective can be to understand the contribution of emissions in any given year to warming, while another can be to understand the contribution of cumulative emissions over an extended time period to warming. In Figure 2.4 the modelled warming from emissions of each gas or group of gases is also shown - calculated using the reduced-complexity climate model FAIRv1.6, which has been calibrated to match several aspects of the overall WGI assessment (Forster et al., 2021a; specifically Cross-Chapter Box 7 in Chapter 10 therein). Additionally, its temperature response to emissions with shorter atmospheric lifetimes such as aerosols, methane or ozone has been adjusted to broadly match those presented in Naik et al. (2021a). There are some differences in actual warming compared to the GWP-100 weighted emissions of each gas (Figure 2.4), in particular a greater contribution from CH_4 emissions to historical warming. This is consistent with warming from CH_4 being short-lived and hence having a more pronounced effect in the near-term during a period of rising emissions. Nonetheless, Figure 2.4 highlights that emissions weighted by GWP-100 do not provide a fundamentally different information about the contribution of individual gases than modelled actual warming over the historical period, when emissions of most GHGs have been rising continuously, with CO_2 being the dominant and CH_4 being the second most important contributor to GHG-induced warming. Other metrics such as GWP* (Cain et al., 2019) offer an even closer resemblance between cumulative CO_2eq emissions and temperature change. Such a metric may be more appropriate when the key objective is to track temperature change when emissions are falling, as in mitigation scenarios.

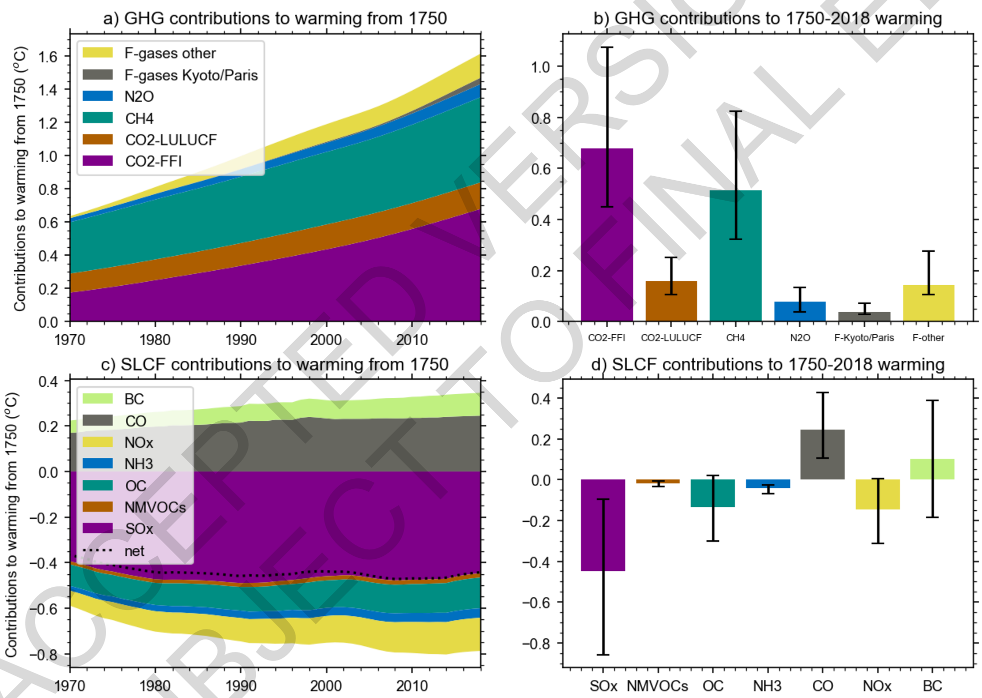

Figure 2.4 Contribution of different GHGs to global warming over the period 1750 to 2018
Top row: contributions estimated with the FaIR reduced-complexity climate model. Major GHGs and aggregates of minor gases as a timeseries in a) and as a total warming bar chart with 90% confidence interval added in b). Bottom row: contribution from short-lived climate forcers as a time series in c) and as a total warming bar chart with 90% confidence interval added in d). The dotted line in c) gives the net temperature change from short-lived climate forcers other than CH_4. F-Kyoto/Paris includes the gases covered by the Kyoto Protocol and Paris Agreement, while F-other includes the gases covered by the Montreal Protocol but excluding the HFCs.
Source: Minx et al., 2021

START CROSS CHAPTER BOX 2 HERE

Cross-Chapter Box 2 GHG emission metrics

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Comprehensive mitigation policy relies on consideration of all anthropogenic forcing agents, which differ widely in their atmospheric lifetimes and impacts on the climate system. GHG emission metrics[6] provide simplified information about the effects that emissions of different GHGs have on global temperature or other aspects of climate, usually expressed relative to the effect of emitting CO_2 (see glossary). This information can inform prioritisation and management of trade-offs in mitigation policies and emission targets for non-CO_2 gases relative to CO_2, as well as for baskets of gases expressed in CO_2-eq. This assessment builds on the evaluation of GHG emission metrics from a physical science perspective by Working Group I (Forster et al., 2021b). For additional details and supporting references, see Chapter 2 Supplementary Material (SM2.3) and Annex II 8.

The Global Warming Potential (GWP) and the Global Temperature change Potential (GTP) were the main metrics assessed in AR5 (Myhre et al., 2013; Kolstad et al., 2014). The GWP with a lifetime of 100 years (GWP_{100}) continues to be the dominant metric used in the scientific literature on mitigation assessed by WGIII. The assessment by Working Group I (Forster et al., 2021) includes updated values for these metrics based on updated scientific understanding of the response of the climate system to emissions of different gases, including changing background concentrations. It also assess new metrics published since AR5. Metric values in the AR6 include climate-carbon cycle feedbacks by default; this provides an important update and clarification from the AR5 which reported metric values both with and without such feedbacks.

The choice of metric, including time horizon, should reflect the policy objectives for which the metric is applied (Plattner et al., 2009). Recent studies confirm earlier findings that the GWP is consistent with a cost-benefit framework (Kolstad et al., 2014), which implies weighting each emission based on the economic damages that this emission will cause over time, or conversely, the avoided damages from avoiding that emission. The GWP time horizon can be linked to the discount rate used to evaluate economic damages from each emission. For methane, GWP_{100} implies a social discount rate of about 3-5% depending on the assumed damage function, whereas GWP_{20} implies a much higher discount rate, greater than 10% (*medium confidence*; Mallapragada and Mignone 2019; Sarofim and Giordano 2018). The dynamic GTP is aligned with a cost-effectiveness framework, as it weights each emission based on its contribution to global warming in a specified future year (e.g. the expected year of peak warming for a given temperature goal). This implies a shrinking time horizon and increasing relative importance of SLCF emissions as the target year is approached (Johansson, 2011; Aaheim and Mideksa, 2017). The GTP with a static time horizon (e.g. GTP_{100}) is not well-matched to either a cost-benefit or a cost-effectiveness framework, as the year for which the temperature outcome is evaluated would not match

FOOTNOTE[6] Emission metrics also exist for aerosols, but these are not commonly used in climate policy. This assessment focuses on GHG emission metrics only.

the year of peak warming, nor the overall damages caused by each emission (Mallapragada and Mignone, 2017; Edwards and Trancik, 2014; Strefler et al., 2014).

A number of studies since the AR5 have evaluated the impact of various GHG emission metrics and time horizons on the global economic costs of limiting global average temperature change to a pre-determined level (e.g. Strefler et al. 2014; Harmsen et al. 2016; Tanaka et al. 2021; see SM2.3 for additional detail). These studies indicate that for mitigation pathways that *likely* limit warming to 2°C above pre-industrial levels or lower, using GWP_{100} to inform cost-effective abatement choices between gases would achieve such long-term temperature goals at close to least global cost within a few percent (*high confidence*). Using the dynamic GTP instead of GWP_{100} could reduce global mitigation costs by a few percent in theory (*high confidence*), but the ability to realise those cost savings depends on the temperature limit, policy foresight and flexibility in abatement choices as the weighting of SLCF emissions increases over time (*medium confidence*; van den Berg et al. 2015; Huntingford et al. 2015). Similar benefits as for the dynamic GTP might be obtained by regularly reviewing and potentially updating the time horizon used for GWP in light of actual emission trends compared to climate goals (Tanaka et al., 2020).

The choice of metric and time horizon can affect the distribution of costs and the timing of abatement between countries and sectors in cost-effective mitigation strategies. Sector-specific lifecycle assessments find that different emission metrics and different time horizons can lead to divergent conclusions about the effectiveness of mitigation strategies that involve reductions of one gas but an increase of another gas with a different lifetime (e.g. Tanaka et al. 2019). Assessing the sensitivity of conclusions to different emission metrics and time horizons can support more robust decision-making (Levasseur et al. 2016; Balcombe et al. 2018; see SM2.3 for details). Sectoral and national perspectives on GHG emission metrics may differ from a global least-cost perspective, depending on other policy objectives and equity considerations, but the literature does not provide a consistent framework for assessing GHG emission metrics based on equity principles.

Literature since the AR5 has emphasized that the GWP_{100} is not well suited to estimating the warming effect at specific points in time from sustained SLCF emissions (e.g. Allen et al. 2016; Cain et al. 2019; Collins et al. 2019). This is because the warming caused by an individual SLCF emission pulse diminishes over time and hence, unlike CO_2, the warming from SLCF emissions that are sustained over multiple decades to centuries depends mostly on their ongoing rate of emissions rather than their cumulative emissions. Treating all gases interchangeably based on GWP_{100} within a stated emissions target therefore creates ambiguity about actual global temperature outcomes (Fuglestvedt et al., 2018; Denison et al., 2019). Supplementing economy-wide emission targets with information about the expected contribution from individual gases to such targets would reduce the ambiguity in global temperature outcomes.

Recently developed step/pulse metrics such as the CGTP (Combined Global Temperature Change Potential; Collins et al. 2019) and GWP* (referred to as GWP-star; Allen et al. 2018; Cain et al. 2019) recognise that a sustained increase/decrease in the rate of SLCF emissions has a similar effect on global surface temperature over multiple decades as a one-off pulse emission/removal of CO_2. These metrics use this relationship to calculate the CO_2 emissions or removals that would result in roughly the same temperature change as a sustained change in the rate of SLCF emissions (CGTP) over a given time period, or as a varying time series of CH_4 emissions (GWP*). From a mitigation perspective, these metrics indicate greater climate benefits from rapid and sustained methane reductions over the next few decades than if such reductions are weighted by GWP_{100}, while conversely, sustained methane increases have greater adverse climate impacts (Lynch et al., 2020; Collins et al., 2019). The ability of these metrics to relate changes in emission rates of short-lived gases to cumulative CO_2 emissions makes them well-suited, in principle, to estimating the effect on the remaining carbon budget from more, or less, ambitious SLCF mitigation over multiple decades compared to a given reference scenario (*high confidence*; Collins et al. 2019; Forster et al. 2021).

The potential application of GWP* in wider climate policy (e.g. to inform equitable and ambitious emission targets or to support sector-specific mitigation policies) is contested, although relevant literature is still limited (Rogelj and Schleussner, 2019; Schleussner et al., 2019; Cain et al., 2021; Rogelj and Schleussner, 2021; Allen et al., 2021). Whereas GWP and GTP describe the marginal effect of each emission relative to the absence of that emission, GWP* describes the equivalent CO_2 emissions that would give the same temperature change as an emissions trajectory of the gas considered, starting at a (user-determined) reference point. The warming based on those cumulative CO_2-equivalent emission at any point in time is relative to the warming caused by emissions of that gas before the reference point. Because of their different focus, GWP* and GWP_{100} can equate radically different CO_2 emissions to the same CH_4 emissions: rapidly declining CH_4 emissions have a negative CO_2-warming-equivalent value based on GWP* (rapidly declining SLCF emissions result in declining temperature, relative to the warming caused by past SLCF emissions at a previous point in time) but a positive CO_2-equivalent value based on GWP or GTP (each SLCF emission from any source results in increased future radiative forcing and global average temperature than without this emission, regardless whether the rate of SLCF emissions is rising or declining). The different focus in these metrics can have important distributional consequences, depending on how they are used to inform emission targets (Reisinger et al., 2021; Lynch et al., 2021), but this has only begun to be explored in the scientific literature.

A key insight from WGI is that for a given emissions scenario, different metric choices can alter the time at which net zero GHG emissions are calculated to be reached, or whether net zero GHG emissions are reached at all (see SM2.3 for details). From a mitigation perspective, this implies that changing GHG emission metrics but retaining the same numerical CO_2-equivalent emissions targets would result in different climate outcomes. For example, achieving a balance of global anthropogenic GHG emissions and removals as stated in Article 4.1 of the Paris Agreement could, depending on the GHG emission metric used, result in different peak temperatures and in either stable or slowly or rapidly declining temperature after the peak(Tanaka and O'Neill, 2018; Allen et al., 2018; Fuglestvedt et al., 2018; Schleussner et al., 2019). A fundamental change in GHG emission metrics used to monitor achievement of existing emission targets could therefore inadvertently change their intended climate outcomes or ambition, unless existing emission targets are re-evaluated at the same time (*very high confidence*).

The WGIII contribution to the AR6 reports aggregate emissions and removals using updated GWP_{100} values from AR6 WGI unless stated otherwise. This choice was made on both scientific grounds (the alignment of GWP_{100} with a cost-benefit perspective under social discount rates and its performance from a global cost-effectiveness perspective) and for procedural reasons, including continuity with past IPCC reports and alignment with decisions under the Paris Agreement Rulebook (see Annex II.8 for further detail). A key constraint in the choice of metric is also that the literature assessed by WGIII predominantly uses GWP100 and often does not provide sufficient detail on emissions and abatement of individual gases to allow translation into different metrics. Presenting such information routinely in mitigation studies would enable the application of more diverse GHG emission metrics in future assessments to evaluate their contribution to different policy objectives.

All metrics have limitations and uncertainties, given that they simplify the complexity of the physical climate system and its response to past and future GHG emissions. No single metric is well-suited to all applications in climate policy. For this reason, the WGIII contribution to the AR6 reports emissions and mitigation options for individual gases where possible; CO_2-equivalent emissions are reported in addition to individual gas emissions where this is judged to be policy-relevant. This approach aims to reduce the ambiguity regarding mitigation potentials for specific gases and actual climate outcomes over time arising from the use of any specific GHG emission metric.

END CROSS CHAPTER BOX 2 HERE

2.2.2 Trends in the global GHG emissions trajectories and short-lived climate forcers

2.2.2.1 Anthropogenic greenhouse gas emissions trends

Global GHG emissions continued to rise since AR5, but the rate of emissions growth slowed (*high confidence*). GHG emissions reached 59±6.6 $GtCO_2eq$ in 2019 (Table 2.1 and Figure 2.5). In 2019, CO_2 emissions from FFI were 38 (±3.0) Gt, CO_2 from LULUCF 6.6±4.6 Gt, CH_4 11±3.2 $GtCO_2eq$, N_2O 2.7±1.6 $GtCO_2eq$ and F-gases 1.4±0.41 $GtCO_2eq$. There is *high confidence* that average annual GHG emissions for the last decade (2010-2019) were the highest on record in terms of aggregate CO_2eq emissions, but *low confidence* for annual emissions in 2019 as uncertainties are large considering the size and composition of observed increases in the most recent years (Minx et al., 2021; UNEP, 2020a).

2019 GHG emissions levels were higher compared to 10 and 30 years ago (*high confidence*): about 12% (6.5 $GtCO_2eq$) higher than in 2010 (53±5.7 $GtCO_2eq$) (AR5 reference year) and about 54% (21 $GtCO_2eq$) higher than in 1990 (38±4.8 $GtCO_2eq$) (Kyoto Protocol reference year and frequent NDC reference). GHG emissions growth slowed compared to the previous decade (*high confidence*): From 2010 to 2019 GHG emissions grew on average by about 1.3% per year compared to an average annual growth of 2.1% between 2000 and 2009. Nevertheless the absolute increase in average annual GHG emissions for 2010-2019 compared to 2000-2009 was 9.1 $GtCO_2eq$ and, as such, the largest observed in the data since 1970 (Table 2.1) – and most likely in human history (Friedlingstein et al., 2020; Gütschow et al., 2021b). Decade-by- decade growth in average annual GHG emissions was observed across all (groups of) gas as shown in Table 2.1, but for N_2O and CO_2-LULUCF emissions this is much more uncertain.

Table 2.1 Total anthropogenic GHG emissions ($GtCO_2eq\ yr^{-1}$) 1990-2019
CO_2 from fossil fuel combustion and industrial processes (FFI); CO_2 from Land Use, Land Use Change and Forestry (LULUCF); methane (CH_4); nitrous oxide (N_2O); fluorinated gases (F-gases: HFCs, PFCs, SF_6, NF_3). Aggregate GHG emission trends by groups of gases reported in Gt CO_2eq converted based on global warming potentials with a 100-year time horizon (GWP-100) from the IPCC Sixth Assessment Report. Uncertainties are reported for a 90% confidence interval.
Source: Minx et al. (2021)

	Average annual emissions ($GtCO_2eq$)					
	CO_2 FFI	CO_2 LULUCF	CH_4	N_2O	Fluorinated gases	GHG
2019	38±3.0	6.6±4.6	11±3.2	2.7±1.6	1.4±0.41	59±6.6
2010-2019	36±2.9	5.7±4.0	10±3.0	2.6±1.5	1.2±0.35	56±6.0
2000-2009	29±2.4	5.3±3.7	9.0±2.7	2.3±1.4	0.81±0.24	47±5.3
1990-1999	24±1.9	5.0±3.5	8.2±2.5	2.1±1.2	0.49±0.15	40±4.9
1990	23±1.8	5.0±3.5	8.2±2.5	2.0±1.2	0.38±0.11	38±4.8

Reported total annual GHG emission estimates differ between the Working Group III contributions in AR5 (Blanco et al., 2014) and AR6 (this chapter) mainly due to differing global warming potentials (*high confidence*). For the year 2010, total GHG emissions were estimated at 49±4.9 Gt CO_2eq in AR5 (Blanco et al., 2014), while we report 53±5.7 Gt CO_2eq here. However, in AR5 total GHG emissions were weighted based on GWP-100 values from IPCC SAR. Applying those GWP values to the 2010 emissions from AR6 yields 50 Gt CO_2eq (Forster et al., 2021a). Hence, observed differences are mainly due to the use of most recent GWP values, which have higher warming potentials for methane (29% higher for biogenic and 42% higher for fugitive methane) and 12% lower values for nitrous oxide (see Cross-Chapter Box 2 in this chapter).

Emissions growth has been persistent but varied in pace across gases. The average annual emission levels of the last decade (2010-2019) were higher than in any previous decade for each group of greenhouse gases: CO_2, CH_4, N_2O, and F-gases (*high confidence*). Since 1990, CO_2-FFI have grown by 67% (15 GtCO_2eq), CH_4 by 29% (2.4 GtCO_2eq), and N_2O by 33% (0.65 GtCO_2eq), respectively (Figure 2.5). Growth in fluorinated gases (F-gas) has been by far the highest with about 250% (1.0 GtCO_2eq), but it occurred from low levels. In 2019, total F-gas levels are no longer negligible with a share of 2.3% of global GHG emissions. Note that the F-gases reported here do not include chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), which are groups of substances regulated under the Montreal Protocol. The aggregate CO_2eq emissions of HFCs, HCFCs and CFCs were each approximately equal in 2016, with a smaller contribution from PFCs, SF_6, NF_3 and some more minor F-gases. Therefore, the GWP-weighted F-gas emissions reported here (HFCs, PFCs, SF_6, NF_3), which are dominated by the HFCs, represent less than half of the overall CO_2eq F-gas emissions in 2016 (Figure 2.3).

The only exception to these patterns of GHG emissions growth is net anthropogenic CO_2-LULUCF emissions, where there is no statistically significant trend due to high uncertainties in estimates (Figure 2.2, Figure 2.5; for a discussion see Chapter 2 Supplementary Material). While the average estimate from the bookkeeping models report a slightly increasing trend in emissions, NGHGI and FAOSTAT estimates show a slightly decreasing trend, which diverges in recent years (Figure 2.2). Similarly, trends in CO_2-LULUCF estimates from individual bookkeeping models differ: while two models (BLUE, OSCAR) show a sustained increase in emissions levels since the mid 1990s, emissions from the third model (HN) declined (see Figure 2.2; Friedlingstein et al., 2020). Differences in accounting approaches and their impacts CO_2 emissions estimates from land use is covered in Chapter 7 and in the Chapter 2 Supplementary Material (SM2.2). Note that anthropogenic net emissions from bioenergy are covered by the CO_2-LULUCF estimates presented here.

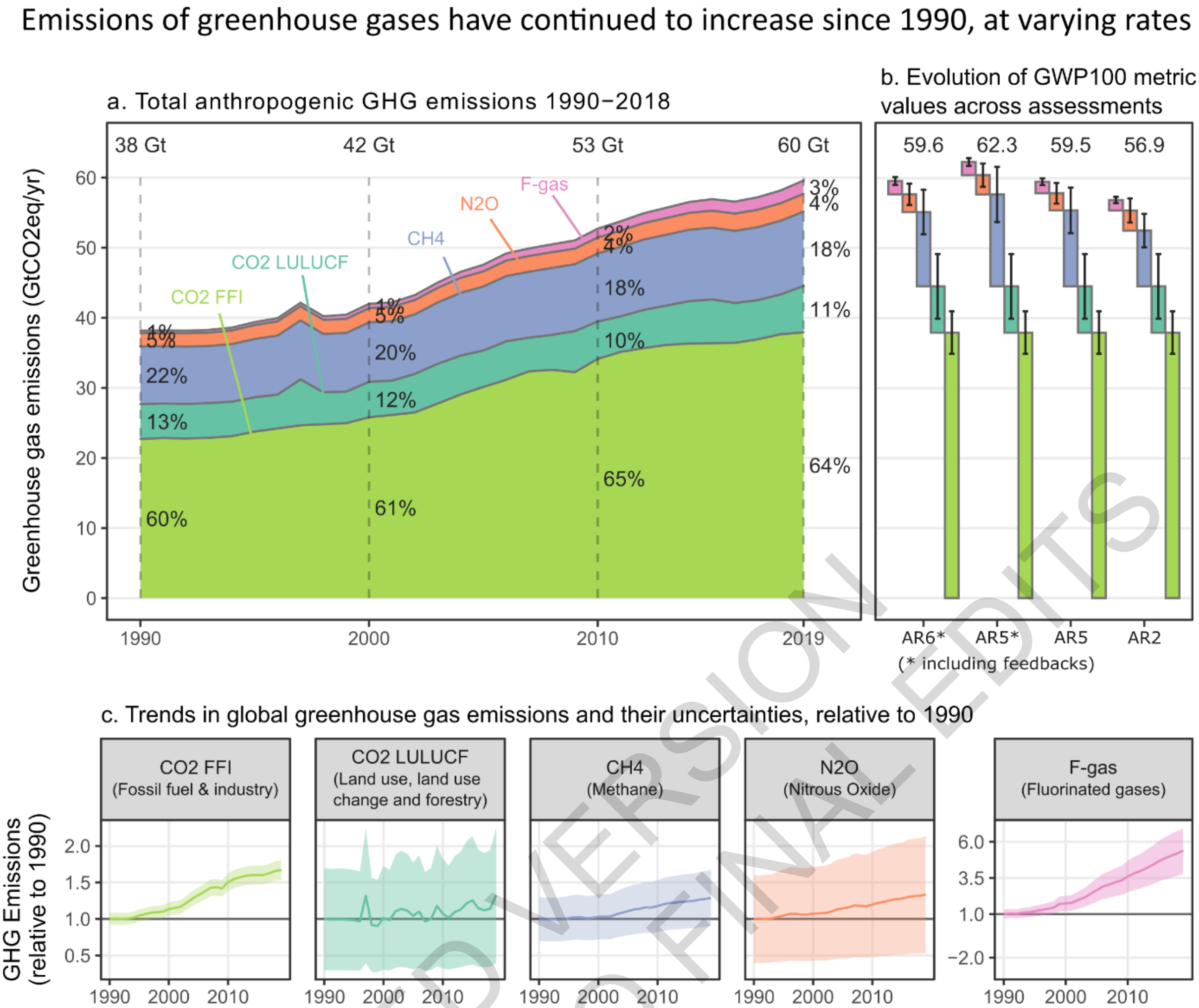


Figure 2.5 Total anthropogenic GHG emissions (Gt CO_2eq yr^{-1}) 1990-2019

CO_2 from fossil fuel combustion and industrial processes (FFI); net CO_2 from Land Use, Land Use Change and Forestry (LULUCF); methane (CH_4); nitrous oxide (N_2O); fluorinated gases (F-gases: HFCs, PFCs, SF_6, NF_3). Panel a: Aggregate GHG emission trends by groups of gases reported in Gt CO_2eq converted based on global warming potentials with a 100-year time horizon (GWP-100) from the IPCC Sixth Assessment Report. Panel b: Waterfall diagrams juxtaposes GHG emissions for the most recent year 2019 in CO_2 equivalent units using GWP-100 values from the IPCC's Second, Fifth, and Sixth Assessment Report, respectively. Error bars show the associated uncertainties at a 90% confidence interval. Panel c: individual trends in CO_2-FFI, CO_2-AFOLU, CH_4, N_2O and F-gas emissions for the period 1990-2019, normalised to 1 in 1990.

Source: Data from Minx et al., 2021

The CO_2-FFI share in total CO_2eq emissions has plateaued at about 65% in recent years and its growth has slowed considerably since AR5 (*high confidence*). CO_2-FFI emissions grew at 1.1% during the 1990s and 2.5% during the 2000s. For the last decade (2010s) - not covered by AR5 - this rate dropped to 1.2%. This included a short period between 2014-2016 with little or no growth in CO_2-FFI emissions mainly due to reduced emissions from coal combustion (Peters et al., 2017a; Qi et al., 2016; Jackson et al., 2016; Canadell et al., 2021). Subsequently, CO_2-FFI emissions started to rise again (Peters et al., 2017b; Figueres et al., 2018; Peters et al., 2020).

Starting in the spring of 2020 a major break in global emissions trends was observed due to lockdown policies implemented in response to the COVID-19 pandemic (*high confidence*) (Quéré et al., 2020; Le Quéré et al., 2021; Liu et al., 2020d; Forster et al., 2020; Bertram et al., 2021). Overall, global CO_2-FFI emissions are estimated to have declined by 5.8% [5.1%-6.3%] in 2020, or about 2.2 (1.9-2.4) $GtCO_2$

in total (Crippa et al., 2021; Friedlingstein et al., 2020; Liu et al., 2020d; IEA, 2021a; BP, 2021). This exceeds any previous global emissions decline since 1970, both in relative and absolute terms (Figure 2.6). Daily emissions, estimated based on activity and power-generation data, declined substantially compared to 2019 during periods of economic lockdown, particularly in April 2020 –as shown in Figure 2.6 – but rebounded by the end of 2020 (Le Quéré et al., 2021; Liu et al., 2020d; Quéré et al., 2020). Impacts were differentiated by sector, with road transport and aviation particularly affected. Inventories estimate the total power sector CO_2 reduction from 2019 to 2020 at 3% (IEA, 2021a) and 4.5% (Crippa et al., 2021). Approaches that predict near real-time estimates of the power sector reduction are more uncertain and estimates range more widely, between 1.8% (Le Quéré et al., 2021; Quéré et al., 2020), 4.1% (Liu et al., 2020d) and 6.8% (Bertram et al., 2021); the latter taking into account the over-proportional reduction of coal generation due to low gas prices and merit order effects. Due to the very recent nature of this event, it remains unclear what the exact short and long-term impacts on future global emissions trends will be.

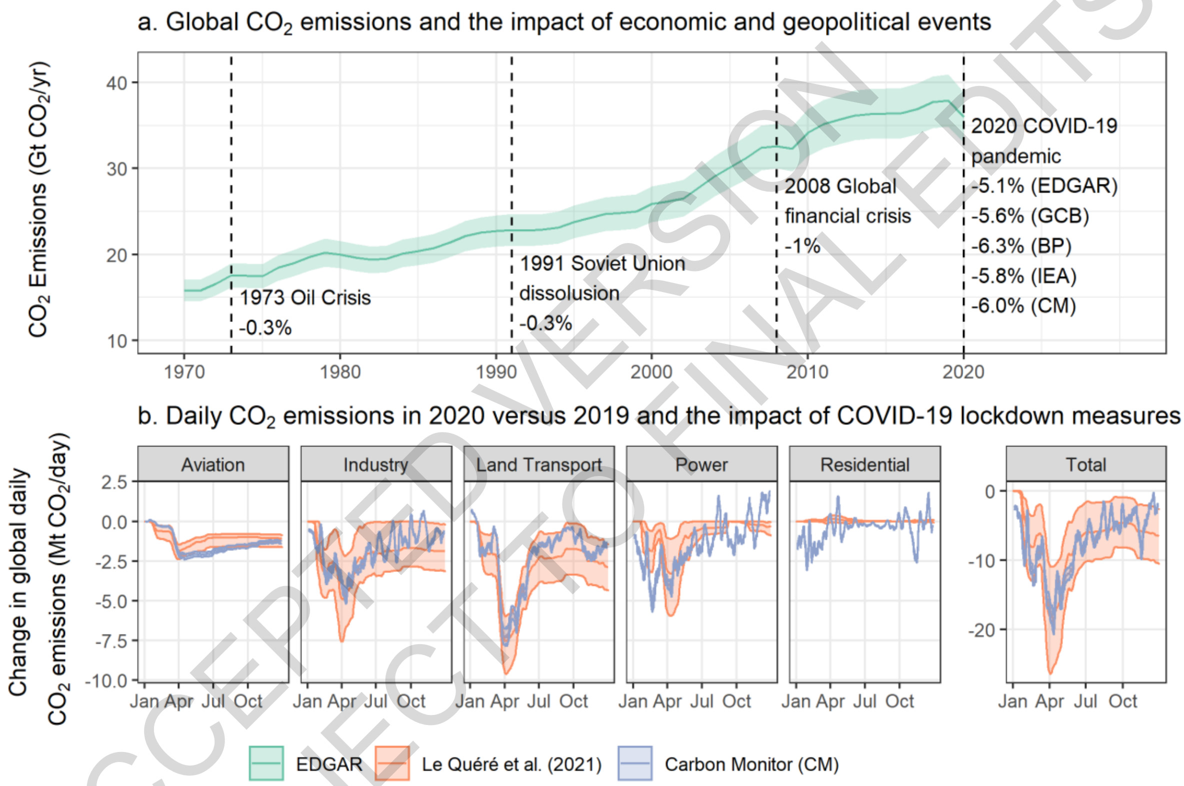


Figure 2.6 Global CO_2 emissions from fossil fuel combustion and industry (FFI) in 2020 and the impact of COVID-19

Panel a depicts CO_2-FFI emissions over the past 5 decades ($GtCO_2yr^{-1}$). The single year declines in emissions following major economic and geopolitical events are shown, as well as the decline recorded in 5 different datasets for emissions in 2020 (COVID-19) compared to 2019 (no COVID-19). Panel b depicts the change in global daily carbon emissions ($MtCO_2$ per day) in 2020 compared to 2019, showing the impact of COVID-19 lockdown policies.

Source: Crippa et al. (2021), Friedlingstein et al. (2020), BP (BP, 2021), IEA (IEA, 2021a), Carbon Monitor (Liu et al., 2020d), Le Quéré et al. (Quéré et al., 2020).

From 1850 until around 1950, anthropogenic CO_2 emissions were mainly (>50%) from land-use, land use change and forestry (Figure 2.7). Over the past half-century CO_2 emissions from LULUCF have remained relatively constant around 5.1±3.6 $GtCO_2$ but with a large spread across estimates (Le Quéré et al., 2018a; Friedlingstein et al., 2020, 2019). By contrast, global annual FFI-CO_2 emissions have continuously grown since 1850 and since the 1960s from a decadal average of 11±0.9 $GtCO_2$ to 36±2.9 $GtCO_2$ during 2010-2019 (see Table 2.1).

Cumulative CO_2 emissions since 1850 reached 2400±240 $GtCO_2$ in 2019 (*high confidence*)[7]. More than half (62%) of total emissions from 1850 to 2019 occurred since 1970 (1500±140 $GtCO_2$), about 42% since 1990 (1000±90 $GtCO_2$) and about 17% since 2010 (410±30 $GtCO_2$) (Friedlingstein et al., 2020; Canadell et al., 2021; Friedlingstein et al., 2019) (Figure 2.7). Emissions in the last decade are about the same size as the remaining carbon budget of 400±220 (500, 650) $GtCO_2$ for limiting global warming to 1.5°C and between one third and half the 1150±220 (1350, 1700) $GtCO_2$ for limiting global warming below 2°C with a 67% (50%, 33%) probability, respectively (Canadell et al., 2021). At current (2019) levels of emissions, it would only take 8 (2-15) and 25 (18-35) years to emit the equivalent amount of CO_2 for a 67th percentile 1.5°C and 2°C remaining carbon budget, respectively. Related discussions of carbon budgets, short-term ambition in the context of NDCs, pathways to limiting warming to well below 2°C and carbon dioxide removals are mainly discussed in Chapters 3, 4, and 12, but also Section 2.7 of this chapter.

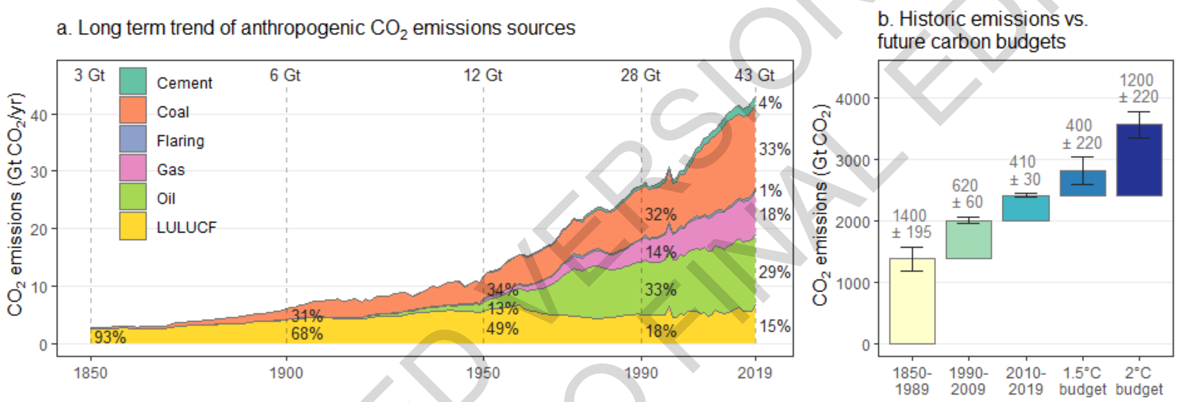


Figure 2.7 Historic anthropogenic CO_2 emission and cumulative CO_2 emissions (1850-2019) as well as remaining carbon budgets for limiting warming to 1.5°C and 2°C

Panel a shows historic annual anthropogenic CO_2 emissions ($GtCO_2\ yr^{-1}$) by fuel type and process. Panel b shows historic cumulative anthropogenic CO_2 emissions for the periods 1850-1989, 1990-2009, and 2010-2019 as well as remaining future carbon budgets as of 1.1.2020 to limit warming to 1.5°C and 2°C at the 67th percentile of the transient climate response to cumulative CO_2 emissions. The whiskers indicate a budget uncertainty of ±220 $GtCO_2eq$ for each budget and the aggregate uncertainty range at 1 standard deviation for historical cumulative CO_2 emissions, consistent with Working Group 1.

Sources: Friedlingstein et al. (2020) and Canadell et al. (2021).

Comparisons between historic GHG emissions and baseline projections provide increased evidence that global emissions are not tracking high-end scenarios (Hausfather and Peters, 2020), and rather followed "middle-of-the-road" scenario narratives in the earlier series, and by combinations of "global-sustainability" and "middle-of-the-road" narratives in the most recent series (SRES and SSP-baselines) (Strandsbjerg Tristan Pedersen et al., 2021; Pedersen et al., 2020). As countries increasingly implement climate policies and technology costs continue to evolve, it is expected emissions will continually shift away from scenarios that assume no climate policy but remain insufficient to limit warming to below 2°C (Hausfather and Peters, 2020; Vrontisi et al., 2018; UNEP, 2020b; Roelfsema et al., 2020).

FOOTNOTE [7] For consistency with WG1, uncertainties in this paragraph are reported at a 68% confidence interval. This reflects the difficulty in the WG1 context of characterizing the uncertainty in the CO2 fluxes between the atmosphere and the ocean and land reservoirs individually, particularly on an annual basis, as well as the difficulty of updating the emissions from land use change.

The literature since AR5 suggests that compared to historical trends baseline scenarios might be biased towards higher levels of fossil fuel use compared to what is observed historically (Ritchie and Dowlatabadi, 2017; Ritchie, 2019; Ritchie and Dowlatabadi, 2018; Creutzig et al., 2021). Ritchie and Dowlatabadi (2017) show that per-capita primary energy consumption in baseline scenarios tends to increase at rates faster than those observed in the long-term historical evidence – particularly in terms of coal use. For example, SSP5 envisions a 6-fold increase in per capita coal use by 2100 – against flat long-term historical observations – while the most optimistic baseline scenario SSP1-Sustainability is associated with coal consumption that is broadly in line with historical long-term trends (Ritchie and Dowlatabadi, 2017). In contrast, models have struggled to reproduce historical upscaling of wind and solar and other granular energy technologies (Creutzig et al., 2017; Wilson et al., 2020b; Sweerts et al., 2020; Wilson et al., 2013; van Sluisveld et al., 2015; Shiraki and Sugiyama, 2020).

2.2.2.2 Other short-lived climate forcers

There are other emissions with shorter atmospheric lifetimes that contribute to climate changes. Some of them like aerosols, sulphur emissions or organic carbon reduce forcing, while others like black carbon, carbon monoxide or non-methane organic compounds (NMVOC) contribute to warming (also see Figure 2.4) as assessed in Working Group I (Forster et al., 2021c; Naik et al., 2021a). Many of these other short-lived climate forcers (SLCFs) are co-emitted during combustion processes in power plants, cars, trucks, airplanes, but also during wildfires and household activities such as traditional cooking with open biomass burning. As these co-emissions have implications for net warming, they are also considered in long-term emission reduction scenarios as covered in the literature (Smith et al., 2020; Rauner et al., 2020b; Vandyck et al., 2020; Harmsen et al., 2020) as well as Chapter 3 of this report. These air pollutants are also detrimental to human health (e.g. Lelieveld et al., 2015, 2018; Vohra et al., 2021). For example, Lelieveld et al. (2015) estimates a total of 3.3 (1.6-4.8) million pre-mature deaths in 2010 from outdoor air pollution. Reducing air-pollutants in the context of climate policies therefore lead to substantial co-benefits of mitigation efforts (Rauner et al., 2020a; Rao et al., 2017; Von Stechow et al., 2015; Lelieveld et al., 2019). Here we only briefly outline the major trends in emissions of short-lived climate forcers.

Conventional air pollutants that are subject to significant emission controls in many countries include SO_2, NO_x, BC and CO. From 2015 to 2019, global SO_2 and NOx emissions have declined, mainly due to reductions in energy systems (Figure 2.8). Reductions in BC and CO emissions appear to have occurred over the same period, but trends are less certain due to the large contribution of emissions from poorly quantified traditional biofuel use. Emissions of CH_4, OC and NMVOC have remained relatively stable in the past five years. OC and NMVOC may have plateaued, although there is additional uncertainty due to sources of NMVOCs that may be missing in current inventories (McDonald et al., 2018).

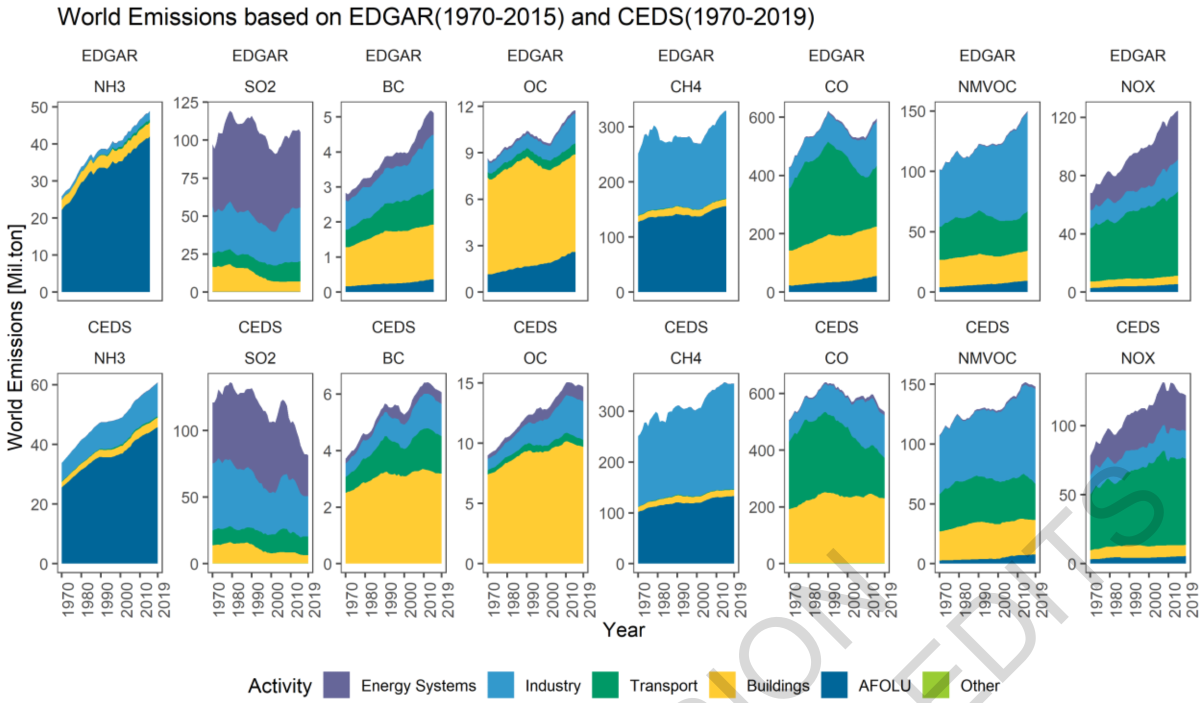


Figure 2.8 Air pollution emissions in by major sectors from CEDS (1970-2019) and EDGAR (1970-2015) inventories

Source: Crippa et al., 2019a, 2018; O'Rourke et al., 2020; McDuffie et al., 2020

2.2.3 Regional GHG emissions trends

Regional contributions to global GHG emissions have shifted since the beginning of the international climate negotiations in the 1990s (*high confidence*). As shown in Figure 2.9, developed countries as a group have not managed to reduce GHG emissions substantially, with fairly stable levels at about 15 $GtCO_2eq\ yr^{-1}$ between 1990 and 2010, while countries in Asia and the Developing pacific have rapidly increased their share of global GHG emissions – particularly since the 2000s (Jackson et al., 2019; Peters et al., 2020; UNEP, 2020c; Crippa et al., 2021; IEA, 2021b).

Most global GHG emission growth occurred in Asia and Developing Pacific, which accounted for 77% of the net 21 $GtCO_2eq$ increase in GHG emissions since 1990, and 83% of the net 6.5 $GtCO_2eq$ increase since 2010.[8] Africa contributed 11% of GHG emissions growth since 1990 (2.3 $GtCO_2eq$) and 10% (0.7 $GtCO_2eq$) since 2010. The Middle East contributed 10% of GHG emissions growth since 1990 (2.1 $GtCO_2eq$) and also 10% (0.7 $GtCO_2eq$) since 2010. Latin America and the Caribbean contributed 11% of GHG emissions growth since 1990 (2.2 $GtCO_2eq$), and 5% (0.3 $GtCO_2eq$) since 2010. Two regions, Developed Countries, and Eastern Europe and West-Central Asia, reduced emissions overall since 1990, by -1.6 $GtCO_2eq$ and -0.8 $GtCO_2eq$, respectively. However, emissions in the latter region started to grow again since 2010, contributing to 5% of the global GHG emissions change (0.3 $GtCO_2eq$).

Average annual GHG emission growth across all regions slowed between 2010-2019 compared to 1990-2010, with the exception of Eastern Europe and West-Central Asia. Global emissions changes tend to be driven by a limited number of countries, principally the G20 group (UNEP, 2020c; Xia et al., 2021; Friedlingstein et al., 2020). For instance, the slowing of global GHG emissions between 2010-

FOOTNOTE[8] Note that GHG emissions from international aviation and shipping could not be attributed to individual regions, while CO_2 emissions from AFOLU could not be attributed to individual countries. Change in GHG emissions that can be easily assigned to regions is 20.3 of 20.8 $GtCO_2eq$ for 1990-2019 and 6.3 of 6.5 $GtCO_2eq$ for 2010-2019.

2019, compared to the previous decade, was primarily triggered by substantial reductions in GHG emissions growth in China. Two countries (China, India) contributed more than 50% to the net 6.5 $GtCO_2eqyr^{-1}$ increase in GHG emissions during 2010-2019 (at 39% and 14%, respectively), while ten countries (China, India, Indonesia, Vietnam, Iran, Turkey, Saudi Arabia, Pakistan, Russian Federation, Brazil) jointly contributed about 75% (Figure 2.9) (see also Minx et al., 2021; Crippa et al., 2021).

GHG and CO_2-FFI levels diverge starkly between countries and regions (*high confidence*) (UNEP, 2020c; Jackson et al., 2019; Friedlingstein et al., 2020; Crippa et al., 2021). Developed Countries sustained high levels of per capita CO_2-FFI emissions at 9.5 t CO_2/cap in 2019 (but with a wide range of 1.9-16 tCO_2/cap). This is more than double that of three developing regions – 4.4 (0.3-12.8) tCO_2/cap in Asia and Developing Pacific, 1.2 (0.03-8.5) tCO_2/cap in Africa, and 2.7 (0.3-24) tCO_2/cap in Latin America[9]. Per capita CO_2-FFI emissions were 9.9 (0.89-15) tCO_2/cap in Eastern Europe and West-Central Asia, and 8.6 (0.36-38) tCO_2/cap in the Middle East. CO_2-FFI emissions in the three developing regions together grew by 26% between 2010 and 2019, compared to 260% between 1990 and 2010, while in Developed Countries emissions contracted by 9.9% between 2010-2019 and by 9.6% between 1990-2010.

Least developed countries contributed only a negligible proportion of historic GHG emissions growth and have the lowest per capita emissions. As of 2019 they contribute 3.3% of global GHG emissions, excluding LULUCF CO_2, despite making up 13.5% of the global population. Since the start of the industrial revolution in 1850 up until 2019, they contributed 0.4% of total cumulative CO_2 emissions (Figure 2.10). Conversely, Developed Countries have the highest share of historic cumulative emissions (Matthews, 2016; Gütschow et al., 2016; Rocha et al., 2015), contributing approximately 57% (Figure 2.10), followed by Asia and developing Pacific (21%), Eastern Europe and West-Central Asia (9%), Latin America and the Caribbean (4%), the Middle East (3%), and Africa (3%). Developed Countries still have the highest share of historic cumulative emissions (45%) when CO_2-LULUCF emissions are included, which typically account for a higher proportion of emissions in developing regions (Figure 2.10).

A growing number of countries have reduced CO_2 and GHG emissions for longer than 10 years (*medium confidence*) (Le Quéré et al., 2019; Lamb et al., 2021a; Wu et al., 2021; Burck et al., 2021). Data up to 2018 indicates that about 24 countries have reduced territorial CO_2 and GHG emissions (excluding LULUCF CO_2), as well as consumption-based CO_2 emissions, for at least 10 years (Lamb et al., 2021a). Uncertainties in emissions levels and changes over time prevents a precise assessment of reductions in some cases. Of these 24 countries, 12 peaked emissions in the 2000s; 6 have sustained longer reductions since the 1970s; and 6 are former members of the Eastern Bloc, where emissions dropped rapidly in the 1990s and continued declining at a slower pace thereafter. Country emissions reductions have been driven by both climate and non-climate policies and factors, including structural changes. To date, most territorial emissions reductions were realised in the electricity and heat sector, followed by industry and buildings, while in many cases transport emissions have increased since countries reached their overall emissions peak (Climate Transparency, 2021; Lamb et al., 2021a). One estimate of the total reduction in annual GHG emissions – from peak years to 2018 – sums to 3.2 $GtCO_2eq$ across all decarbonising countries (Lamb et al., 2021a). These reductions have therefore been far outweighed by recent emissions growth. However, climate policy related reductions may be even larger when compared against a counterfactual case of emissions growth across different sectors (Eskander and Fankhauser, 2020b) (Cross-Chapter Box 1 in Chapter 1; Section 2.8).

The recent (2010-2019) emissions changes of some countries are in line with pathways that limit *likely* warming to below 2°C (e.g. -4% average annual reductions) (Figure 2.10). Overall, there are first

FOOTNOTE[9] In all cases, constraining countries within the emissions range to those larger than 1 million population.

country cases emerging that highlight the feasibility of sustained emission reductions outside of periods of economic disruption (Lamb et al., 2021a). However, such pathways will need to be taken by many more countries for keeping the goals of the Paris Agreement in reach (Höhne et al., 2020; Kriegler et al., 2018a; Roelfsema et al., 2020; den Elzen et al., 2019) as analysed by Chapter 4 of this report. Moreover, observed reductions are not yet consistent and long-term, nor achieved across all sectors, nor fully aligned with country NDC targets (Le Quéré et al., 2019; Lamb et al., 2021a; den Elzen et al., 2019; Climate Transparency, 2021; Burck et al., 2021).

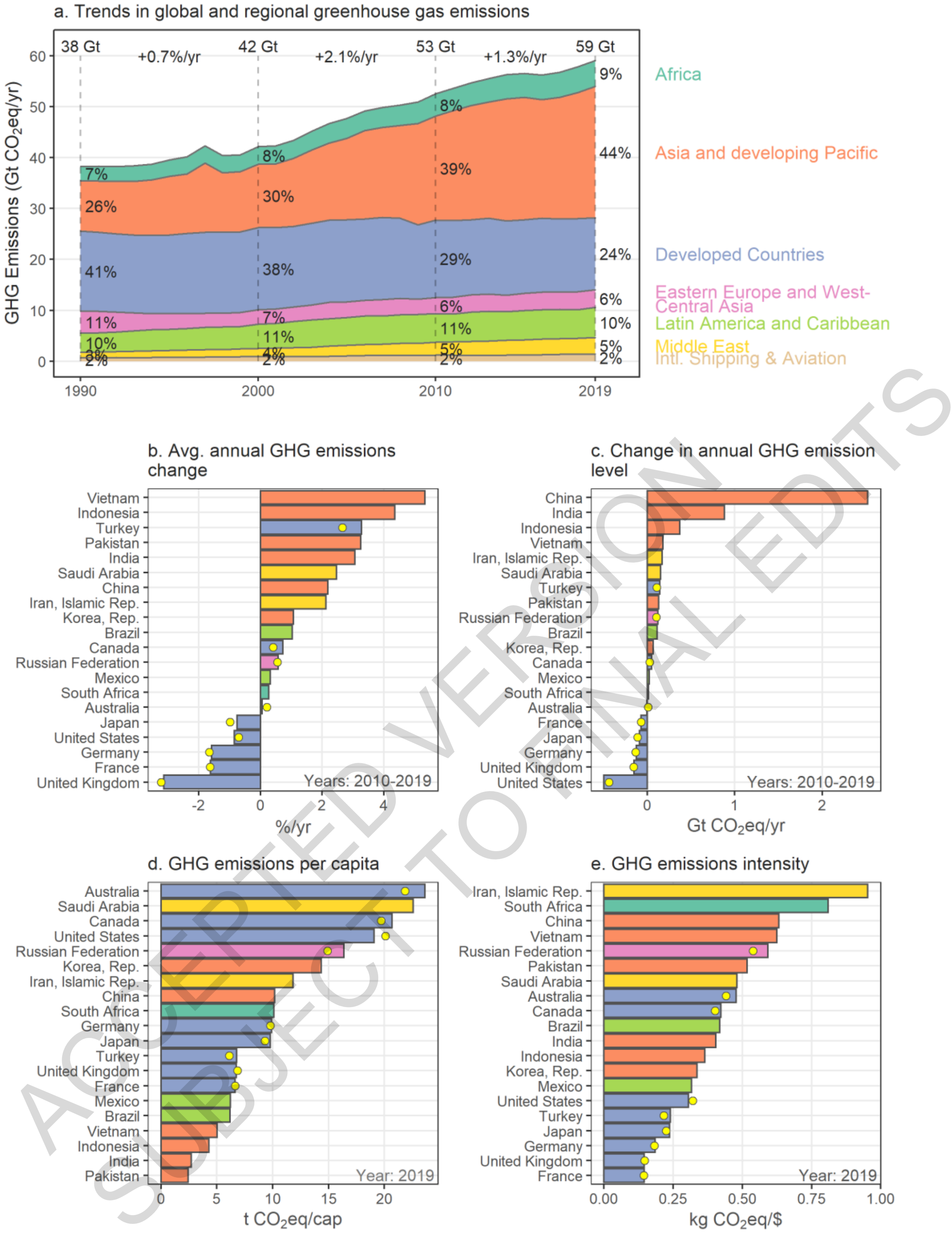


Figure 2.9 Change in regional GHGs from multiple perspectives and their underlying drivers
Panel a: Regional GHG emission trends (in $GtCO_2eq\ yr^{-1}$) for the time period 1990-2019. GHG emissions from international aviation and shipping are not assigned to individual countries and shown separately. Panels b and c: Changes in GHG emissions for the 20 largest emitters (as of 2019) for the post-AR5 reporting period 2010-2019 in relative (% annual change) and absolute terms ($GtCO_2eq$). Panels d and e: GHG emissions per capita and per GDP in 2019 for the 20 largest emitters (as of 2019). GDP estimated using constant international purchasing power parity (USD 2017). Emissions are converted into CO_2-equivalents based on global warming potentials with a 100 year time horizon (GWP-100) from the IPCC

Sixth Assessment Report (Forster et al., 2021a)**. The yellow dots represent the emissions data from UNFCCC-CRFs (2021) that were accessed through Gütschow et al.** (2021a)**. Net LULUCF CO_2 emissions are included in panel a, based on the average of three bookkeeping models (see Section 2.2), but are excluded in panels b due to a lack of country resolution.**

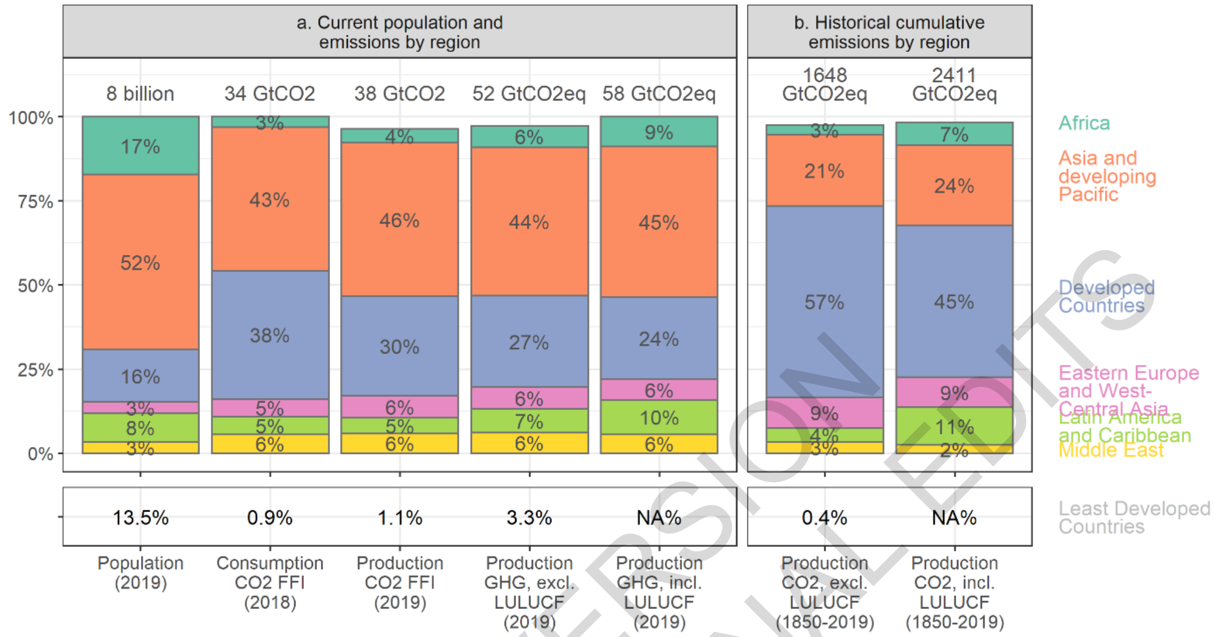


Figure 2.10 Different perspectives on historic emissions and equity

Panel a shows the regional proportion (%) of total global population or emissions in 2018 or 2019, for five categories: population (persons), consumption-based CO_2-FFI emissions ($GtCO_2$), production-based CO_2-FFI emissions ($GtCO_2$), production-based GHG emissions excluding CO_2-LULUCF ($GtCO_2eq$), and production-based GHG emissions including CO_2-LULUCF ($GtCO_2eq$). Panel b shows the regional proportion (%) of total cumulative production-based CO_2 emissions from 1850 to 2019, including and excluding CO_2-LULUCF ($GtCO_2$). In the lower panels the proportion of each population or emissions category attributable to Least Developed Countries is shown, where available (CO_2-LULUCF data is not available for this region). GHG emissions are converted into CO_2-equivalents based on global warming potentials with a 100 year time horizon (GWP-100) from the IPCC Sixth Assessment Report (Forster et al., 2021a)**.**

Source: Data from Friedglinstein et al. (2020)

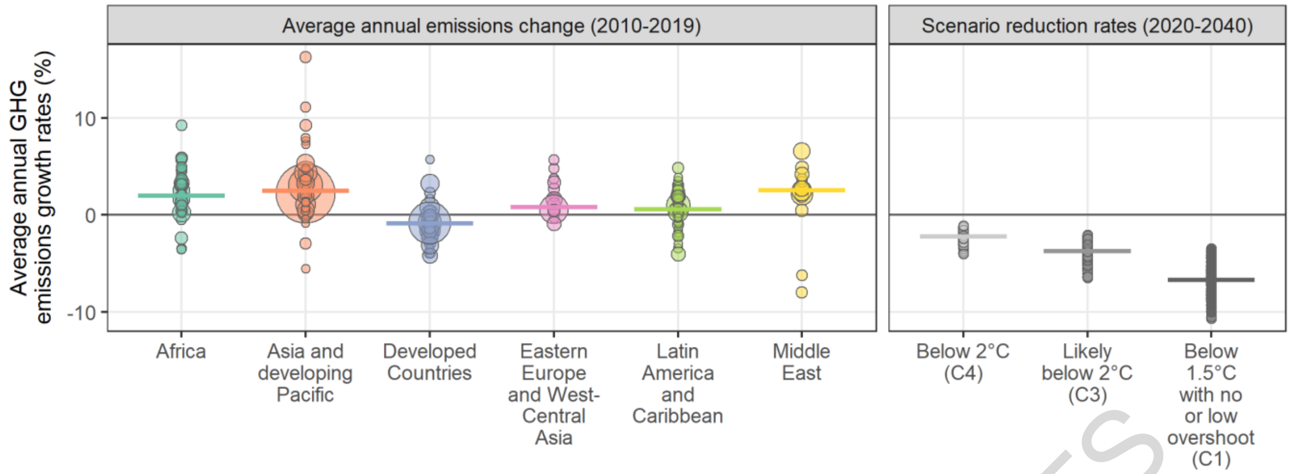


Figure 2.11 Recent average annual GHG emissions changes of countries (left panel) versus rates of reduction in 1.5°C and 2°C mitigation scenarios

Scenario data is taken from Chapter 3 of this report with the scenario categories defined and summarised in Table 3.2 in Chapter 3. Emissions are converted into CO_2-equivalents based on global warming potentials with a 100 year time horizon (GWP-100) from the IPCC Sixth Assessment Report (Forster et al., 2021a)**. Circles indicate countries (left panel) or individual scenarios (right panel), the former scaled by total emissions in 2019. Horizontal lines indicate the region average emissions change (left panel), or scenario category average emissions change (right panel).**

Source: Data from Minx et al., 2021

2.2.4 Sectoral GHG emission trends

In 2019, 34% (20 $GtCO_2eq$) of the 59 $GtCO_2eq$ GHG emissions came from the energy sector, 24% (14 $GtCO_2eq$) from industry, 22% (13 $GtCO_2eq$) from AFOLU, 15% (8.7 $GtCO_2eq$) from transport and 6% (3.3 $GtCO_2eq$) from buildings (Figure 2.12). The relative size of each sector depends on the exact definition of sector boundaries (de la Rue du Can et al., 2015; Lamb et al., 2021b). The largest individual sub-sector contributing to global GHG emissions in 2019 was electricity and heat generation at 14 $GtCO_2eq$. This subsector can be reallocated to consuming sectors as indirect (Scope 2) emissions to emphasize the role of final energy demand and demand-side solutions in climate change mitigation (Creutzig et al., 2018) (Chapter 5). This increases the emission share of the industry sector to 34% and of the buildings sector to 16%.

Average annual GHG emissions growth has been fastest in the transport sector with about 1.8% for the most recent period 2010-2019, followed by direct emissions in the industry sector (1.4%) and the energy sector (1%) (Figure 2.13). This is different to growth patterns observed in the previous decade as reported in AR5 (IPCC, 2014a; Blanco et al., 2014). Between 2000 and 2009 fastest GHG emissions growth was observed for industry with 3.4% followed by the energy sector with 2.3%. GHG emission growth in the transport sector has been stable across both periods at about 1.8%, while direct building emissions growth averaged below 1% during 2010-2019. Ranking of high emitting sectors by direct emissions highlights the importance of the LULUCF CO_2 (6.6 $GtCO_2eq$), road transport (6.1 $GtCO_2eq$), metals (3.1 $GtCO_2eq$), and other industry (4.4 $GtCO_2eq$) sub-sectors. Overall, some of the fastest growing sources of sub-sector emissions from 2010 to 2019 have been international aviation (+3.4%)[10],

FOOTNOTE[10] Note that this does not include the additional warming impacts from aviation due to short lived climate forcers, which are assessed in Chapter 10 (Section 10.5) domestic aviation (+3.3%), inland shipping (+2.9%), metals (+2.3%), international shipping (+1.7%), and road transport (+1.7%).

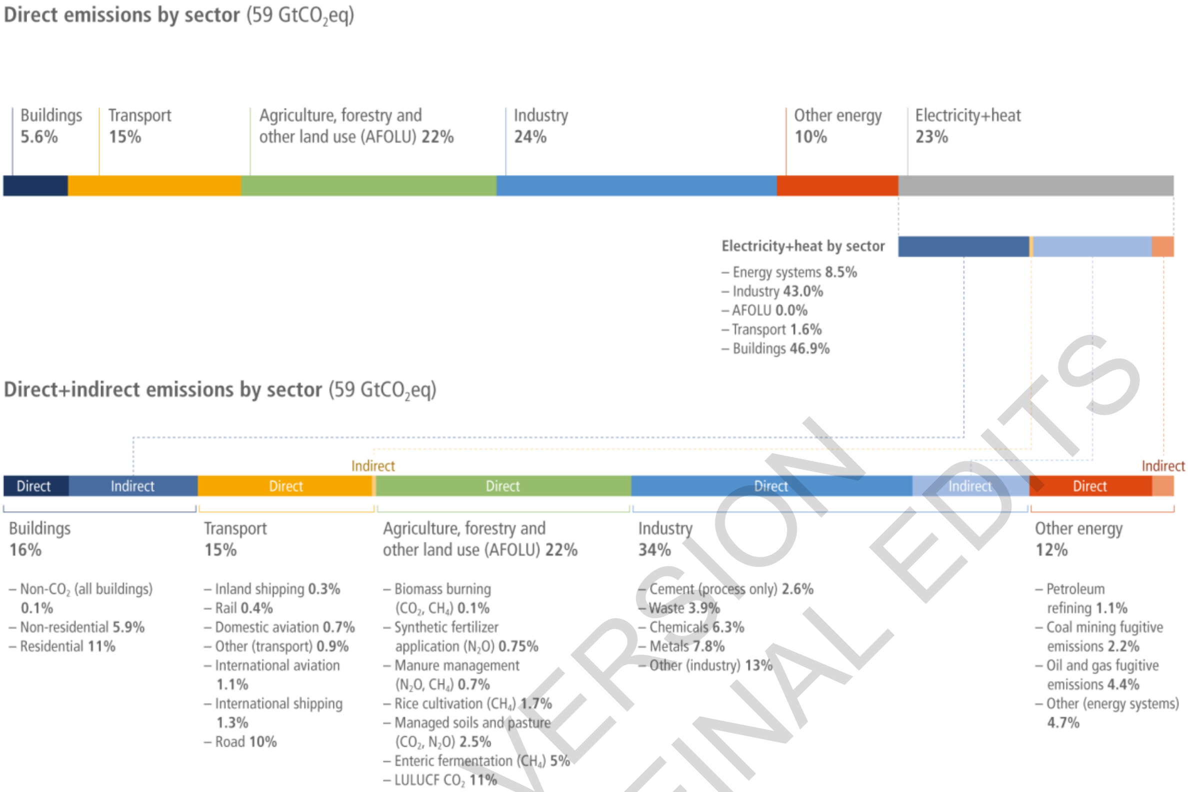


Figure 2.12 Total anthropogenic direct and indirect GHG emissions for the year 2019 (in $GtCO_2eq$) by sector and sub-sector.

Direct emissions estimates assign emissions to the sector in which they arise (scope 1 reporting). Indirect emissions – as used here - refer to the reallocation of emissions from electricity and heat to the sector of final use (scope 2 reporting). Note that cement refers to process emissions only, as a lack of data prevents the full reallocation of indirect emissions to this sector. More comprehensive conceptualisations of indirect emissions including all products and services (scope 3 reporting) are discussed in Section 2.3 of this chapter. Emissions are converted into CO_2-equivalents based on global warming potentials with a 100 year time horizon (GWP-100) from the IPCC Sixth Assessment Report. Percentages may not add up to 100 across categories due to rounding at the second significant digit.

Source: Based on Lamb et al. (2021b); Data: Minx et al., 2021

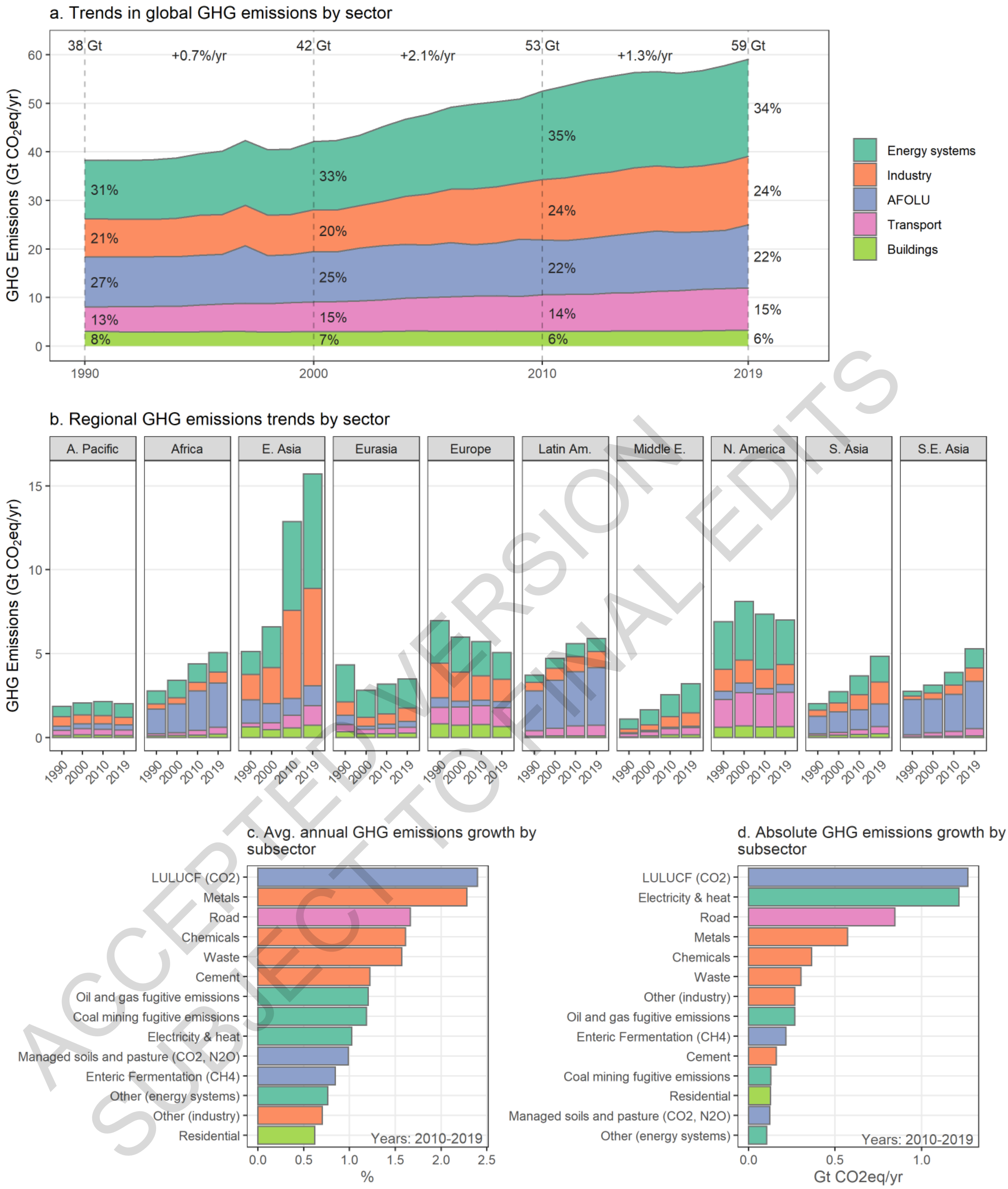


Figure 2.13 Total annual anthropogenic GHG emissions by major economic sector and their underlying trends by region

Panel a: Trends in total annual anthropogenic GHG emissions (in $GtCO_2eq\ yr^{-1}$) by major economic sector. Panel b: Trends in total annual anthropogenic GHG emissions (in $GtCO_2eq\ yr^{-1}$) by major economic sector and region. Panels c and d: Largest sub-sectoral changes in GHG emissions for the reporting period 2010-2019 in relative (% annual change) and absolute terms ($GtCO2eq\ yr^{-1}$). Emissions are converted into CO_2-equivalents based on global warming potentials with a 100 year time horizon (GWP-100) from the IPCC Sixth Assessment Report.

Source: Based on Lamb et al. (2021b); Data: Minx et al. (2021), Crippa et al. (2021)

2.3 Past and present trends of consumption-based CO_2 emissions (CBEs) and emissions embodied in trade

2.3.1 Scope, variability, and uncertainty of CBEs

Consumption is increasingly met by global supply chains often involving large geographical distances and causing emissions in producing countries (Hubacek et al., 2014, 2016; Wiedmann and Lenzen, 2018). Therefore, accounting of emissions of production along the entire supply chain to fulfil final demand, so-called consumption-based emissions (CBEs) is necessary to understand why emissions occur and to what extent consumption choices and associated supply chains contribute to total emissions, and ultimately how to influence consumption to achieve climate mitigation targets and environmental justice (Vasconcellos, 2019).

Production-based emissions (PBEs) and territorial emissions resulting from the production and consumption of goods and services within a region as well as for export production are often used by authorities to report carbon emissions (Peters, 2008) (see also Section 2.2). PBEs also include emissions from international activities (e.g., international aviation/shipping and non-resident activities), which are excluded from territorial emissions (Karstensen et al., 2018; Shan et al., 2018). In contrast, CBEs refer to emissions along the entire supply chains induced by consumption irrespective of the place of production (Liu et al., 2015b). This reflects a shared understanding that a wider system boundary going beyond territorial emissions is important to avoid outsourcing of pollution and to achieve global decarbonisation. CBEs allow to identify new policy levers through providing information on a country's trade balance of embodied emissions, households' carbon implications of their lifestyle choices, companies' upstream emissions as input for supply chain management, and cities' footprints outside their administrative boundaries (Davis and Caldeira, 2010; Feng et al., 2013). Kander et al., (2015) proposed a technology-adjusted consumption-based emission accounting (TCBA) approach to address the issue of carbon intensity in exports. TCBA incorporates emissions embodied in trade but also adjust for differences in carbon efficiency in exports of different countries. Unlike PBEs, there are no internationally agreed upon approaches to calculate CBEs, making it a major drawback for mainstreaming the use of this indicator in policy making.

There are other proposed emission accounting approaches used in different circumstances. Historical cumulative emissions (HCEs) are used when analysing countries' historic contribution to emissions and responsibility for emission reduction. HCEs account for a country's cumulative past emissions, which may be significantly different from the country's current annual emissions (Botzen et al., 2008; Ritchie 2019b), but are sensitive to the choice of cut-off period. For example, the United States and EU-27 countries plus the United Kingdom contributed respectively 13.4% and 8.7% to global PBEs in 2019 (Crippa et al., 2020), however, they emitted around 25% and 22% of global historical PBEs since 1751 (Ritchie, 2019). In contrast, extraction-based emissions (EBEs) accounting allocates all emissions from burning fossil fuels throughout the supply chains to the country where the fuels were extracted (Steininger and Schinko, 2015). EBEs can be calculated by multiplying primary energy extraction of fossil fuels with their respective carbon content adjusting for the fraction of fossil fuels that is not combusted (Erickson and Lazarus, 2013). Another approach for accounting emissions is income-based emission accounting (IBE), which traces emissions throughout all supply chains and allocates emissions to primary inputs (e.g., capital and labour). In other words, IBEs investigates a country's direct and indirect downstream GHG emissions enabled by its primary inputs (Liang et al., 2017a). All these approaches provide complementary information and different angles to assigning responsibility for emissions reductions.

START BOX 2.2 HERE

Box 2.2 Policy applications of consumption-based emissions

- Consumption-based emissions provide additional or complementary information to production-based emissions that can be used for a variety of policy applications. These include:Complementary national-level emissions accounting and target or budget setting
- Raising awareness and increasing understanding of the GHG effects of consumption
- Accounting for and understanding of distributional and responsibility issues in GHG emissions mitigation, both nationally and internationally.
- Incentives to change consumption patterns or reduce consumption (e.g., through taxation policies)
- Accounting for and understanding of carbon leakage and emissions embodied in trade*)
- International emissions trading schemes or linked national schemes
- Trade policies addressing emissions embodied in trade and international supply chains (e.g., border tax adjustments and clean technology transfers, carbon offsetting or financing, etc.)
- Including embodied emissions in product performance standards and labelling
- Policies of public and private procurement
- Agreements with international suppliers
- Discussing the climate impacts of lifestyles and inequalities in consumption and associated emissions

Above points are based on a synopsis of studies (Steininger et al., 2014; Afionis et al., 2017; Hubacek et al., 2017b; Wang and Zhou, 2018; Bolea et al., 2020)

* Note, however, that comparing embodied emissions in trade between countries is further complicated by the fact that emission intensities differ across countries. Approaches to adjust for these differences and facilitate comparisons have been suggested, e.g., by (Baumert et al., 2019; Dietzenbacher et al., 2020; Jakob, 2020; Kander et al., 2015). Many different approaches on how to share responsibility between producers and consumers have been proposed in designing effective integrated global climate policies (Yang et al., 2015; Liu and Fan, 2017; Zhu et al., 2018; Khajehpour et al., 2019; Jakob et al., 2021). Ultimately, assigning responsibility is normative.

END BOX 2.2 HERE

The dominant method for calculating CBEs of nations is global multi-region input-output (GMRIO) analysis (Wiedmann and Lenzen, 2018), with other methods playing a minor role, e.g. analysing bilateral trade flows of products and their life-cycle emission factors (Sato, 2014). Generally, the uncertainties associated with CBEs depends on the choice of the dataset/model used for calculation, which differs according to a) the national economic and trade data used, b) the emissions data used, c) the sector or product-level aggregation, d) the regional aggregation, e) the conceptual scope (e.g., residential vs territorial accounting principle) and f) the model construction techniques, which include table balancing algorithms and ways of dealing with missing or conflicting data (Moran and Wood, 2014; Owen, 2017; Wieland et al., 2018; Wood et al., 2018b, 2019a). When excluding systematic error sources, research has shown that the stochastic relative standard variation (RSD) of total national CBE is not significantly different to that from PBE accounts and in the region of 5-15% (Lenzen et al., 2010; Wood et al., 2018b, 2019a)

Six global accounts for consumption-based GHG emissions at the country level are widely used (Table 2.2). Each dataset has been constructed by different teams of researchers, covers different time periods and contains CBEs estimates for different sets of countries and regions (Owen, 2017).

Table 2.2 Features of six global datasets for consumption-based emissions accounts

Name of consumption-based account datasets (and references)	Years available	Number of countries/regions	Number of sectors
Eora (Lenzen et al., 2013); (https://worldmrio.com)	1990-2015	190	Varies from 25 to >500
EXIOBASE (Stadler et al., 2018); (https://www.exiobase.eu)	1995-2016	49	200 products and 163 industries
GTAP (Aguiar et al., 2019; Peters, et al., 2011b); (https://www.gtap.agecon.purdue.edu)	2004, 2007, 2011, 2014	140	57
OECD/ICIO (Yamano and Guilhoto, 2020); (http://oe.cd/io-co2)	1995-2015	67	36
WIOD (Dietzenbacher et al., 2013; Timmer et al., 2015); (http://wiod.org)	2000-2014	44	56
Global Carbon Budget (Friedlingstein et al., 2020)	1990-2018	118	N/A

Wood et al. (2019b) present the first comprehensive and systematic model intercomparison and find a variation of 5-10% for both PBEs and CBEs accounts of major economies and country groups (e.g., EU28, OECD). The estimates for the US were the most closely aligned, with 3.7% Relative Standard Deviation (RSD). For smaller countries, variability is in the order of 20-30% and can reach more than 40% in cases of very small, highly trade-exposed countries such as Singapore and Luxembourg (Wood et al., 2019a). It is recommended to interpret CBE results for such countries with care.

Overall, production accounts showed a slightly higher convergence (8% average of RSD) than consumption-based accounts (12%). The variation across model results can be approximately halved, when normalising national totals to one common value for a selected base year. The difference between PBE result variation (4% average RSD after normalisation) and CBEs results (7%) remains after normalisation.

In general, the largest contributors to uncertainty of CBEs results are - in descending order of priority - the total of territorial GHG emission accounts, the allocation of emissions to economic sectors, the total and composition of final demand, and lastly the structure of the economy. Harmonising territorial emissions across GMRIO datasets is the single most important factor that reduces uncertainty by about 50% (Tukker et al., 2020). More work is required to optimise or even institutionalise the compilation of multi-region input-output data and models to enhance the accuracy of consumption-based accounting (Tukker et al., 2018; Wood et al., 2018).

2.3.2 Trends in global and regional CBEs trajectories

In comparison to territorial emissions discussed in Section 2.2, Figure 2.14 shows the trends of global and regional CBEs from 1990 to 2018. This section uses the PBEs and CBEs data from the latest Global Carbon Budget (Friedlingstein et al., 2020), which are slightly different from the PBEs used in Section 2.2. The Global Carbon Budget only includes CO_2 emissions from fossil fuels and cement production.

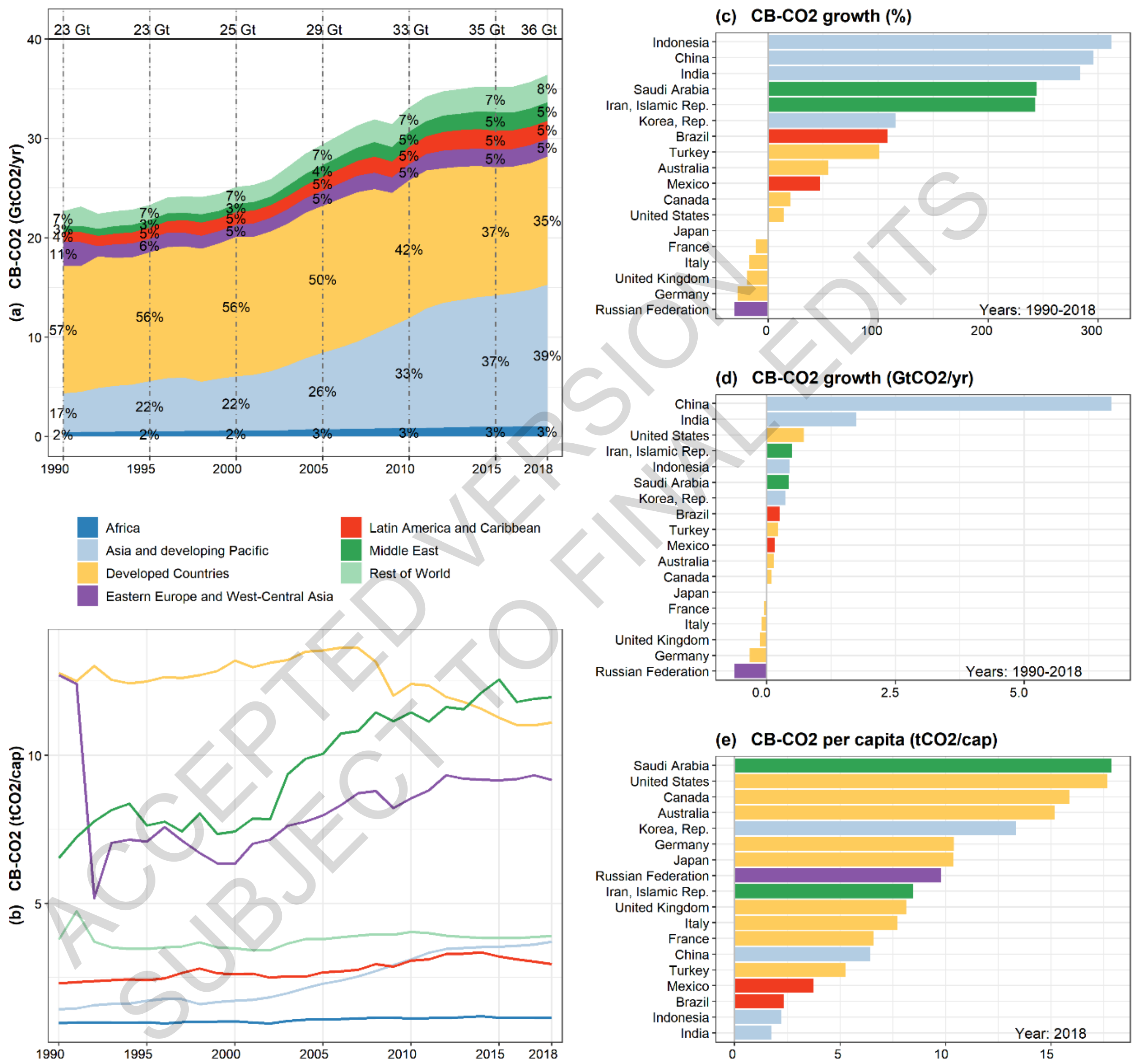


Figure 2.14 Consumption-based CO_2 emission trends for the period 1990-2018. The CBEs of countries are collected from the Global Carbon Budget 2020 (Friedlingstein et al., 2020)

Source: This figure is modified based on Hubacek et al. (2021).

The left two panels in Figure 2.14 show total and per capita CBEs for six regions. The three panels on the right show additional information for the 18 top-emitting countries with the highest CBEs in 2018. In developed countries, consumption-based CO_2 emissions peaked at 15 $GtCO_2$ in 2007 with a subsequent 16% decline until 2016 (to 12.7 $GtCO_2$) and a slight rebound of 1.6% until 2018 (to 12.9 $GtCO_2$). Asia and Developing Pacific has been a major contributor to consumption-based CO_2 emissions growth since 2000 and exceeded developed countries as the global largest emissions source in 2015. From 1990 to 2018, the average growth rate of Asia and Developing Pacific was 4.8% per year, while in other regions emissions declined by -1.1%-4.3%/year on average. In 2018, 35% of global consumption-based CO_2 emissions were from developed countries and 39% from Asia and Developing Pacific, 5% from Latin American and Caribbean, 5% from Eastern Europe and West-Central Asia, 5% from Middle East, and 3% from Africa (Hubacek et al., 2021). Global CBEs kept growing over the period with a short-lived decline in 2008 due to the global financial crisis. In 2020, lockdowns associated with COVID-19 significantly reduced global emissions (Section 2.2.2), including CBEs (Shan et al., 2020).

2.3.3 Decoupling of emissions from economic growth

There has been a long-standing discussion on whether environmental impacts such as carbon emissions and use of natural resources can be decoupled from economic growth. It is controversial whether absolute decoupling can be achieved at a global scale (Ward et al., 2016; Hickel and Kallis, 2020). However, a number of studies found that it is feasible to achieve decoupling at the national level and have explored the reasons for such decoupling (Ward et al., 2016; Zhao et al., 2016; Schandl et al., 2016; Deutch, 2017; Roinioti and Koroneos, 2017; Li et al., 2019; Vadén et al., 2020; Habimana Simbi et al., 2021; Shan et al., 2021).

Table 2.3 shows the extent of decoupling of CBEs and GDP of countries based on CBEs from the Global Carbon Budget (Friedlingstein et al., 2020) and GDP data from the World Bank. Table 2.4 also presents countries' degree of decoupling of PBEs and GDP. These data allow a comparison of decoupling between GDP and both PBEs and CBEs. Absolute decoupling refers to a decline of emissions in absolute terms or as being stable while GDP grows (i.e., a decoupling index[11] greater than 1); relative decoupling refers to growth of emissions being lower than growth of GDP (a decoupling index between 0 and 1); and no decoupling, which refers to a situation where emissions grow to the same extent or faster than GDP (a decoupling index of less than 0) (Wu et al., 2018).

Table 2.3 Country groups with different degree of CBE-GDP decoupling from 2015 to 2018

		Absolute decoupling	Relative decoupling	No decoupling	Economic recession
Number of countries		23	67	19	6
CBEs (gigatons)	Total	5.40	25.33	1.93	0.85
	Global share	16.1%	75.6%	5.8%	2.5%
PBEs (gigatons)	Total	4.84	25.73	2.16	0.84
	Global share	14.4%	76.6%	6.4%	2.5%
Population (million)	Total	625	5195	768	270
	Global share	9.1%	75.7%	11.2%	3.9%
GDP (billion)	Total	19,891	54,240	2,300	2,997
	Global share	25.0%	68.3%	2.9%	3.8%
	Average	31.45	16.29	6.57	17.78
	Median	23.55	8.03	2.56	13.12

FOOTNOTE[11] The decoupling index can be calculated based on changes of a country's GDP and CO_2 emissions (Wu et al., 2018; Akizu-Gardoki et al., 2018), see the equation below. DI refers to decoupling index; G_1 refers to the GDP of reporting year while G_0 refers to the base year; E_1 refers to emissions of the reporting year while E_0 refers to emissions of the base year.

$$DI = \frac{\Delta G\% - \Delta E\%}{\Delta G\%} = \left(\frac{G_1 - G_0}{G_0} - \frac{E_1 - E_0}{E_0}\right) / \frac{G_1 - G_0}{G_0}$$

Per capita GDP (thousand USD in 2010 prices)	Max	110.70	79.23	63.93	33.11
	Min	1.31	0.49	0.52	5.80
Per capita CBEs (tons)	Average	10.27	5.30	4.47	12.55
	Median	8.87	4.13	1.67	11.33
	Max	37.95	17.65	25.35	23.21
	Min	0.64	0.09	0.18	2.33
CBE intensity (tons per thousand USD in 2010 prices)	Average	0.45	0.50	0.93	0.66
	Median	0.36	0.42	0.62	0.69
	Max	1.16	2.41	4.10	1.22
	Min	0.11	0.10	0.28	0.21
Per capita PBEs (tons)	Average	8.20	4.36	5.32	14.15
	Median	6.79	3.02	1.19	13.22
	Max	19.58	20.13	39.27	27.24
	Min	0.49	0.09	0.08	2.23
PBE intensity (tons per thousand USD in 2010 prices)	Average	0.42	0.40	0.94	0.75
	Median	0.28	0.31	0.58	0.68
	Max	1.57	1.47	4.83	1.80
	Min	0.10	0.05	0.16	0.20

Note: CBEs are obtained from the Global Carbon Budget 2020 (Friedlingstein et al., 2020), GDP and population are from the World Bank. One country (Venezuela) does not have GDP data after 2015, so the degree of decoupling was only calculated for 115 countries. This table is modified from Hubacek et al. (2021)

Table 2.4 Country groups with different degree of PBE-GDP decoupling from 2015 to 2018

		Absolute decoupling	Relative decoupling	No decoupling	Economic recession
Number of countries		32	41	36	6
CBEs (gigatons)	Total	6.41	23.43	2.83	0.85
	Global share	19.1%	69.9%	8.4%	2.5%
PBEs (gigatons)	Total	5.33	24.36	3.04	0.84
	Global share	15.9%	72.6%	9.1%	2.5%
Population (million)	Total	857	4518	1213	270
	Global share	12.5%	65.9%	17.7%	3.9%
GDP (billion)	Total	27091	45255	4086	2,997
	Global share	34.1%	57.0%	5.1%	3.8%
Per capita GDP (thousand USD in 2010 prices)	Average	28.83	19.53	6.00	17.78
	Median	26.36	12.04	3.64	13.12
	Max	79.23	110.70	63.93	33.11
	Min	1.09	0.57	0.49	5.80
Per capita CBEs (tons)	Average	7.70	6.98	3.99	12.55
	Median	6.78	6.00	1.95	11.33
	Max	23.22	37.95	25.35	23.21
	Min	0.43	0.09	0.18	2.33
CBEs intensity (tons per thousand USD in 2010 prices)	Average	0.41	0.50	0.77	0.66
	Median	0.31	0.44	0.52	0.69
	Max	2.41	1.68	4.10	1.22
	Min	0.12	0.10	0.20	0.21
Per capita PBEs (tons)	Average	6.02	5.69	4.33	14.15
	Median	5.36	4.88	1.67	13.22
	Max	20.13	16.65	39.27	27.24
	Min	0.30	0.09	0.01	2.23

PBEs intensity (tons per thousand USD in 2010 prices)	Average	0.33	0.45	0.71	0.75
	Median	0.20	0.31	0.44	0.68
	Max	1.47	1.76	4.83	1.80
	Min	0.05	0.10	0.13	0.20

Note: CBEs are obtained from the Global Carbon Budget 2020 (Friedlingstein et al., 2020), GDP and population are from the World Bank. One country (Venezuela) does not have GDP data after 2015, so the degree of decoupling was only calculated for 115 countries. In order to be consistent with the results of CBEs, we calculate the decoupling of PBE until 2018. The latest PBE data of 2019 may not change the key messages.

During the most recent three-year period from 2015 to 2018, 23 countries (or 20% of the 116 sample countries) have achieved absolute decoupling of CBEs and GDP, while 32 countries (or 28%) achieved absolute decoupling of PBEs and GDP. 14 of them (e.g., the UK, Japan, and the Netherlands) also decoupled PBEs and GDP. Countries with absolute decoupling of CBEs tend to achieve decoupling at relatively high levels of economic development and high per capita emissions. Most of EU and North American countries are in this group. Decoupling was not only achieved by outsourcing carbon intensive production, but also improvements in production efficiency and energy mix, leading to a decline of emissions. Structural Decomposition Analysis shows that the main driver for decoupling has been a reduction in carbon intensity (that is change in energy mix and energy efficiency) from both domestic production and imports (Hubacek et al., 2021). Similarly, Wood et al., (2019c) found that EU countries have reduced their overall consumption-based GHG emissions by 8% between 1995 and 2015, mainly due to the use of more efficient technology. The literature also shows that changes in the structure of economy with a shift to tertiary sectors of production may contribute to such decoupling (Xu and Ang, 2013; Kanitkar et al., 2015; Su and Ang, 2016).

67 (or 58%) countries, including China and India, have relatively decoupled GDP and CBEs between 2015 and 2018, reflecting a slower growth in emissions than GDP. It is worth noting that the USA shows relative decoupling of emissions (both CBEs and PBEs) and GDP over the most recent period, although it strongly decoupled economic growth from emissions between 2005 and 2015. Thus decoupling can be temporary and countries' emissions may again increase after a period of decoupling.

Another 19 (or 16%) countries, such as South Africa and Nepal, have experienced no decoupling between GDP and CBEs from 2015 to 2018, meaning the growth of their GDP is closely tied with the consumption of emission-intensive goods. As a result, a further increase of GDP in these countries will likely lead to higher emissions, if they follow the historical trend without substantive improvement in efficiency of production and energy use.

It is important to note that a country's degree of decoupling changes over time. For example, 32 countries achieved absolute decoupling from 2010 to 2015 but only 10 of them remained decoupled over the next three years. More importantly, although absolute decoupling has reduced annual emissions, the remaining emissions are still contributing to an increase in atmospheric carbon concentration. Absolute decoupling is not sufficient to avoid consuming the remaining CO_2 emission budget under the global warming limit of 1.5°C or 2°C and to avoid climate breakdown (Stoknes and Rockström, 2018; Hickel and Kallis, 2020). Even if all countries decouple in absolute terms this might still not be sufficient and thus can only serve as one of the indicators and steps toward fully decarbonizing the economy and society.

2.3.4 Emissions embodied in trade (EET)

As global trade patterns have changed over recent decades, so have emissions embodied in trade (EET) (Jiang & Green, 2017). EET refers to emissions associated with production of traded goods and services and is equal to the difference between PBEs and CBEs (Wiebe and Yamano, 2016). EET includes two parts: emissions embodied in imports (EEI) and emissions embodied in exports (EEE). For a given country or region with CBEs higher than PBEs, a country is a net importer with a higher EEI than EEE, and vice versa.

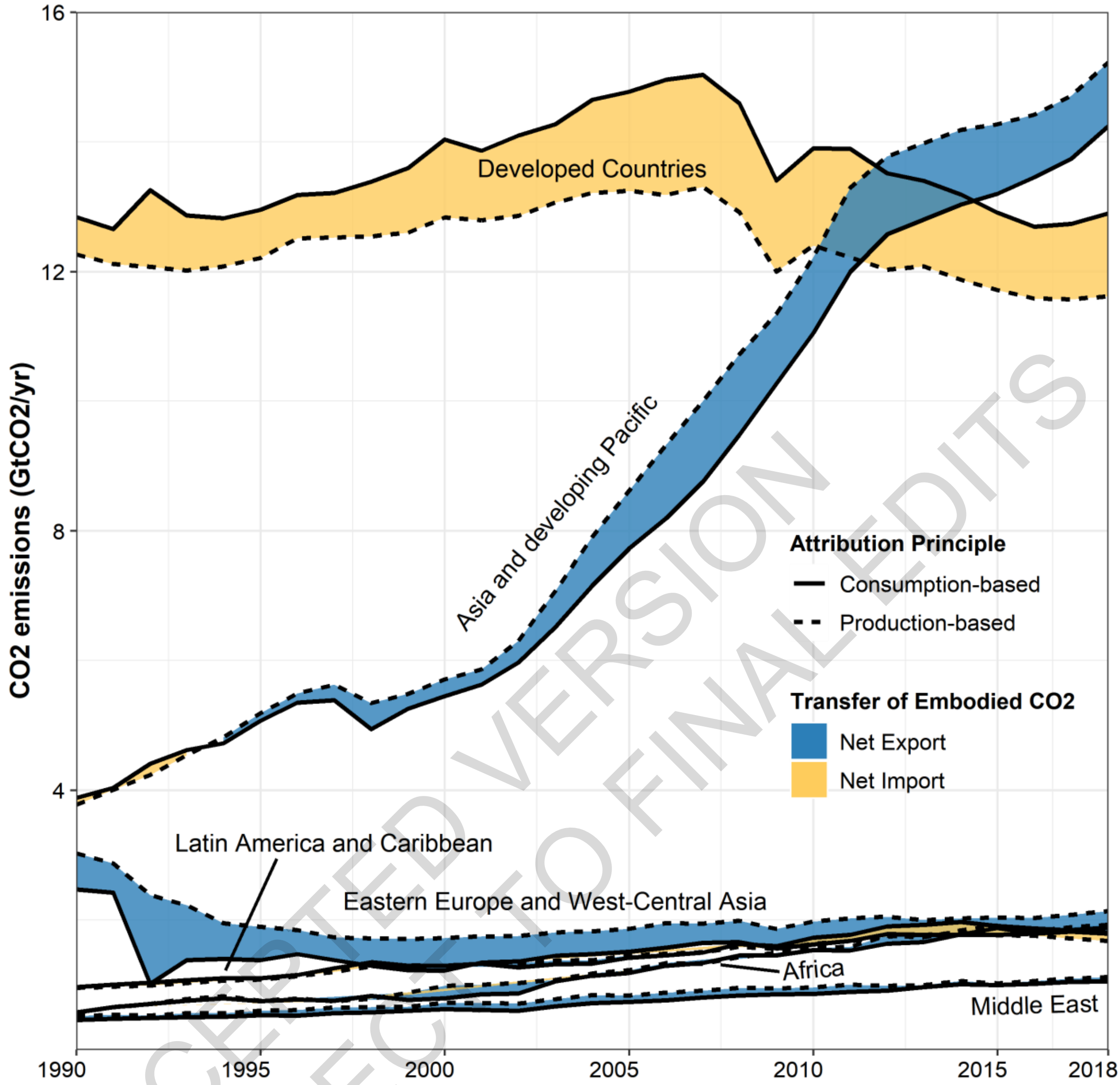


Figure 2.15 Total annual CO_2 emissions for 116 countries by global region based on consumption and production-based emissions

The shaded areas are the net CO_2 trade balances (differences) between each of the regions. Yellow shading indicates that the region is a net importer of embodied CO_2 emissions, leading to consumption-based emission estimates that are higher than traditional territorial emission estimates. Blue shading indicates the reverse. Production-based emissions are collected from EDGAR and consumption-based emissions from the Global Carbon Budget 2020 (Friedlingstein et al., 2020)**.**

Source: This figure is modified based on Hubacek et al. (2021).

EET have been rising faster since the 1980s due to an increase in trade volume (Xu and Dietzenbacher, 2014; Wood et al., 2018b; Zhong et al., 2018). CO_2 emissions from the production of internationally traded products peaked in 2006 at about 26% of global CO_2 emissions. Since then, international CO_2 emissions transfers declined but are likely to remain an important part of the climate policy agenda (Wood et al., 2019c). About 24% of global economic output and 25% of global CO_2 emissions are embodied in the international trade of goods and services as of 2014 (Hubacek et al., 2021).

2.3.4.1 Net emission transfers

Located downstream in global supply chains, developed countries (mostly in Western Europe and North America) tend to be net emission importers, i.e., EEI are larger than EEE. For example, over 40% of national CO_2 footprints in France, Germany, Italy, and Spain are from imports (Fan et al., 2017). Developing countries tend to be net emission exporters with higher PBEs than their CBEs (Peters et al., 2011b; Le Quéré et al., 2018), especially for Asia and Developing Pacific (as shown in Figure 2.15). That is to say, there is a net emission transfer and outsourcing of carbon-intensive production from developed to developing economies via global trade (Jiang et al., 2018), mainly caused by cheap labour costs (Tate and Bals, 2017) and cheap raw materials (Mukherjee, 2018). Increasing openness to trade (Fernández-Amador et al., 2016) and less stringent environmental legislation (acting as so-called pollution havens) are also possible reasons (Hoekstra et al., 2016; Malik and Lan, 2016; Banerjee and Murshed, 2020).

Net emissions transferred between developing and developed countries peaked at 7.3% of global CO_2 emissions in 2006 and then subsequently decline (Wood et al., 2019c). The main reason for the decline was an improvement in the carbon intensity of traded products of about 40% between 1995 and 2015, rather than a decline in trade volume (Wood et al., 2019c). Despite continued improvements, developing economies tend to have higher emission intensity than developed economies due to less efficient technologies and a carbon-intensive fuel mix (Liu et al., 2015a; Jiang and Guan, 2017).

2.3.4.2 Geographical shifts of trade embodied emissions

With the rapid growth of developing countries, the geographical centre of global trade as well as trade embodied emissions is changing. The fast growth of Asian countries is shifting the global trade centre from Europe to Asia (Zhang et al., 2019). Asian exports in monetary units increased by 235% from 1996 to 2011, and its share in global exports increased from 25% to 46%, whereas Europe's share in global exports decreased from 51% in 1996 to 39% in 2011. After 2011, global trade has stalled, but Asia's share of global exports further increased to 42% in 2020 (UNCTAD, 2021).

In addition to changes in trade volume, trading patterns have also been changing significantly in Asian countries. These countries are replacing traditional trading hubs (such as Russia and Germany) due to the fast growth in trade flows, especially with countries of the global South (Zhang et al., 2019). The largest geographical shifts in trade-embodied emissions between 1995 and 2011 occurred in high-tech, electronics, and machinery (Malik and Lan, 2016; Jiang et al., 2018a). For example, China is shifting its exports to include more low-carbon and higher value-added goods and services. As a result, China's exported emissions declined by 20% from 2008 to 2015 (Mi et al., 2018).

As a result, developing countries are increasingly playing an important role in global trade. Emissions embodied in trade between developing countries, so-called South-South trade, has more than doubled between 2004 (0.47 Gt) and 2011 (1.11 Gt), which is seen as a reflection of a new phase of globalisation (Meng et al., 2018). Developing countries, therefore, have gained importance as global suppliers of goods and services and have also become more relevant as global consumers as they grow their domestic demand (Fernández-Amador et al., 2016). Since 2014, CO_2 emission transfer between developing countries has plateaued and then slightly declined and seems to have stabilised at around the same level of transfers between non-OECD and OECD countries at around 2.4 $GtCO_2$ yr^{-1} (Wood et al., 2019a). In both cases, a decrease in carbon intensity of trade just about offset increased trade volumes (Wood et al., 2019a).

2.4 Economic Drivers and Their Trends by Regions and Sectors

This section provides a summary of the main economic drivers of GHG emissions (mostly territorial) by regions and sectors, including those that are more indirect drivers related to economic activity, such as inequality and rapid urbanisation. Trade as a driver of global GHG emissions is described in the Chapter 2 Supplementary Material. Socio-demographic drivers are described in Section 2.6. The Kaya decomposition presented in this section is based on the IEA and EDGAR v6 databases and tracks global, regional, and sectoral GHG emissions from 1990 to 2019 (Crippa et al., 2021; Minx et al., 2021; Lamb et al., 2021b; IEA, 2021c). It shows main contributors to GHG emissions as independent factors, although these factors also interact with each other.

2.4.1 Economic Drivers at Global and Regional Levels

Economic growth (measured as GDP) and its main components, GDP per capita and population growth, remained the strongest drivers of GHG emissions in the last decade, following a long-term trend *(robust evidence, high agreement)* (Liddle, 2015; Malik et al., 2016; Sanchez and Stern, 2016; Chang et al., 2019; Dong et al., 2019; Liobikiene and Butkus, 2019; Liu et al., 2019a; Mardani et al., 2019; Pan et al., 2019; Dong et al., 2020; Parker and Bhatti, 2020; Xia et al., 2021). Globally, GDP per capita remained by far the strongest upward driver, increasing almost in tandem with energy consumption and CO_2 emissions up until 2015, after which some modest decoupling occurred (Deutch, 2017; Wood et al., 2018b) (Section 2.3.3). The main counteracting, yet insufficient, factor that led to emissions reductions was decreased energy use per unit of GDP in almost all regions (-2.0% yr^{-1} between 2010 and 2019 globally (Figure 2.16), see also (Lamb et al., 2021b) *(robust evidence, high agreement)*. These reductions in energy intensity are a result of technological innovation, structural changes, regulation, fiscal support, and direct investment, as well as increased economic efficiency in underlying sectors (Yao et al., 2015; Sanchez and Stern, 2016; Chang et al., 2019; Dong et al., 2019a; Mohmmed et al., 2019; Stern, 2019; Azhgaliyeva et al., 2020; Goldemberg, 2020; Gao et al., 2021; Liddle and Huntington, 2021; Xia et al., 2021; Liu et al., 2019b).

The decades-long trend that efficiency gains were outpaced by an increase in worldwide GDP (or income) per capita continued unabated in the last ten years *(robust evidence, high agreement)* (Wiedmann et al., 2020; Xia et al., 2021). In addition, the emissions-reducing effects of energy efficiency improvements are diminished by the energy rebound effect, which has been found in several studies to largely offset any energy savings *(robust evidence, high agreement)* (Rausch and Schwerin, 2018; Bruns et al., 2021; Colmenares et al., 2020; Stern, 2020; Brockway et al., 2021). The rebound effect is discussed extensively in Section 9.9.2.

A significant decarbonisation of the energy system was only noticeable in North America, Europe and Eurasia. Globally, the amount of CO_2 per unit of energy used has practically remained unchanged over the last three decades (Chang et al., 2019; Tavakoli, 2018), although it is expected to decrease more consistently in the future (Xia et al., 2021). Population growth has also remained a strong and persistent upward driver in almost all regions (+1.2% yr^{-1} globally from 2010 to 2019, Figure 2.16 , see also Lamb et al., 2021), although per capita emission levels are very uneven across world regions. Therefore, modest population increases in wealthy countries may have a similar impact on emissions as high population increases in regions with low per capita emission levels.

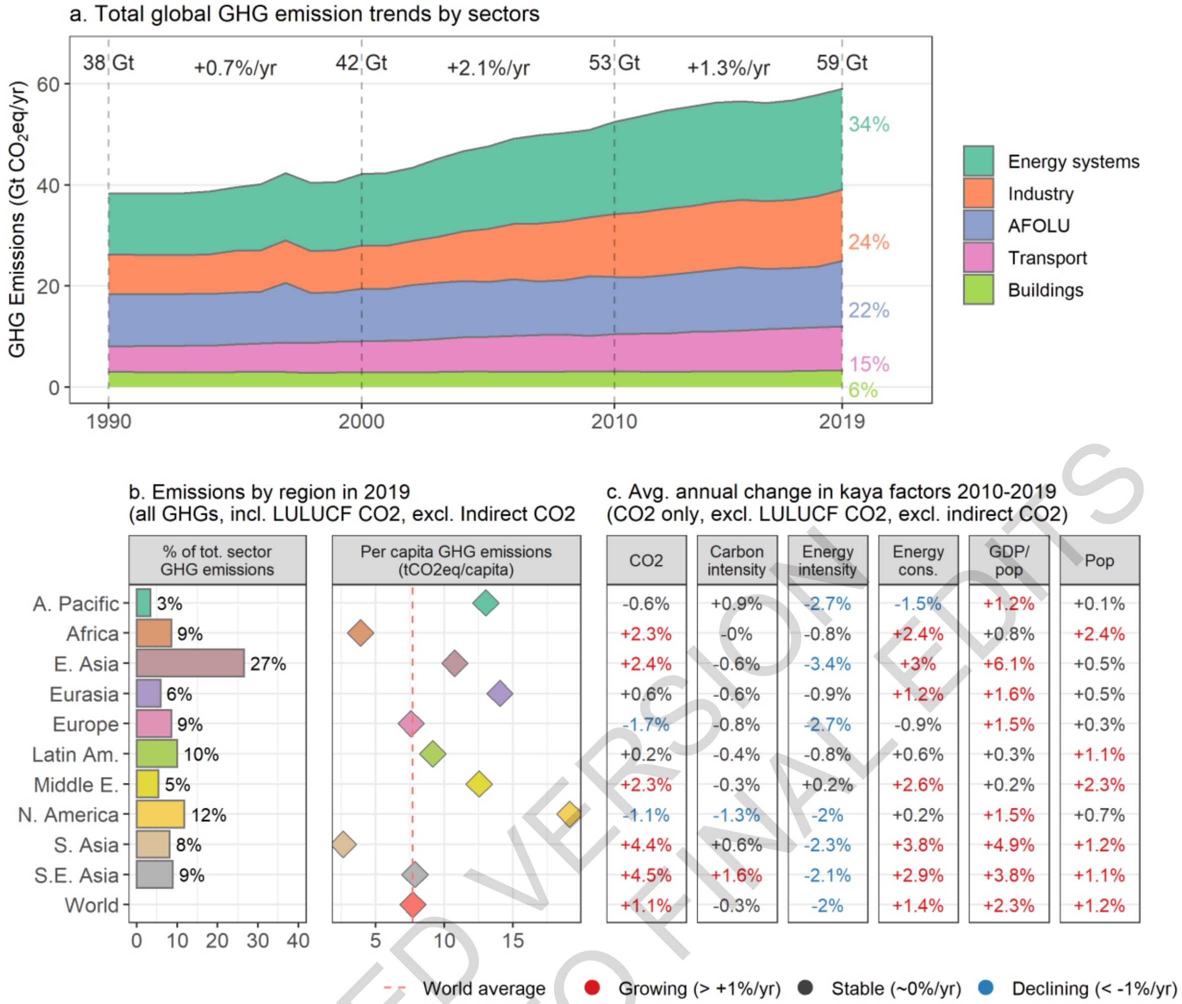


Figure 2.16 Trends and drivers of global GHG emissions, including a) trends of GHG emissions by sectors 1990–2019, b) share of total and per capita GHG emissions by world region in 2019, and c) Kaya decomposition of CO_2 emissions drivers

The Kaya decomposition is based on the equation F = P(G/P)(E/G)(F/E), where F is CO_2 emissions, P is population, G/P is GDP per capita, E/G is the energy intensity of GDP and F/E is the carbon intensity of energy. The indicated annual growth rates are averaged across the years 2010–2019 (in panel c, these are for fossil fuel CO_2 emissions only, in order to ensure compatibility with underlying energy data). Note that the energy consumption by itself (primary energy supply) is not part of the decomposition, but is listed here for comparison with the Kaya factors.

Source: Data from Crippa et al. (2021), IEA (IEA, 2021c), Minx et al. (2021)

Developing countries remained major accelerators of global CO_2 emissions growth since 2010, mostly driven by increased consumption and production, in particular in East Asia *(robust evidence, high agreement)* (Jiborn et al., 2020). While energy intensity declined to a similar extent in countries of the OECD (Organisation for Economic Co-operation and Development) and non-OECD countries over the last 30 years, economic growth has been much stronger in non-OECD countries (González-Torres et al., 2021). This led to an average annual growth rate of 2.8% of CO_2 emissions in these countries, whereas they decreased by 0.3% yr^{-1} in OECD countries (UNEP, 2019). The majority of developed economies reduced both production-based and consumption-based CO_2 emissions modestly (Jiborn et al., 2020; Xia et al., 2021). This was due to slower economic growth, increased energy efficiency (less energy per unit of GDP), fuel switching from coal to gas (mostly in North America) (Wang et al., 2020b), and the use of less and cleaner energy from renewables in Europe (Peters et al., 2017; Karstensen et al., 2018; Chang et al., 2019; Wood et al., 2019c).

Economic growth as the main driver of GHG emissions plays out particularly strong in China and India *(robust evidence, high agreement)* (Liu et al., 2019b; Ortega-Ruiz et al., 2020; Wang et al., 2020c; Yang et al., 2020; Zheng et al., 2020; Xia et al., 2021), although both countries show signs of relative decoupling because of structural changes (Marin and Mazzanti, 2019). A change in China's production structure (with relatively less heavy industry and lower-carbon manufacturing) and consumption patterns (i.e., the type of goods and services consumed) has become the main moderating factor of emissions after 2010, while economic growth, consumption levels, and investment remain the dominating factors driving up emissions (Wang and Jiang, 2019; Jiborn et al., 2020; Zheng et al., 2020). In India, an expansion of production and trade as well as a higher energy intensity between 2010 and 2014 caused growth of emissions (Kanitkar et al., 2015; Wang and Zhou, 2020; (Wang et al., 2020d)).

2.4.2 Sectoral Drivers

GHG emissions continued to rise since 2010 across all sectors and subsectors, most rapidly in electricity production, industry, and transport. Decarbonisation gains from improvements in energy efficiency across different sectors and worldwide have been largely wiped out by increases in demand for goods and services. Prevailing consumption patterns have also tended to aggravate energy use and emissions, with the long-term trend led by developed regions. Decarbonisation trends in some developed regions are limited in size and geographically. Globally, there are enormous unexploited mitigation potentials from adopting best available technologies.

The following subsections discuss main emissions drivers by sector. More detailed analyses of sectoral emissions and mitigation options are presented in Chapters 6–11.

2.4.2.1 Energy systems

Global energy system emissions growth has slowed down in recent years, but global oil and gas use was still growing (Jackson et al., 2019) and the sector remained the single largest contributor to global GHG emissions in 2019 with 20 $GtCO_2$-eq (34%) *(high confidence)* (Figure 2.17). Most of the 14 $GtCO_2$-eq from electricity and heat generation (23% of global GHG emissions in 2019) were due to energy use in industry and in buildings, making these two sectors also prominent targets for mitigation (Davis et al., 2018; Crippa et al., 2019) (see subsections below).

Growth in CO_2 emissions from energy systems has closely tracked rising GDP per capita globally (Lamb et al., 2021b), affirming the substantial literature describing the mutual relationship between economic growth and demand for energy and electricity *(robust evidence, high agreement)* (Khanna and Rao, 2009; Stern, 2011). This relationship has played out strongly in developing regions, particularly in Asia, where a massive scale up of energy supply has accompanied economic growth – with average annual increases of energy demand between 3.8 and 4.3% in 2010–2019 (Figure 2.17). The key driver for slowing the growth of energy systems CO_2 emissions has been declining energy intensities in almost all regions. Annually, 1.9% less energy per unit of GDP was used globally between 2010 and 2019.

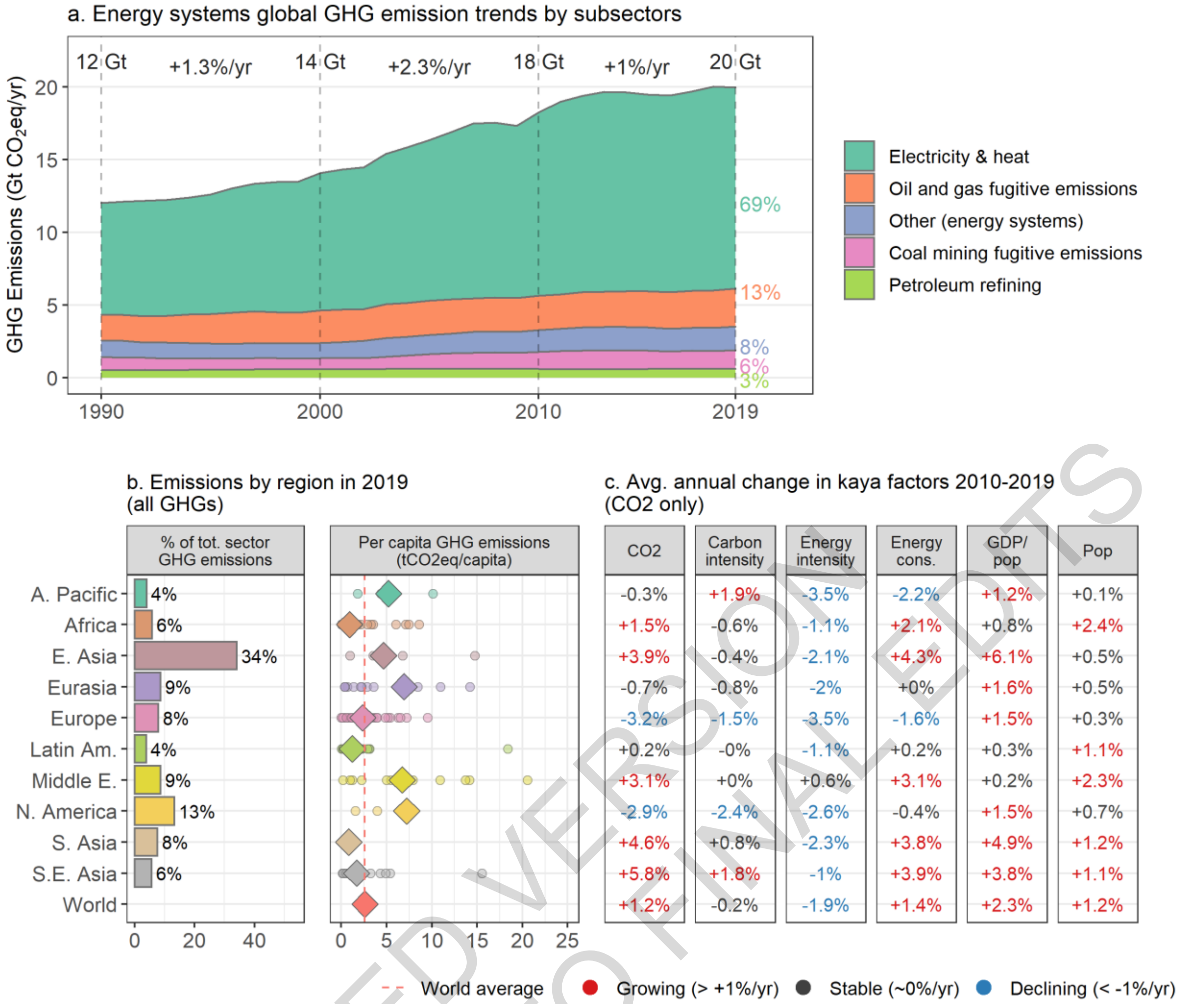


Figure 2.17 Trends and drivers of global energy sector emissions (see caption of Figure 2.16 for details) Energy is here measured as primary energy supply.

The carbon intensity of power generation varies widely between (and also within) regions (see also Chapter 6). In North America, both a switch from coal to gas for power generation (Peters et al., 2017, 2020; Feng, 2019; Mohlin et al., 2019) as well as an overall decline in the share of fossil fuels in electricity production (from 66% in 2010 to 59% in 2018) (Mohlin et al., 2019) has decreased carbon intensity and CO_2 emissions. Since 2007, Europe's carbon intensity improvements have been driven by the steady expansion of renewables in the share of electricity generation *(medium evidence, high agreement)* (Peters et al., 2017, 2020; Le Quéré et al., 2019; Rodrigues et al., 2020). Some studies attribute these effects to climate policies, such as the carbon floor price in the UK, the EU emissions trading scheme, and generous renewable energy subsidies across the continent (Dyrstad et al., 2019; Wang et al., 2020a). South-East Asian and Asia-Pacific developed countries stand out in contrast to other developed regions, with an increase of regional carbon intensity of 1.8 and 1.9% yr^{-1}, respectively (Figure 2.17). Generally, the use of natural gas for electricity production is growing strongly in most countries and gas has contributed to the largest increase in global fossil CO_2 emissions in recent years (Jackson et al., 2019; Peters et al., 2020). Furthermore, gas brings the risk of increased CH_4 emissions from fugitive sources, as well as large cumulative emissions over the lifetime of new gas power plants that may erase early carbon intensity reductions (Shearer et al., 2020).

The growth of emissions from coal power slowed after 2010, and even declined between 2011 and 2019, primarily due to a slowdown of economic growth and fewer coal capacity additions in China (Peters et al., 2020; Friedlingstein et al., 2019). Discussions of a global ‘peak coal’, however, may be premature, as further growth was observed in 2019 (Peters et al., 2020; Friedlingstein et al., 2019). Large ongoing and planned capacity increases in India, Turkey, Indonesia, Vietnam, South Africa, and other countries have become a driver of thermal coal use after 2014 (UNEP, 2017; Steckel et al., 2019; Edenhofer et al., 2018).

2.4.2.2 Industry sector

When indirect emissions from electricity and heat production are included, industry becomes the single highest emitting sector of GHGs (20.0 $GtCO_2$-eq in 2019) *(high confidence)*. Facilitated by globalisation, East Asia has been the main source and primary driver of global industry emissions growth since 2000 *(robust evidence, high agreement)* (Lamb et al., 2021). However, while East Asia has emitted 45% of the world’s industry GHG emissions in 2019, a remarkable decrease of 5.0% yr^{-1} in energy intensity and 1.6% in carbon intensity helped to stabilise direct industrial CO_2 emissions in this region (-0.3% yr^{-1} between 2010 and 2019; Figure 2.18). Direct industry CO_2 emissions have also declined in Latin America, Europe and Asia-Pacific developed regions and – to a smaller extent – in North America. In all other regions, they were growing – most rapidly in southern Asia (+4.3% annually for direct CO_2 emissions since 2010, Figure 2.18).

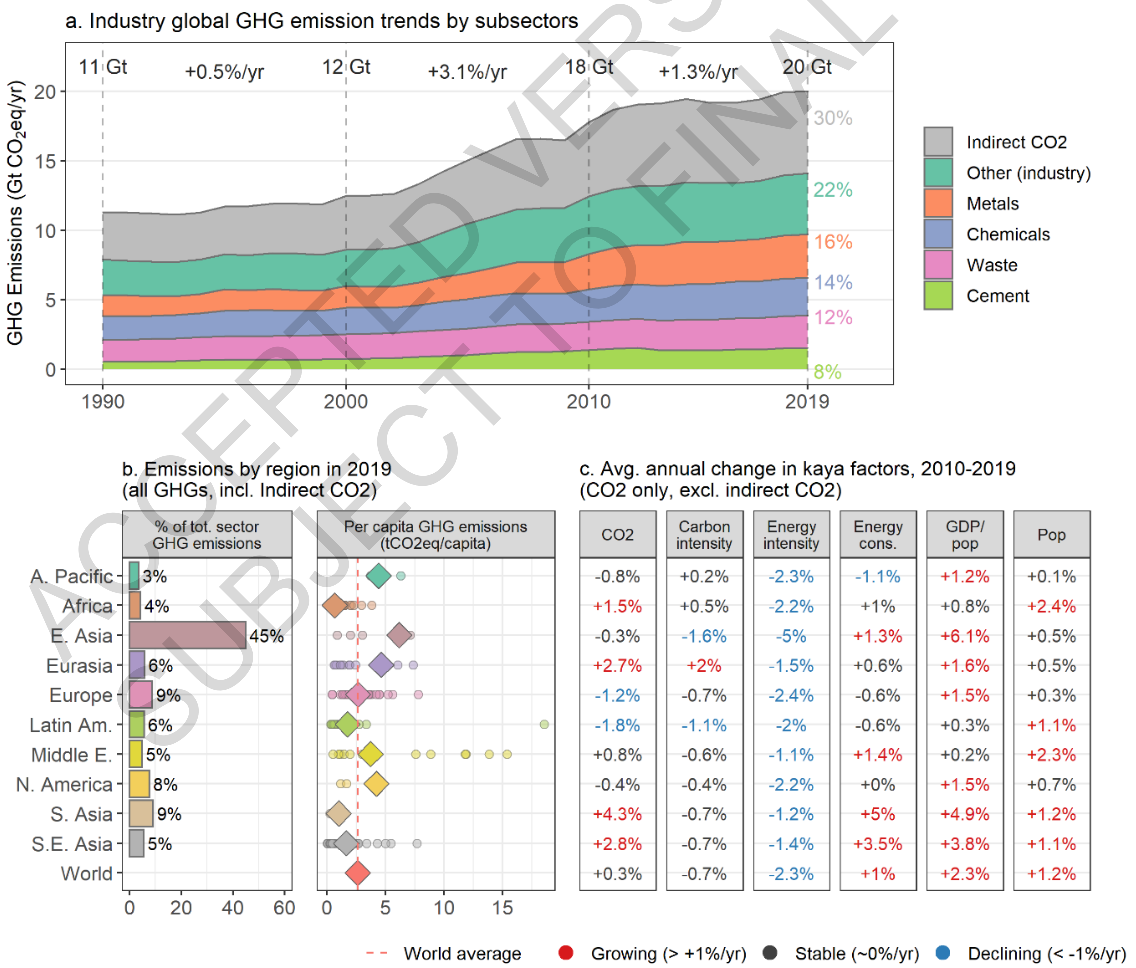


Figure 2.18 Trends and drivers of global industry sector emissions (see caption of Figure 2.16 for details). Energy is here measured as total final energy consumption.

The main global driver of industry emissions has been a massive rise in the demand for products that are indirectly used in production, such as cement, chemicals, steel, aluminium, wood, paper, plastics, lubricants, fertilizers, and so on. This demand was driven by economic growth, rising affluence, and consumption, as well as a rapid rise in urban populations and associated infrastructure development *(robust evidence, high agreement)* (Krausmann et al., 2018). There is strong evidence that the growing use of concrete, steel, and other construction materials is particularly tightly coupled to these drivers (Cao et al., 2017; Pauliuk et al., 2013; Plank et al., 2018; Haberl et al., 2020; Krausmann et al., 2017). Per capita stocks of cement and steel show a typical pattern of rapid take-off as countries urbanise and industrialise, before slowing down to low growth at high levels of GDP. Hence, in countries that have recently been industrialising and urbanising – that is Eastern, Southern and South-Eastern Asia – a particularly strong increase of emissions from these subsectors can be observed. Selected wealthy countries seem to stabilise at high per capita levels of stocks, although it is unclear if these stabilizations persist and if they result in significant absolute reductions of material use (Wiedenhofer et al., 2015; Cao et al., 2017; Krausmann et al., 2018). Opportunities for prolonging lifetimes and improving end of life recycling in order to achieve absolute reductions in extraction activities are as yet unexploited (Krausmann et al., 2017; Zink and Geyer, 2017).

On the production side, improvements in the efficiency of material extraction, processing, and manufacturing have reduced industrial energy use per unit of output (Wang et al., 2019b). These measures, alongside improved material substitution, lightweight designs, extended product and servicing lifetimes, improved service efficiency, and increased reuse and recycling will enable substantial emissions reductions in the future (Hertwich et al., 2019). In absence of these improvements in energy intensity, the growth of population and GDP per capita would have driven the industrial CO_2 emissions to rise by more than 100% by 2017 compared with 1990, instead of 56% (Lamb et al., 2021b). Nonetheless, many studies point to deep regional differences in efficiency levels and large globally unexploited potentials to improve industrial energy efficiency by adopting best available technologies and practices for metal, cement, and chemical production (Gutowski et al., 2013; Talaei et al., 2018; Schulze et al., 2016; Hernandez et al., 2018).

2.4.2.3 ***Buildings sector***

Global direct and indirect GHG emissions from the buildings sector reached 9.7 $GtCO_2$-eq in 2019, or 16% of global emissions). Most of these emissions (66%, or 6.4 $GtCO_2$-eq) were upstream emissions from power generation and commercial heat (Figure 2.19). The remaining 33% (3.3 $GtCO_2$-eq) of emissions were directly produced in buildings, for instance by gas and coal boilers, and cooking and lighting devices that burn kerosene, biomass, and other fuels (Lamb et al., 2021). Residential buildings accounted for the majority of this sector's emissions (64%, 6.3 $GtCO_2$-eq, including both direct and indirect emissions), followed by non-residential buildings (35%, 3.5 $GtCO_2$-eq) *(high confidence)*.

Global buildings sector GHG emissions increased by 0.7% yr^{-1} between 2010 and 2019 (Figure 2.19), growing the most in absolute terms in East and South Asia, whereas they declined the most in Europe, mostly due to the expansion of renewables in the energy sector and increased energy efficiency (Lamb et al., 2021). North America has the highest per capita GHG emissions from buildings and the second highest absolute level after East Asia (Figure 2.19).

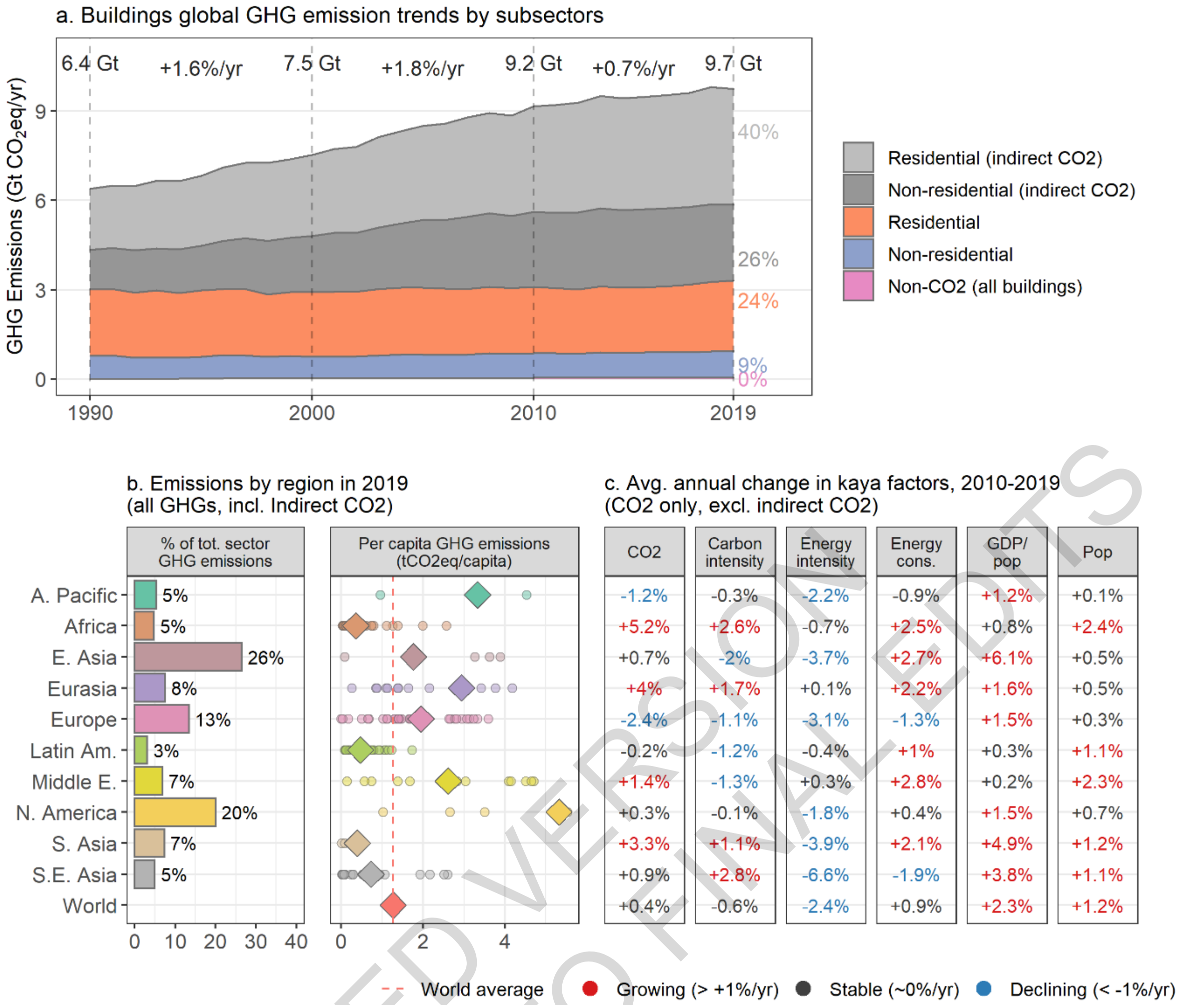


Figure 2.19 Trends and drivers of global buildings sector emissions (see caption of Figure 2.16 for details). Energy is here measured as total final energy consumption.

Rising wealth has been associated with more floor space being required to service growing demand in the retail, office, and hotel sectors *(medium evidence, high agreement)* (Daioglou et al., 2012; Deetman et al., 2020). In addition, demographic and social factors have driven a cross-national trend of increasing floor space per capita. As populations age and decrease in fertility, and as individuals seek greater privacy and autonomy, households declined in size, at least before the COVID-19 pandemic (Ellsworth-Krebs, 2020). These factors lead to increased floor space per capita, even as populations stabilise. This in turn is a key driver for building sector emissions, because building characteristics such as size and type, rather than occupant behaviour, tend to explain the majority of energy use within dwellings (Guerra Santin et al., 2009; Ürge-Vorsatz et al., 2015; Huebner and Shipworth, 2017) (see Chapter 9).

Energy activity levels further drive regional differences. In Eurasia, Europe and North America, thermal demands for space heating dominate building energy use, at 66%, 62% and 48% of residential energy demand, respectively (IEA, 2020a). In contrast, cooking has a much higher share of building energy use in regions of the global South, including China (Cao et al., 2016). And despite temperatures being on average warmer in the global South, electricity use for cooling is a more prominent factor in the global North (Waite et al., 2017). This situation is changing, however, as rapid income growth and demographic changes in the global South enable households to heat and cool their homes (Ürge-Vorsatz et al., 2015, 2020).

Steady improvements in building energy intensities across regions can be attributed to baseline improvements in building fabrics, appliance efficiencies, energy prices, and fuel shifts. Many countries have adopted a mix of relevant policies, such as energy labelling, building energy codes, and mandatory energy performance requirements (Nie and Kemp, 2014; Nejat et al., 2015; Economidou et al., 2020). Efforts towards buildings refurbishments and retrofits have also been pursued in several nations, especially for historical buildings in Europe, but evidence suggests that the recent rates of retrofits have not made a significant dent on emissions (Corrado and Ballarini, 2016). The Chinese central government launched various policies, including command and control, economic incentives, and technology measures, but a big gap remains between the total rate of building green retrofit in the nation and the future retrofit potential (Liu et al., 2020a, 2020b). Still, one major global factor driving down energy intensities has been the global transition from inefficient coal and biomass use in buildings for heating and cooking, towards natural gas and electricity, in part led by concerted policy action in Asian countries (Kerimray et al., 2017; Thoday et al., 2018; Ürge-Vorsatz et al., 2015). As developing countries construct new buildings, there is sizable potential to reduce and use less carbon-intensive building materials and adopt building designs and standards that lower life cycle buildings energy use and allow for passive comfort. Chapter 9 describes the mitigation options of the buildings sector.

2.4.2.4 ***Transport sector***

With a steady, average annual growth of +1.8% yr^{-1} between 2010 and 2019, global transport GHG emissions reached 8.9 $GtCO_2$-eq in 2019 and accounted for 15% of all direct and indirect emissions (Figure 2.20). Road transport passenger and freight emissions represented by far the largest component and source of this growth (6.1 $GtCO_2$-eq, 69% of all transport emissions in 2019) *(high confidence)*. National plus international shipping and aviation emissions together accounted for 2.0 $GtCO_2$-eq or 22% of the sector's total in 2019. North America, Europe and Eastern Asia stand out as the main regional contributors to global transport emissions and together account for 50% of the sector's total.

The proportion of total final energy used in transport (28%) and its fast expansion over time weighs heavily on climate mitigation efforts, as 92% of transport energy comes from oil-based fuels (IEA, 2020b). These trends situate transport as one of the most challenging sectors for climate change mitigation – no country has so far been able to realise significant emissions reductions in the sector. North America's absolute and per capita transport emissions are the highest amongst world regions, but those of South, South-East and East Asia are growing the fastest (between +4.6% and +5.2% yr^{-1} for CO_2 between 2010 and 2019, Figure 2.20) *(high confidence)*.

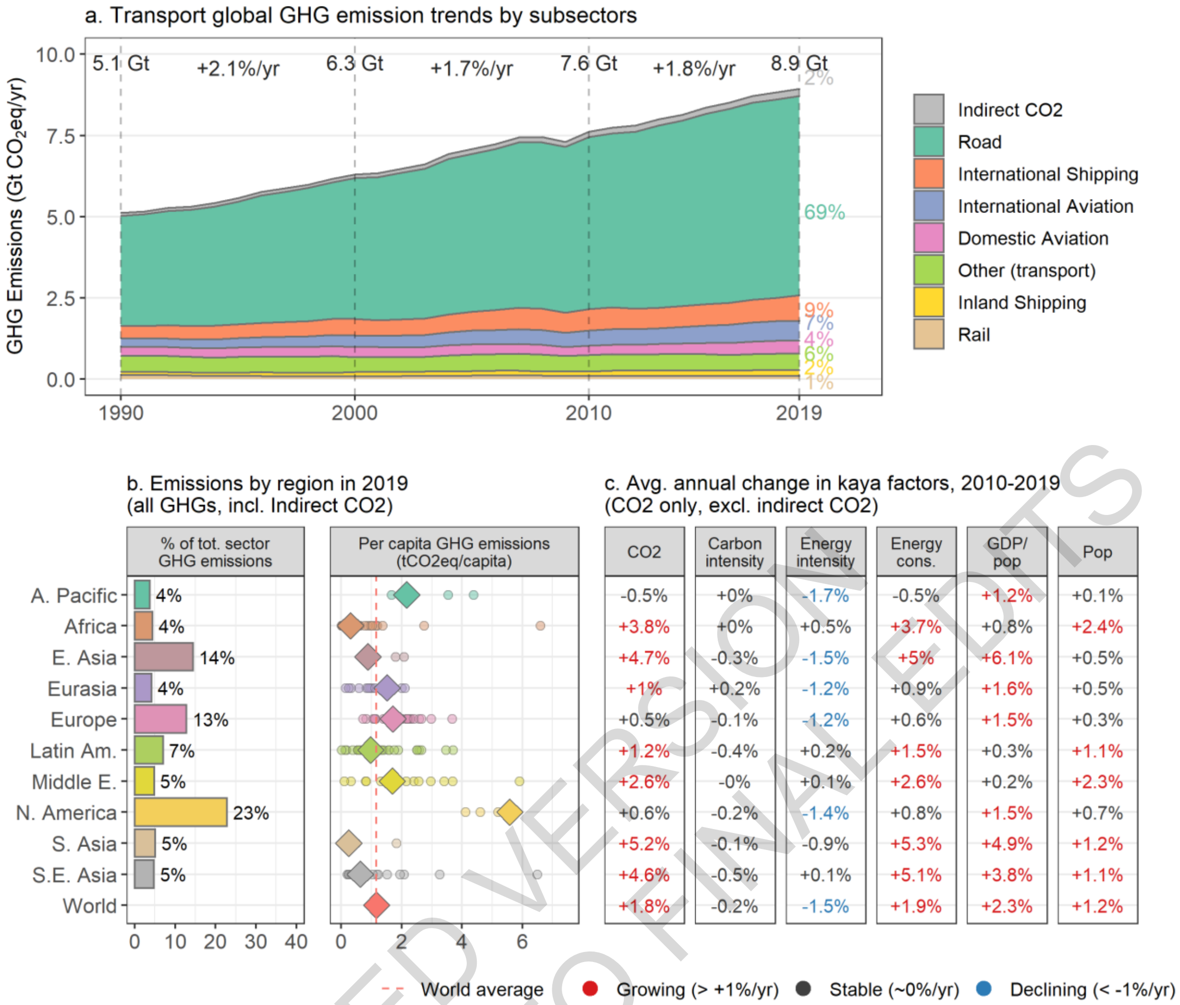


Figure 2.20 Trends and drivers of global transport sector emissions (see caption of Figure 2.16 for details). Energy is here measured as total final energy consumption.

More so than any other sector, transport energy use has tracked GDP per capita growth (Figure 2.20), (Lamb et al., 2021). With the exception of road gasoline demand in OECD countries, the demand for all road fuels generally increases at least as fast as the rate at which GDP per capita increases (Liddle and Huntington, 2020). Developments since 1990 continue a historical trend of increasing travel distances and a shift from low- to high-speed transport modes that goes along with GDP growth (Schäfer et al., 2009; Gota et al., 2019). Modest improvements in energy efficiency have been realised between 2010 and 2019, averaging -1.5% yr^{-1} in energy intensity globally, while carbon intensities of the transport sector have remained stable in all world regions (Figure 2.20). Overall, global increases in passenger and freight travel activity levels have outpaced energy efficiency and fuel economy improvements, continuing a long-term trend for the transport sector (Gucwa and Schäfer, 2013; Grübler, 2015; McKinnon, 2016) *(medium evidence, high agreement)*.

Despite some policy achievements, energy use in the global transport system remains to the present deeply rooted in fossil fuels *(robust evidence, high agreement)* (IEA, 2019; Figueroa et al., 2014). In part this is due to the increasing adoption of larger, heavier combustion-based vehicles in some regions, which have tended to far outpace electric and hybrid vehicle sales (Chapter 10). Yet, stringent material efficiency and lightweight design of passenger vehicles alone would have the potential to cut cumulative global GHG emissions until 2060 by 16–39 $GtCO_2$-eq (Pauliuk et al., 2020).

While global passenger activity has expanded in all world regions, great disparities exist between low and high income regions, and within countries between urban and rural areas (ITF, 2019). While private car use is dominant in OECD countries (EC, 2019), the growth of passenger-km (the product of number of travellers and distance travelled) has considerably slowed there, down to an increase of just 1% yr^{-1} between 2000 and 2017 (SLoCaT, 2018) (Chapter 10). Meanwhile, emerging economies in the global South are becoming more car-dependent, with rapidly growing motorisation, on-demand private transport services, urban sprawl, and the emergence of local automotive production, while public transport struggles to provide adequate services (Dargay et al., 2007; Hansen and Nielsen, 2017; Pojani and Stead, 2017).

Freight travel activity grew across the globe by 68% in the last two decades driven by global GDP increases, together with the proliferation of online commerce and rapid (i.e., same-day and next-day) delivery (SLoCaT, 2018). Growth has been particularly rapid in heavy-duty road freight transport.

While accounting for a small share of total GHG emissions, domestic and international aviation have been growing faster than road transport emissions, with average annual growth rates of +3.3% and +3.4%, respectively, between 2010 and 2019 (Crippa et al., 2021; Minx et al., 2021;). Energy efficiency improvements in aviation were considerably larger than in road transport, but were outpaced by even larger increases in activity levels (SLoCaT, 2018; Lee et al., 2021) (Chapter 10).

2.4.2.5 AFOLU sector

GHG emissions from agriculture, forestry and land use reached 13 $GtCO_2$-eq globally in 2019 (Figure 2.21) *(medium confidence)*. AFOLU trends, particularly those for CO_2-LULUCF, are subject to a high degree of uncertainty (Section 2.2.1). Overall, the AFOLU sector accounts for 22% of total global GHG emissions, and in several regions – Africa, Latin America, and South-East Asia – it is the single largest emitting sector (which, at the same time, is also significantly affected itself by climate change; see WGI Chapters 8, 11, and 12, and WGII Chapter 5). Latin America has the highest absolute and per capita AFOLU GHG emissions of any world region (Figure 2.21). CO_2 emissions from land-use change and CH_4 emissions from enteric fermentation together account for 74% of sector-wide GHGs. Note that CO_2-LULUCF estimates included in this chapter are not necessarily comparable with country GHG inventories, due to different approaches to estimate anthropogenic CO_2 sinks (Grassi et al., 2018) (Chapter 7).

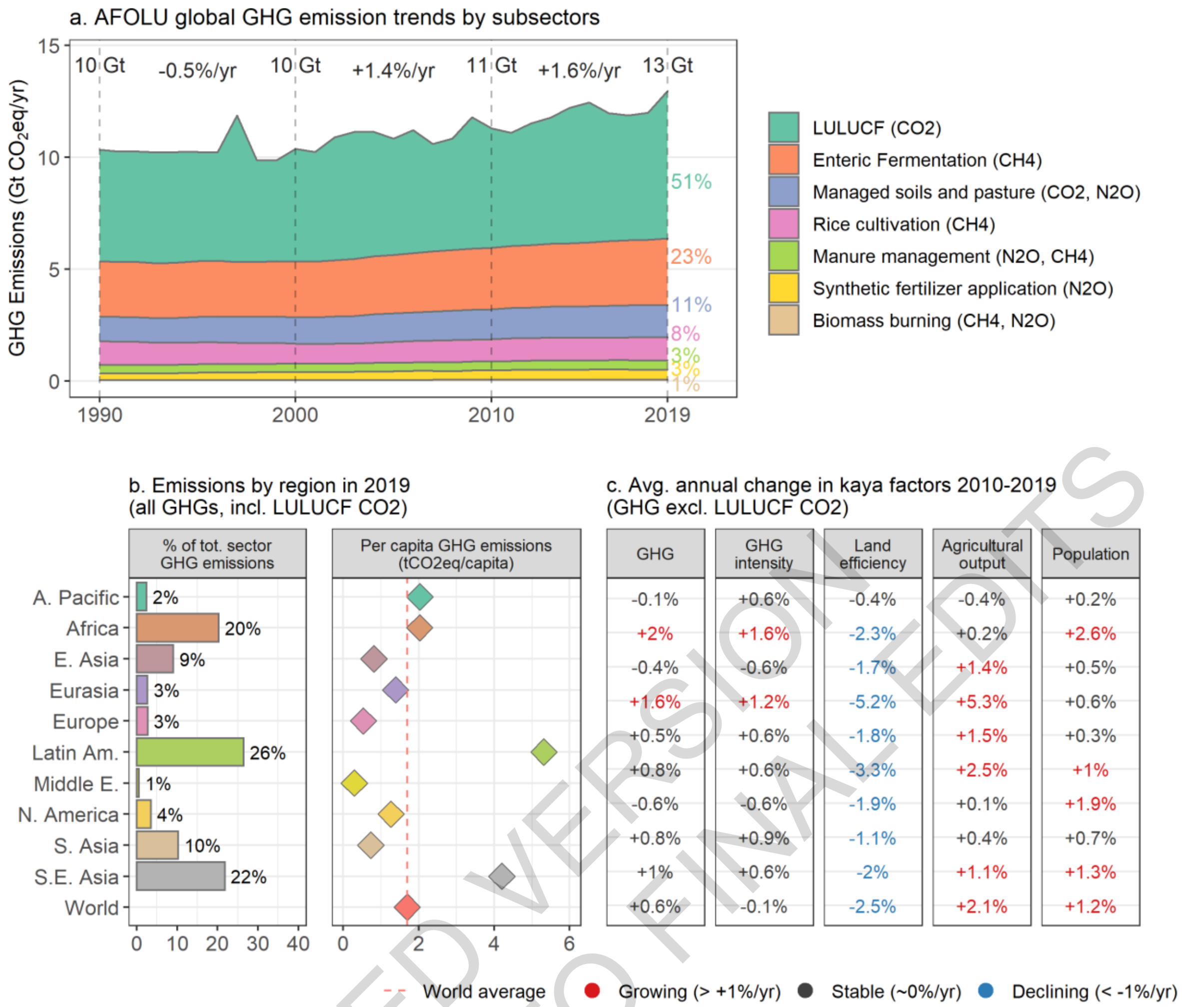


Figure 2.21 Trends and drivers of global AFOLU sector emissions, including a) trends of GHG emissions by subsectors 1990–2019, b) share of total sector and per capita GHG emissions by world region in 2019, and c) Kaya decomposition of GHG emissions drivers

Based on the equation H=P(A/P)(L/A)(H/L), where P is population, A/P is agricultural output per capita, L/A is the land required per unit of agricultural output (land efficiency), and H/L is GHG emissions per unit of land (GHG intensity) (Hong et al., 2021). GHG emissions H comprise agricultural CH_4 and N_2O emissions from EDGAR v6.0. The indicated annual growth rates are averaged across the years 2010–2019 (LULUCF CO_2 emissions are excluded in panel c). (Note: due to different datasets, the population breakdown for AFOLU emissions is slightly different than that in the other sector figures above).

Unlike all other sectors, AFOLU emissions are typically higher in developing compared to developed regions *(medium confidence)*. In Africa, Latin America, and South-East Asia, CO_2 emissions associated with land-use change and management predominate, dwarfing other AFOLU and non-AFOLU sources and making AFOLU the single largest sector with more than 50% of emissions in these regions (Lamb et al., 2021b). Land-use and -management emissions there is associated with the expansion of agriculture into carbon-dense tropical forest areas (Vancutsem et al., 2021), where large quantities of CO_2 emissions result from the removal and burning of biomass and draining of carbon rich soils (Pearson et al., 2017; IPCC, 2018; Hong et al., 2021). Ruminant livestock rearing takes place on vast tracts of pasture land worldwide, contributing to large quantities of CH_4 emissions from enteric fermentation in Latin America (0.8 $GtCO_2$-eq in 2018), Southern Asia (0.6 $GtCO_2$-eq), and Africa (0.5

$GtCO_2$-eq), while also playing a sizable role in the total AFOLU emissions of most other regions (Lamb et al., 2021b).

In all regions, the amount of land required per unit of agricultural output has decreased significantly from 2010 to 2019, with a global average of -2.5% yr^{-1} (land efficiency metric in Figure 2.21). This reflects agricultural intensification and technological progress. However, in most regions this was mirrored by an increase in output per capita, meaning that absolute GHG emissions in most regions increased over the last decade. A significant increase in total AFOLU emissions occurred in Africa, driven by both increased GHG emissions per unit of land and increased populations (Figure 2.21).

The AFOLU sector and its emissions impacts are closely tied to global supply chains, with countries in Latin America and South-East Asia using large portions of their land for agricultural and forestry products exported to other countries (see Chapter 7). The strong increases in production per capita and associated GHG emissions seen in these regions are at least partly attributable to growing exports and not national food system or dietary changes. At the same time, efforts to promote environmental sustainability in regions like the EU and the USA (but also fast-growing emerging economies such as China) can take place at the cost of increasing land displacement elsewhere to meet their own demand (Meyfroidt et al., 2010; Yu et al., 2013; Creutzig et al., 2019).

Global diets are a key driver of production per capita, and thus land pressure and AFOLU emissions (Chapter 7). As per capita incomes rise and populations urbanise, traditional, low-calorie diets that emphasise starchy foods, legumes, and vegetables transition towards energy-intensive products such as refined sugars, fats, oils, and meat (Tilman and Clark, 2014; Pradhan et al., 2013). At a certain point in national development, affluence and associated diets thus override population growth as the main driver of AFOLU emissions (Kastner et al., 2012). Very high calorie diets have high total GHG emissions per capita (Heller and Keoleian, 2015) and are common in the developed world (Pradhan et al., 2013). Over the last few decades, a "westernisation" of diets has also been occurring in developing countries (Pradhan et al., 2013). Low- and middle-income countries such as India, Brazil, Egypt, Mexico, and South Africa have experienced a rapid dietary shift towards western-style diets (De Carvalho et al., 2013; Pradhan et al., 2013; Popkin, 2015). Another driver of higher food requirements per capita is food waste, the amounts of which increased more or less continuously since the 1960s in all regions but Europe (Porter and Reay, 2016).

2.4.3 Poverty and Inequality

Increasing economic inequality globally has given rise to concern that unequal societies may be more likely to pollute and degrade their environments (Chancel, 2020; Hailemariam et al., 2020; Millward-Hopkins and Oswald, 2021; Masud et al., 2018). The nature of this relationship has important implications for the design of income redistribution policies aiming to reduce inequalities (Section 2.6 presents evidence on how affluence and high consumption relate to emissions). Income inequality and carbon intensity of consumption differs across countries and individuals (Baležentis et al., 2020) (Section 2.3.3). Reduced income inequality between nations can reduce emissions intensity of global income growth, if energy intensity reductions from income growth in some nations offset increases in energy and emissions from higher growth in other nations (Rao and Min, 2018). Increasing income inequality between individuals can translate into larger energy and emissions inequality if higher incomes are spent on more energy-intensive consumption and affluent lifestyles (Oswald et al., 2020; Wiedmann et al., 2020) (Section 2.6).

Literature shows that more equitable income distributions can improve environmental quality, but the nature of this relationship can vary by level of development *(low evidence, medium agreement)* (Knight et al., 2017; Chen et al., 2020; Hailemariam et al., 2020; Huang and Duan, 2020; Liobikienė and Rimkuvienė, 2020; Rojas-Vallejos and Lastuka, 2020; Uddin et al., 2020). Differences in the energy and carbon intensities of consumption and the composition of consumption baskets across populations and nations matter for emissions. (Jorgenson et al., 2016; Grunewald et al., 2017). There is evidence to suggest that more equal societies place a higher value on environmental public goods (Baumgärtner et al., 2017; Drupp et al., 2018). Additional research shows that reducing top income inequality in OECD countries can reduce carbon emissions and improve environmental quality (Hailemariam et al., 2020) and that the effect of wealth inequality, measured as the wealth share of the top decile, on per capita emissions in high-income countries is positive (Knight et al., 2017). Evidence from 40 sub-Saharan African countries suggests that a rise in income inequality contributed to increasing CO_2 emissions between 2010 and 2016, controlling for other drivers like economic growth, population size, and inflation (Baloch et al., 2020).

The key development objective of eradicating extreme poverty (Hubacek et al., 2017a; Chakravarty and Tavoni, 2013; Malerba, 2020) and providing universal access to modern energy services (Pachauri et al., 2018, 2013; Singh et al., 2017; Pachauri, 2014) only marginally effect carbon emissions *(robust evidence, medium agreement)*. Shifts from biomass to more efficient energy sources and collective provisioning systems for safe water, health, and education are associated with reduced energy demand (Baltruszewicz et al., 2021). Efforts to alleviate multi-dimensional poverty by providing decent living standards universally, however, may require more energy and resources. Recent estimates of the additional energy needed are still within bounds of projections of energy demand under climate stabilisation scenarios (Rao et al., 2019; Pascale et al., 2020; Hubacek et al., 2017b; a); Kikstra et al., 2021). Bottom-up estimates suggest that achieving decent living standards requires 13–40 GJ per capita annually, much less than the current world average energy consumption of 80 GJ per capita in 2020 (Millward-Hopkins et al., 2020) *(medium evidence, high agreement)*. Aggregate top-down estimates suggest that achieving a high Human Development Index (HDI) score above 0.8 requires energy consumption between 30–100 GJ per capita yr^{-1} (Lamb and Rao, 2015). There is some evidence, however, of a decoupling between energy consumption and HDI over time (Akizu-Gardoki et al., 2018). The emissions consequences of poverty alleviation and decent living also depend on whether improvements in well-being occur via energy- and carbon-intensive industrialisation or low-carbon development (Semieniuk and Yakovenko, 2020; Fu et al., 2021; Huang and Tian, 2021).

2.4.4 Rapid and Large-scale Urbanisation as a Driver of GHG Emissions

Economic growth and urbanisation go hand in hand and are both influencing GHG emissions. However, the exact role of urban development in driving emissions is multi-faceted and heterogeneous, depending on development status and other regional factors *(medium evidence, high agreement)* (Jorgenson et al., 2014; Lamb et al., 2014; Liddle and Lung, 2014; Creutzig et al., 2015; Pincetl, 2017; Azizalrahman and Hasyimi, 2019; Muñoz et al., 2020). This calls for a differentiated assessment. This section assesses the process of rapid urban growth in developing countries and how emissions change over time when cities grow rapidly, that is, when urban populations and infrastructure expand at fast speed and at a massive scale (Seto et al., 2017; Elmqvist et al., 2021). To distinguish, Section 2.6 includes the carbon footprint of urban lifestyles and the difference in emissions profiles between already urbanised and less urbanised areas. Chapter 8 deals with urban strategies for climate change mitigation.

Urban development is most significant and rapid in developing and transition countries, accompanied by a substantial migration of rural populations to urban areas (Apergis and Li, 2016; Azizalrahman and Hasyimi, 2019; Wang et al., 2019c) and associated impacts on land use (Richardson et al., 2015). If the trend of developing countries following infrastructure stock patterns in industrialised nations continues until 2050, this could cause approximately 350 $GtCO_2$ from the production of materials (Müller et al., 2013). This would be equivalent to 70% of the 500 $GtCO_2$ estimated remaining carbon budget from the beginning of 2020 to limit global warming to 1.5°C with a likelihood of 50% (IPCC, 2021b).

In many developing countries across the world, the process of urban expansion leads to higher per capita consumption-based GHG emissions *(medium evidence, high agreement)* (Jorgenson et al., 2014; Yao et al., 2015; Zhang et al., 2016; Wood et al., 2018a; Muñoz et al., 2020). The high disparity between rural and urban personal carbon footprints in these countries (Wiedenhofer et al., 2017) (see Section 2.6) means that migration to urban areas increases overall emissions as levels of income and expenditure rise, leading to further economic growth and infrastructure development in urban areas (Müller et al., 2013; Li et al., 2015; Wang and Yang, 2016; Zhang et al., 2016; Wiedenhofer et al., 2017; Cetin and Bakirtas, 2019; Fan et al. 2019; Li and Zhou, 2019; Xia et al., 2019; Sarkodie et al., 2020).

For total production-based emissions in general, urbanisation is thought to have a smaller effect than changes in population, GDP per capita, and energy and emissions intensities, which are all more influential (Lin et al., 2017). Another driver of urban emissions is rising ambient air temperature caused by urban land expansion, which will likely drive a substantive increase in air conditioning use and cold storage for food (Huang et al., 2019). Specific emission drivers, however, depend on city- and place-specific circumstances such as income, household size, density, or local climate (Baiocchi et al., 2015; Wang et al., 2019a). Geographical factors, urban form, and transport/fuel costs are dependent on each other, and, together with economic activity, have been found to explain 37% of urban direct energy use and 88% of urban transport energy use in a global sample of 274 cities (Creutzig et al., 2015).

2.5 Technological Change is Key to Reducing Emissions

Technological change for climate change mitigation involves improvement in and adoption of technologies, primarily those associated with energy production and use. Technological change has had a mitigating effect on emissions over the long term and is central to efforts to achieving climate goals (*high confidence*). Progress since AR5 shows multiple low-carbon technologies are improving and falling in cost (*high confidence*); technology adoption is reaching substantial shares, and small-scale technologies are particularly promising on both *(medium confidence)*. Faster adoption and continued technological progress can play a crucial role in accelerating the energy transition. However, the historical pace of technological change is still insufficient to catalyse a complete and timely transition to a low-carbon energy system; technological change needs to accelerate (*high confidence*). This section assesses the role of technological change in driving emissions reductions and the factors that drive technological change, with an emphasis on the speed of transitions. Incentives and support for technological change affect technology outcomes (Sivaram et al., 2018; Wilson et al., 2020a). Work since AR5 has focused on evaluating the effectiveness of policies, both those that accelerate technological change by enhancing knowledge – technology push – and those that increase market opportunities for successful technologies – demand pull – (Nemet, 2013), as well as the importance of tailoring support to country contexts (Rosenbloom et al., 2020; Barido et al., 2020), including the limits of policies to date that price carbon (Lilliestam et al., 2020). Section 2.8 and Chapter 13 describe how these polices affect emissions, Cross-Chapter box 12 in Chapter 16 and Chapter 14 discuss transition dynamics, and Chapter 16 provides a more detailed assessment of the evolution and mitigation impacts of technology development, innovation, and transfer.

2.5.1 Technological Change Has Reduced Emissions

Technological change that facilitates efficient energy utilisation from production to its final conversion into end-use services is a critical driver of carbon emissions reductions *(high confidence)*. Technological change can facilitate stringent mitigation, but it also can reduce these effects by changing consumer behaviour such as through rebound effects (see Section 2.6 and Chapter 16). AR6 includes an entire chapter on innovation, technology development, and transfer (Chapter 16). A focus gained in this section is the extent to which aligned, credible, and durable policies can accelerate technological change factors to put emissions reductions on a trajectory compatible with reaching UNFCCC goals.

Technological change has facilitated the provision of more diverse and efficient energy services (heating, cooling, lighting, and mobility) while generating fewer emissions per unit of service. As seen in Section 2.4, in Kaya identity terms (Lima et al., 2016) (see Glossary): population and economic growth are factors that have increased emissions, while technological change has reduced emissions (Peters et al., 2017). These Kaya statistics show that while technological change can facilitate the transition to a low-carbon economy, it needs to proceed at a much faster pace than historical trends (Peters et al., 2017).

Multiple challenges exist in accelerating the past rate of technological change. First, an array of physical assets in the energy system are long-lived and thus involve substantial committed carbon (see Section 2.7) (Knapp, 1999; Cui et al., 2019). A process of "exnovation," accelerating the phase-out of incumbent technology through intentional policy (e.g., by pricing carbon), provides a means to address long lifetimes (Davidson, 2019; Rosenbloom and Rinscheid, 2020). Second, countries may not have the capacity to absorb the flows of ideas and research results from international knowledge spillovers due to weak infrastructure, limited research capacity, lack of credit facilities (see Chapter 15, Section 15.5), and other barriers to technology transfer (Adenle et al., 2015). In a developing country context, processes of innovation and diffusion need to include competence-building systems (Lema et al., 2015; Perrot and Sanni, 2018; Stender et al., 2020). Third, public policy is central to stimulating technological change to reduce emissions; policy depends on creating credible expectations of future market opportunities (Alkemade and Suurs, 2012), but the historical evidence shows that, despite recent progress, policies related to energy and climate over the long term have been inconsistent (Taylor, 2012; Nemet et al., 2013; Koch et al., 2016). Bolstering the credibility and durability of policies related to low-carbon technology are crucial to accelerating technological change and inducing the private sector investment required (Helm et al., 2003; Habermacher et al., 2020).

2.5.2 A Low-Carbon Energy Transition Needs to Occur Faster Than Previous Transitions

An illuminating debate on the possibility of faster transitions has emerged since AR5 – with diverging assumptions about future technological change at the core of the discourse (Bazilian et al., 2020; Lu and Nemet, 2020). Table 2.5 summarises these arguments.

2.5.2.1 Energy transitions can occur faster than in the past

Recent studies have identified examples supporting fast energy transitions (Sovacool, 2016; Bond et al., 2019; Reed et al., 2019). One describes five rapid national-scale transitions in end-use technologies, including lighting in Sweden, cook-stoves in China, liquefied petroleum gas stoves in Indonesia, ethanol vehicles in Brazil, and air conditioning in the USA (Sovacool, 2016). Adoption of electric vehicles in Norway and in cities in China have also been rapid (Rietmann and Lieven, 2019; Li et al., 2020; Fridstrøm, 2021). Examples in energy supply, include electrification in Kuwait, natural gas in the Netherlands, nuclear electricity in France and Sweden, combined heat and power in Denmark, renewable energy in Uruguay, and coal retirements in Ontario, Canada (Qvist and Brook, 2015). Reasons that these exemplars could be applied more broadly in the future include: growing urgency on climate change, shifting motivation from price response to proactive resource scarcity, and an increase in the likelihood of technological breakthroughs *(medium confidence)* (Sovacool, 2016; Bazilian et al., 2020). The emergence of smaller unit scale, "granular" technologies described below also creates the potential for faster system change (Trancik, 2006; Grubler et al., 2018; Wilson et al., 2020a). Prices of energy services and government actions that affect demand are critical to the speed and extent of energy transitions (Kramer and Haigh, 2009). Reasons scholars consider for expecting a fast transition include: intentional policy and alignment with goals; globalisation which diversifies sources and integrates supply chains; collective action via the Paris Agreement; as well as bottom-up grassroots movements and private sector initiatives (Kern and Rogge, 2016). Political support for change can also speed transitions (Burke and Stephens, 2017; Stokes and Breetz, 2018), as can the credibility of transition-related targets (Li and Pye, 2018; Rogge and Dütschke, 2018).

The important role of leader countries is often missed when looking only at global aggregates (Meckling and Hughes, 2018); leaders accumulate important knowledge, provide scaled market, and set positive examples for followers *(medium confidence)* (Schwerhoff, 2016; Buchholz et al., 2019). In recent years, the conception of where leadership, climate-relevant innovation, and technology transfer originate has shifted to considering more meaningfully direct South-South and South-North forms of technology transfer, flows of capital, drivers for market access, origins of innovation, and other forms of cooperation (Urban, 2018; Köhler et al., 2019). Recent evidence shows South-South trade is enabling clean technology transfer (Gosens, 2020). Leaders can initiate a process of "catalytic cooperation" in which they overcome collective action problems and stimulate rapid change (Hale, 2018). Similarly, "sensitive intervention points" – targeted support of social movements, technologies, or policies themselves – can lead to rapid and self-sustaining change (Farmer et al., 2019), such as support for photovoltaics in Germany in the 2000s and student climate activism in Europe in 2019. The focus on leadership, catalysts, and intervention points reflects a systemic view of transitions that emphasises interactions and interdependence (Geels, 2018; Meckling and Hughes, 2018). Technological change has been at the core of transitions, but is best understood as part of a system in which social aspects are crucial *(medium confidence)* (Cherp et al., 2018; Köhler et al., 2019; Overland and Sovacool, 2020).

Table 2.5 Summary reasons to expect a fast energy transition and reasons to expect a slow transition.

	Fast transition	Slow transition
Evidentiary basis	Technology and country cases over 50 years	Historical global system over 200 years
Systems	Complementary technologies enable integration	Difficult integration with existing infrastructure
Economics	Falling costs of nascent technology	Mature incumbent technologies
		Up-front costs and capital constraints
Technology	Digitalisation and global supply chains	Long lifetimes of capital stock
	More abundant innovation	Difficult to decarbonise sectors
	Granular technology	
Actors	Proactive efforts for transition	Risk-averse adopters
	Bottom-up public concern	Attributes do not appeal to consumers
	Mobilised low-carbon interest groups	Rent-seeking by powerful incumbents
Governance	Leaders catalyse faster change	Collective action problems

2.5.2.2 Reasons that transitions will occur at historical rates of change

Recent work has also reasserted previous claims that the speed of a low-carbon transition will follow historical patterns *(low confidence)*. Broad transitions involve technological complexity, time-consuming technological development, risk-averse adopters, high up-front costs, and low immediate individual adoption benefits, attributes which are not all present in the examples of rapid change described above (Grubler et al., 2016). Additional factors that slow transitions include: the need for the transition to occur globally, thus requiring nations with unequal economic resources and development circumstances to engage in near-universal participation; slow progress in recent decades; intermittence of renewables, and the time involved in building supporting infrastructure (Smil, 2016); difficulty in decarbonising transportation and industry (Rissman et al., 2020); and material resource constraints (Davidsson et al., 2014).

2.5.3 Improvements in Technologies Enable Faster Adoption

Since AR5, multiple low-carbon technologies have shown dramatic improvement, particularly solar PV, wind, and batteries *(high confidence)*. The observed pace of these changes and the likelihood of their continuation support the arguments in the previous section that future energy transitions are likely to occur more quickly than in the past *(medium confidence)*.

2.5.3.1 Technological change has produced dramatic cost reductions

A wide array of technologies shows long-term improvements in performance, efficiency, and cost. Among the most notable are solar photovoltaics, wind power, and batteries *(high confidence)* (see Chapters 6 and 16). PV's dynamics are the most impressive, having fallen in cost by a factor of 10,000 from the first commercial application on a satellite in 1958 (Maycock and Wakefield, 1975) to power purchase agreements signed in 2019 (IRENA, 2020). Wind has been on a nearly as steep trajectory (Wiser and Bolinger, 2019) as are lithium-ion battery packs for electric vehicles (Nykvist and Nilsson, 2015; Service, 2019). The future potential for PV and batteries seems especially promising given that neither industry has yet begun to adopt alternative materials with attractive properties as the cost reductions and performance improvements associated with the current generation of each technology continue *(medium confidence)* (Kwade et al., 2018). A key challenge is improving access to finance, especially in developing country contexts, where the costs of financing are of crucial importance (Creutzig et al., 2017; Schmidt, 2019).

2.5.3.2 Technological change has accelerated since AR5

Figure 2.22 shows changes in the costs of four dynamic energy technologies. One can see rapid changes since AR5, cost data for which ended in 2010. Solar PV is by far the most dynamic technology, and its cost since AR5 has continued on its steep decline at about the same rate of change as before AR5, but now costs are well within the range of fossil fuels *(high confidence)* (see Chapter 6). Very few concentrating solar power (CSP) plants had been built between the 1980s and 2012. Since AR5, 4 GW have been built and costs have fallen by half. Onshore wind has continued its pace of costs reductions such that it is well within the range of fossil fuels. Offshore wind has changed the most since AR5. Whereas costs were increasing before AR5, they have decreased by 50% since. None of these technologies shows indications of reaching a limit in their cost reductions. Crucial to their impact will be extending these gains in the electricity and transportation sectors to the industrial sector (Davis et al., 2018).

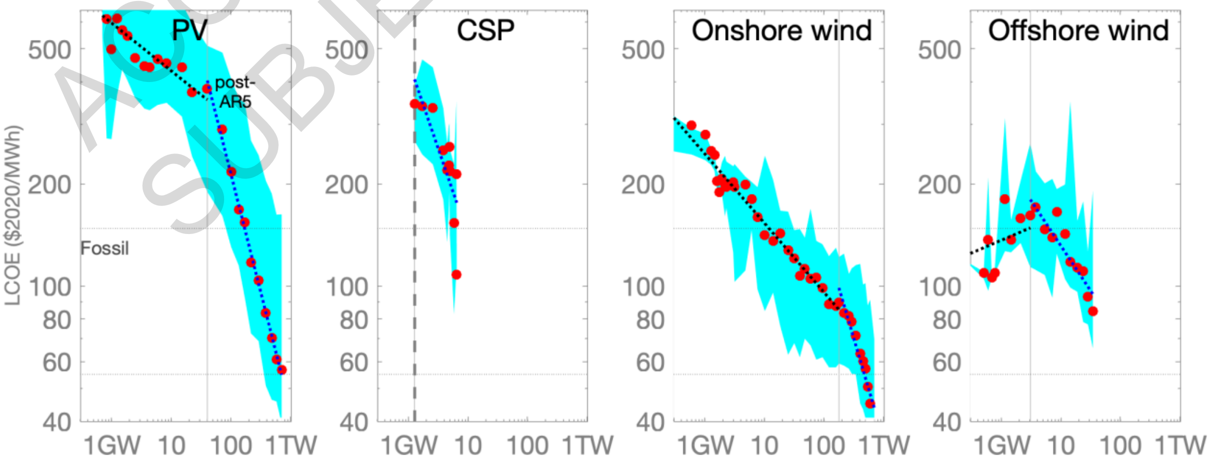


Figure 2.22: Learning curves for renewable energy technologies 2000–2019

Range of fossil fuel levelised cost of electricity indicated as horizontal dashed lines spanning the range of USD50–177 MWh^{-1}. Dashed lines are power functions fit to data for AR4–AR5 in black and for post-AR5 (2012) in blue. Blue areas show ranges between the 10th and 90th percentile in each year.
Source: Data from Nemet (2019), IRENA (2020).

2.5.3.3 Granular technologies improve faster

The array of evidence of technology learning that has accumulated both before and since AR5 (Thomassen et al., 2020) has prompted investigations about the factors that enable rapid technology learning. From the wide variety of factors considered, unit size has generated the strongest and most robust results. Smaller unit sizes, sometimes referred to as 'granularity', tend to be associated with faster learning rates *(medium confidence)* (Sweerts et al., 2020; Wilson et al., 2020). Examples include solar PV, batteries, heat pumps, and to some extent wind power. The explanatory mechanisms for these observations are manifold and well established: more iterations are available with which to make improvements (Trancik, 2006); mass production can be more powerful than economies of scale (Dahlgren et al., 2013); project management is simpler and less risky (Wilson et al., 2020); the ease of early retirement can enable risk-taking for innovative designs (Sweerts et al., 2020); and they tend to be less complicated (Malhotra and Schmidt, 2020; Wilson et al., 2020). Small technologies often involve iterative production processes with many opportunities for learning by doing and have much of the most advanced technology in the production equipment than in the product itself. In contrast, large unit scale technologies – such as full-scale nuclear power, CCS, low-carbon steel making, and negative emissions technologies such as bioenergy with carbon capture and sequestration (BECCS) – are often primarily built on site and include thousands to millions of parts such that complexity and system integration issues are paramount (Nemet, 2019). Despite the accumulating evidence of the benefits of granularity, these studies are careful to acknowledge the role of other factors in explaining learning. In a study of 41 energy technologies (Figure 2.23), unit size explained 22% of the variation in learning rates (Sweerts et al., 2020) and a study of 31 low-carbon technologies showed unit size explained 33% (Wilson et al., 2020). Attributing that amount of variation to a single factor is rare in studies of technological change. The large residual has motivated studies, which find that small-scale technologies provide opportunities for rapid change, but they do not make rapid change inevitable; a supportive context, including supportive policy and complementary technologies, can stimulate more favourable technology outcomes *(high confidence)*.

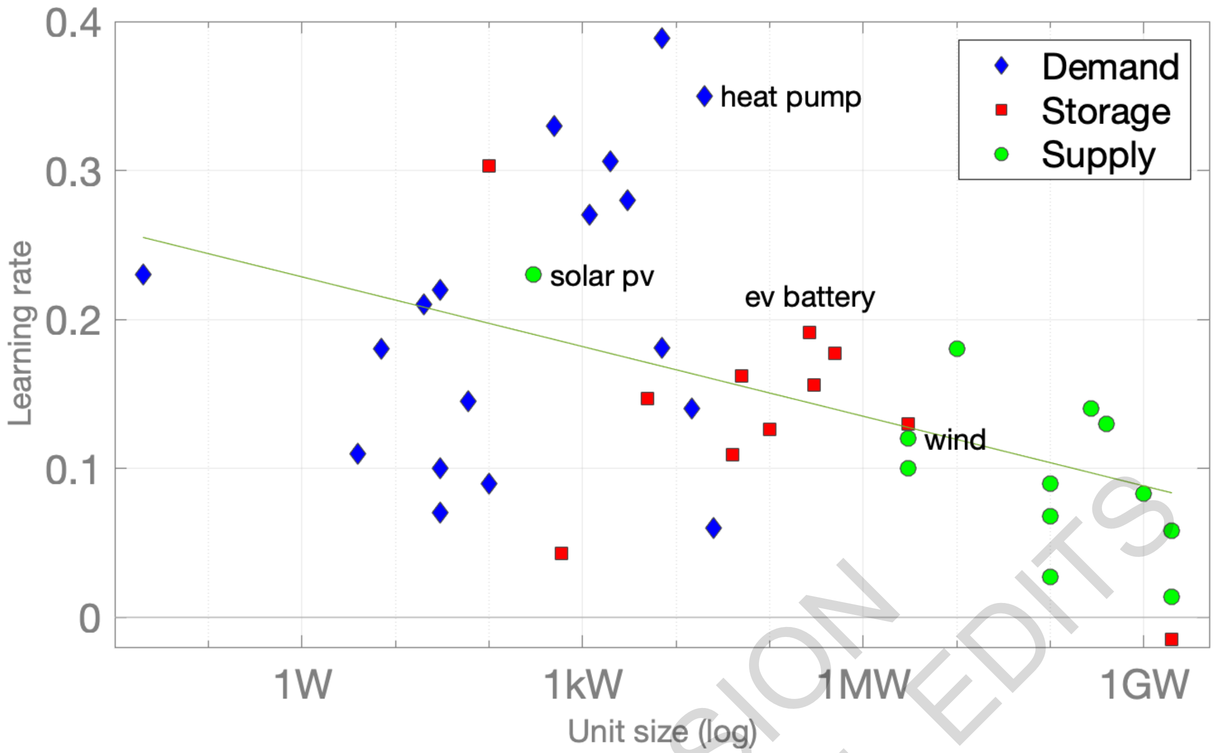


Figure 2.23 Learning rates for 41 energy demand, supply, and storage technologies
Source: Sweerts et al. (2020).

There is also evidence that small technologies not only learn but get adopted faster than large technologies *(medium confidence)* (Wilson et al., 2020b). Some of the mechanisms related to the adoption rate difference are related to those for cost reductions; for example, smaller, less lumpy investments involve lower risk for adopters (Dahlgren et al., 2013; Wilson et al., 2020b). The shorter lifetimes of small technologies allow users to take advantage of new performance improvements (Knapp, 1999) and access a large set of small adopters (Finger et al., 2019). Other mechanisms for faster adoption are distinctly related to markets: modular technologies can address a wide variety of niche markets (Geels, 2018) with different willingness to pay (Nemet, 2019) and strategically find protected niches while technology is maturing (Coles et al., 2018).

2.5.4 Rapid Adoption Accelerates Energy Transitions

The transition to a more sustainable energy system depends not just on improvement in technologies, but also on their widespread adoption. Work since AR5 has also substantiated the bidirectional causal link between technology improvement and adoption. Cost reductions facilitate adoption, which generates opportunities for further cost reductions through a process of learning by doing *(medium confidence)*. The rate of adoption is thus closely related to the speed at which an energy transition is possible.

Results of integrated assessment models (IAMs) show that scale-up needs are massive for 2°C scenarios. Using logistic growth rates of energy shares as in previous work (Wilson, 2012; Cherp et al., 2021), most of these technologies include annual adoption growth rates of 20% in the 2020s and 2030s, and are in line with recent adoption of wind and solar. However, it is important to realise that IAMs include faster adoption rates for some mitigation technologies than for others (Peters et al., 2017). Growth rates in IAMs for large-scale CCS – biomass, coal, and gas – are between 15 and 30% (25th and 75th percentiles) (Figure 2.24). So few plants have been built that there is little historical data to which to compare this expected growth; with only two full scale CCS power plants built and a 7% growth rate if including industrial CCS. In contrast, IAMs indicate that they expect much lower rates of growth in future years for the set of technologies that has been growing fastest in recent years (wind and solar), without strong evidence for why this should occur.

The overall pattern shows that IAMs expect growth in small-scale renewables to fall to less than half of their recent pace and large-scale CCS to more than double from the limited deployment assessed *(high confidence)*. The emerging work since AR5 showing the rapid adoption and faster learning in small-scale technologies should prompt a keener focus on what technologies the world can depend on to scale up quickly (Grubb et al., 2021). In any case, the scenario results make quite clear that climate stabilisation depends on rapid adoption of low-carbon technologies throughout the 2020–2040 period.

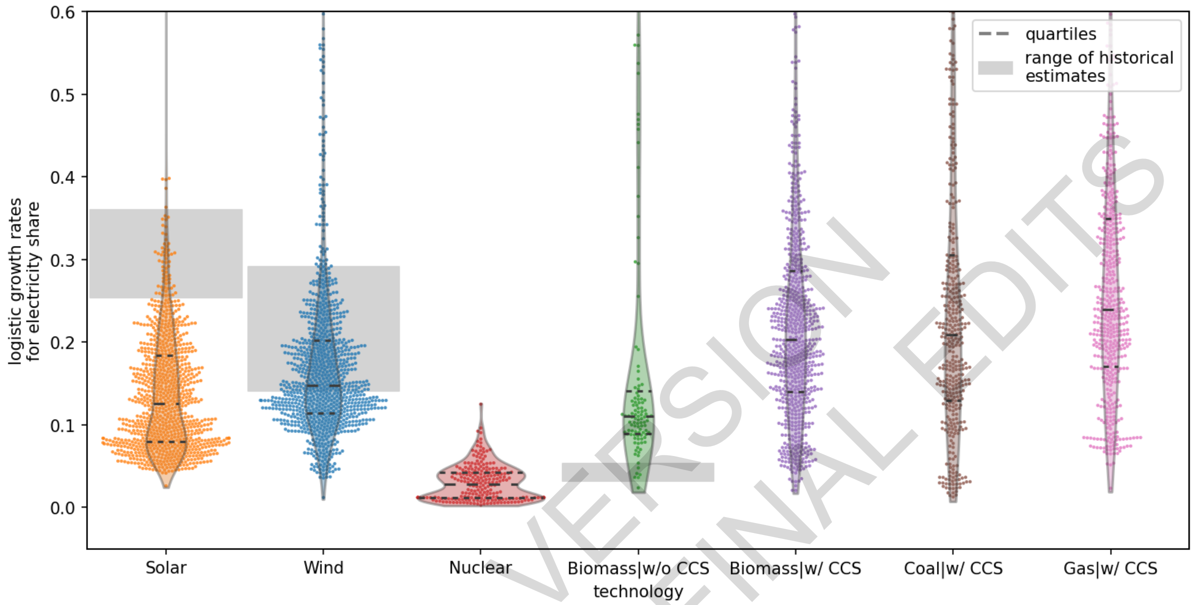


Figure 2.24 Growth of key technologies (2020–2040) in Paris-consistent mitigation scenarios compared to historical growth

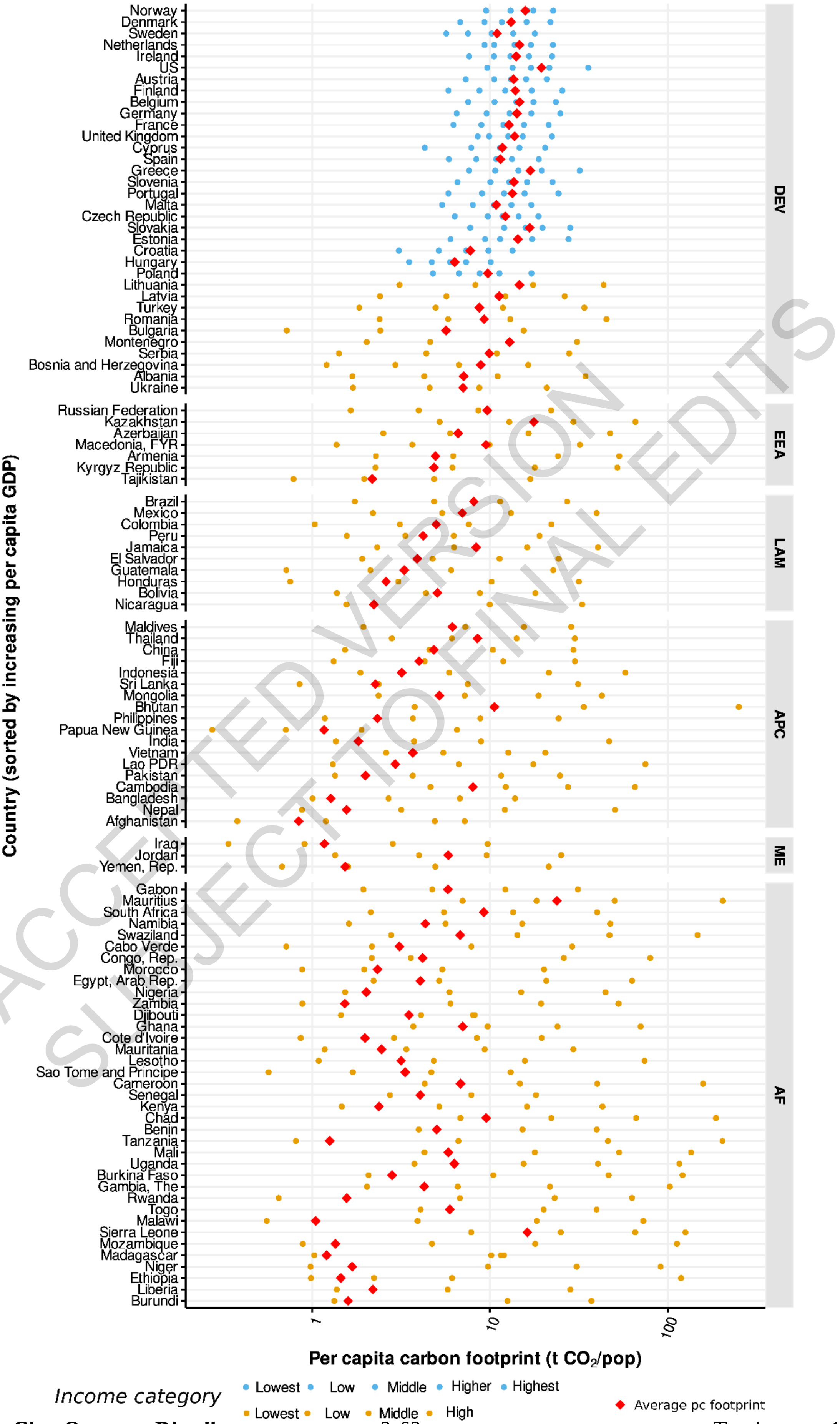
Comparisons of historical growth (grey bars) to growth in 2020–2040 mitigation scenarios (dots). Values on vertical axis are logistic annual growth rates for share of each technology in electricity supply. Horizontal arrangement of dots within technology categories indicates count of scenarios at each growth rate.

Source: Data on scenarios from Chapter 3, historical data from BP (2021).

2.6 Behavioural Choices and Lifestyles

2.6.1 Introduction

This section synthesises how behavioural choices, lifestyles, and consumption preferences affect energy use and emissions. Household consumption is the largest component of a country's gross domestic product (GDP) and the main contributor to greenhouse gas emissions through direct energy consumption for heating and cooling or private transportation and indirectly through carbon emitted during production of final consumption items. There is great variation in individual, groups and household behavior and consumption patterns within and between countries and over time. A number of factors affect people's consumption patterns and associated carbon emissions, such as socio-demographics, socio-economic status, infrastructure and access to public services; the regulatory frame; availability, affordability and accessibility of more or less sustainable choices on markets; individual values and preferences (Dietz et al., 2009).



Norway
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Austria
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Portugal
Malta
Czech Republic
Slovakia
Estonia
Croatia
Hungary
Poland
Lithuania
Latvia
Turkey
Romania
Bulgaria
Montenegro
Serbia
Bosnia and Herzegovina
Albania
Ukraine
Russian Federation
Kazakhstan
Azerbaijan
Macedonia, FYR
Armenia
Kyrgyz Republic
Tajikistan
Brazil
Mexico
Colombia
Peru
Jamaica
El Salvador
Guatemala
Honduras
Bolivia
Nicaragua
Maldives
Thailand
China
Fiji
Indonesia
Sri Lanka
Mongolia
Bhutan
Philippines
Papua New Guinea
India
Vietnam
Lao PDR
Pakistan
Cambodia
Bangladesh
Nepal
Afghanistan
Iraq
Jordan
Yemen, Rep.
Gabon
Mauritius
South Africa
Namibia
Swaziland
Cabo Verde
Congo, Rep.
Morocco
Egypt, Arab Rep.
Nigeria
Zambia
Djibouti
Ghana
Cote d'Ivoire
Mauritania
Lesotho
Sao Tome and Principe
Cameroon
Senegal
Kenya
Chad
Benin
Tanzania
Mali
Uganda
Burkina Faso
Gambia, The
Rwanda
Togo
Malawi
Sierra Leone
Mozambique
Madagascar
Niger
Ethiopia
Liberia
Burundi
DEV
EEA
LAM
APC
ME
AF
Country (sorted by increasing per capita GDP)
1
10
100
Per capita carbon footprint (t CO2/pop)
Income category
Lowest
Low
Middle
Higher
Highest
Lowest
Low
Middle
High
Average pc footprint

Figure 2.25 Carbon footprints per capita income and expenditure category for 109 countries ranked by per capita income (consumption-based emissions)

Notes: Countries and income categories are dependent on data availability. Blue dots represent income quintiles (lowest, low, middle, higher, and highest) of EU countries and the United States. Orange dots are for the developing country group provided by the World Bank for 4 expenditure categories: lowest, low, middle and higher (Hubacek et al., 2017b). Red diamonds represent average per capita carbon footprints. Countries are ranked from the lowest per capita income (bottom) to the highest income (top) within each country group. Countries are grouped using the IPCC's six categories high-level classification. Footprint values for higher income groups in the World Bank data are less reliable.

Carbon footprints vary between and within countries and show an uneven distribution because of differences in development levels, economic structure, economic cycle, available public infrastructure, climate and residential lifestyles (Bruckner et al., 2021). Similar emission characteristics can also be found within a country, see, for example for China (Feng et al., 2013), for the US (Pizer et al., 2010; Wang et al., 2018; Miehe et al., 2016; Feng et al., 2013; Hubacek et al., 2017b) for Brazil (Sanches-Pereira et al., 2016), for Latin American countries (Zhong et al., 2020).

In western countries, the largest contribution to the household carbon footprint is from transportation, housing, and consumption of food (Druckman and Jackson, 2015). These three items' joint contribution varies in different countries depending on consumption patterns and account for 58.5%, on average, in EU 25 countries. (Tukker and Jansen, 2006). However, different countries and even regions within countries may have different emission patterns due to differences in income, lifestyle, geography, infrastructure, political and economic situation. For example, the main contributors to the average US household is private transport (19.6%), followed by electricity (14.8%) and meat (5.2%) (Jones and Kammen, 2011), while the UK households have 24.6% emissions on energy and housing, 13.7% emissions on food, and 12.2% emissions on consumables (Gough et al., 2011). A study of 49 Japanese cities found that energy (31%), food (27%), and accommodation (15%) were the largest sources of household emissions (Long et al., 2017). An overview investigation of Japan's household emissions found that energy, food, and utility are the three main emissions sources, but their shares are dependent on age (Shigetomi et al., 2014). See section 12.4 in chapter 12 and Box 5.4 in chapter 5 for more in-depth discussion on food systems and dietary shifts towards lower emission food.

In terms of rapidly growing economies, China is the most extensively researched country. China's household emissions were primarily derived from electricity and coal consumption, as well as residents' consumption of emission-intensive products, such as housing (33.4%), food (23.6%), private transportation and communications (14.8%) (Wang et al., 2018). Space heating was the largest contributor among various daily energy uses in northern cities (Yang and Liu, 2017). In comparison, Indonesian rural households have a larger emission share on foods and a much smaller share on services and recreation than urban households (Irfany and Klasen, 2017). Urban Indonesian households have a much larger share of transport related emissions (Irfany and Klasen, 2017). Analysis from the Philippines shows that on average households in urban areas emit twice as much as rural ones because of much lower direct energy use in homes and for transport in rural areas (Serino, 2017). In other emerging economies, such as India, Brazil, Turkey and South Africa, a high share of transport related carbon emissions among urban middle- and high-income households is evident (Huang and Tian, 2021).

2.6.2 Factors affecting household consumption patterns and behavioural choices

Households' carbon emissions are closely linked to activities and consumption patterns of individuals and as a group in households. Individual and group behaviour, in turn, is shaped by economic, technological, and psychological factors, social contexts (such as family ties, friends and peer-pressure) and cultural contexts (social identity, status, and norms) as well as the natural environment (number of heating and cooling days) and physical infrastructure, or geography (Jorgenson et al., 2019). For example, a city with an excellent bicycle infrastructure will make it safer and easier for citizens to become highly mobile by using their bikes; a city that has less density and is dominated by automobile infrastructure induces more people to travel by car (see Chapter 8 and 10). As a consequence, many climate relevant consumption acts are not consciously decided upon or deliberately made part of a lifestyle but are strongly influenced by the factors listed above. Chapter 5 provides more in-depth discussion on behavioural drivers and examples of behavioural interventions and policies that can be used to reduce emissions.

Demographic characteristics such as age, sex, and education constitute an important set of determinants influencing emissions patterns. People of different genders have different consumption patterns. For example, men tend to consume more food (especially meat) than women, leading to higher food-related emissions. Also, men spend more money on vehicles and driving (Wang et al., 2018). Similar evidence has been found in Germany, Greece, Norway, and Sweden, where men's energy use is 8%, 39%, 6%, and 22% higher than women's, respectively (Räty and Carlsson-Kanyama, 2010).

Income. Due to the differences that shape individuals' consumption patterns there are enormous differences in carbon footprints associated with income being one of the most important predictors. Globally, households with income in the top 10% (income higher than USD23.03 PPP per capita per day) are responsible for 36% to 45% of GHG emissions, while those in the bottom 50% (income less than USD2.97 PPP per capita per day) are responsible for only 13-15% of emissions depending on the study (Chancel and Piketty, 2015; Semieniuk and Yakovenko, 2020; Hubacek et al., 2017b) (Figure 2.25). The average carbon footprint of the high household incomes is more than an order of magnitudes larger than that of the lowest expenditure group (Feng et al. 2021). For example, Zhang et al. (2016) analysed the impact of household consumption across different income households on the whole CO_2 emissions in China and concluded that the impact on CO_2 emissions generated by urban households' consumption are 1.8 times as much as that of rural ones. High-income households have higher emission related to transport and entertainment, such as recreational expenditure, travel, and eating out, than low-income households. Low-income households tend to have a larger share on necessities such as fuel for heating and cooking (Kerkhof et al., 2009). Figure 2.25, shown above, depicts the carbon footprint per capita ranked by per capita income.

Age. The effect of population ageing on emissions is contested in literature. Ageing when accompanied by shrinking household size and more energy-intensive consumption and activity patterns results in increased emissions. However, an ageing labour force can also dampen economic growth and result in less of energy-intensive activity like driving, which decreases emissions (Liddle, 2011; Liddle and Lung, 2010). An ageing of the population characterises the demographic transition in both developed and developing countries. The implications of ageing for emissions depend on labour force participation of the elderly and difference in the consumption and investment patterns of different age groups (O'Neill et al., 2012). Analysis using panel macro data from OECD countries suggests that shifts in age and cohort composition have contributed to rising GHG emissions since the 1960s (Menz and Welsch, 2012; Nassen, 2014). Household-level data over time for the US provides evidence that residential energy consumption increases over the lifetime of household members, largely also due to accompanying changes in household size (Estiri and Zagheni, 2019). Similar insights emerge from Japan, where analysis shows that those in their 70s or older, a group that is growing in size in Japan, have higher emissions than other age groups (Shigetomi et al., 2014, 2019, 2018). Recent analysis from China suggests that the shift to smaller and ageing households is resulting in higher carbon emissions because of the accompanying time-use and consumption shifts (Yu et al., 2018; Li and Zhou, 2019). An increase in the dependency ratio, i.e. the proportion of children under 15 and people over 65 relative to the working-age population, in other analysis, has been shown to lead to reduced CO_2 emissions in China (Wei et al., 2018; Li and Zhou, 2019). Implications of the nature of this relationship are important to policy discussions of working hours and retirement age that are likely to have an influence on emissions. For example, children and youth tend to emit more education related emissions than adults (Han et al., 2015). Older people tend to have higher emissions related to heating and cooling being more sensitive to temperature (Meier and Rehdanz, 2010).

Household size. Per capita emissions tend to decrease with family size as living together becomes more energy efficient (Qu et al., 2013). The household size in most countries is decreasing (Liu et al., 2011), but the decrease rate differs across countries and show, for example, higher decrease rate in China than Canada and UK (Maraseni et al., 2015). The evidence shows that shifts to smaller households are associated with larger per-capita footprints (Liddle and Lung, 2014; Underwood and Zahran, 2015; Wiedenhofer et al., 2018; Ivanova et al., 2017), at least in developed countries (Meangbua et al., 2019).

Urban Living. The carbon footprint of individuals and households is also significantly influenced by urban-rural differences (Ivanova et al., 2018; Wiedenhofer et al., 2018). In some part, the difference can be explained by the effect of locational and spatial configuration characteristics such as levels of compactness/density, centrality, proximity and ease of access to services. In all these parameters, urban areas score higher as compared with rural or peri-urban (outlying and suburban) areas, thus influencing household emissions in different ways. Urban households tend to have higher emissions than rural households (O'Neill et al., 2010; Liu et al., 2011), but with different energy and consumption structure. For example, rural households have more diverse energy inputs, such as biomass, biogas, solar, wind, small hydro and geothermal in addition to coal (Maraseni et al., 2016).

In terms of indirect emissions, urban households have more service related emissions, such as from education and entertainment than rural households, while rural households tend to have higher emissions related to food consumption or transportation (Büchs and Schnepf, 2013; Maraseni et al., 2016) but this is strongly dependent on the specific situation of the respective country as in poorer regions rural transport might be mainly based on public transport with lower carbon emissions per capita. Centrality and location also place a role on the level of urban household emissions. Studies on US households found that residents in the urban core have 20% lower household emissions than residents in outlying suburbs, which show a large range of household emissions (from -50% to +60%) (Kahn, 2000; Jones and Kammen, 2014). From a global average perspective, higher population density is associated with lower per capita emissions (Liddle and Lung, 2014; Liu et al., 2017).

Location choices are a significant contributor to household emissions. Suburbanites generally purchase large, spacious homes with larger heating and cooling requirements. Commuting distance and access to public transportation, recreation areas, city centres, public services, and shops are other important neighbourhood-specific determinants of carbon emissions (Baiocchi et al., 2010) (see more on this in urban and the transport chapters 8 and 10).

Time Use. A study on the emissions implications of time use (Wiedenhofer et al., 2018) found that the most carbon intensive activities are personal care, eating and drinking and commuting. Indirect emissions are also high for repairs and gardening. In contrast, home-based activities such as sleep and resting, cleaning and socializing at home have low carbon intensities per hour of time use. The same study also found that households in cities and with higher incomes tend to substitute personal activities for contracted services, thus shifting away from households to the service sector (Wiedenhofer et al., 2018). Improvements in the efficiency of time or resource use are diminished by rebound effects which have been shown to reduce emissions savings by 20-40% on average (Gillingham et al., 2015), while other authors argue that potentially the size of the rebound effect could be larger (Saunders, 2015) (see more coverage of the rebound effect in Chapters 9 and 16). Lifestyle shifts brought about by using information technologies and socio-technological changes are inducing alterations in people's daily activities and time-use patterns.

The reduction of working hours is increasingly discussed as an approach to improve well-being and reduce emissions (Wiedenhofer et al., 2018; Fitzgerald et al., 2015, 2018; Melo et al., 2018; Smetschka et al., 2019). For instance, analysis of differences in working hours across US states for the period 2007-2013 shows that there is a strong positive relationship between carbon emissions and working hours, which holds even after controlling for other differences in political, demographic and economic drivers of emissions (Fitzgerald et al., 2018). In other analysis, this relationship is seen to hold in both developed and developing countries (Fitzgerald et al., 2015). One recent study, however, finds evidence of nonlinear relationships between working time and environmental pressure in EU-15 countries between 1970 and 2010, in cases where non-work time is spent instead in carbon-intensive leisure activities (Shao and Shen, 2017).

Social Norms. Evidence from experiments in the US shows that social norms can not only help in reducing a household's absolute level of electricity use but also shift the time of use to periods when more renewable electricity is in the system (Horne and Kennedy, 2017). Analysis from Sweden shows that adoption of sustainable innovations like solar panels is influenced by perceived behaviour and expectations of others (Palm, 2017). Similar conclusions emerge from analysis in the Netherlands on the adoption of electric vehicles and smart energy systems (Noppers et al., 2019).

Broader contextual factors and cultural trends towards consumerism, individualization and defining self-worth through conspicuous consumption can drive emissions up (Chancel and Piketty, 2015). However, cohort and generational shifts can drive emissions down. For instance, evidence, from millennials in the OECD shows that fewer younger people have driving licenses compared to older generations (Kuhnimhof et al., 2012). Similar, findings are evident from analysis for the US, where changing attitudes, decreased employment and rising virtual mobility explain decreased travel by Millennials (McDonald, 2015). Analysis for France shows that baby boomers are higher emitters than other generations (Chancel, 2014). A change in social norms is taking place with the spread of the sharing economy by which consumers share or borrow goods from other consumers. Sharing opportunities are more advanced within the mobility sector (Greenblatt and Shaheen, 2015). Successful car and bike sharing have rapidly expanded in countries such as China, Indonesia, Mexico, Brazil and Turkey. Technology and data advances are currently barriers to spreading of sharing in low- and lower middle-income cities but the potential offered by these technologies to allow poor countries to leapfrog to more integrated, efficient, multimodal transport systems is important (Yanocha et al., 2020). Despite this potential it is unclear how much shared mobility contributes to transport decarbonization or to make it worse as it takes away riders from public transit (ITF, 2019). The evidence so far shows that the potential positive impacts of shared mobility with pooled rides in lowering travel costs, abating congestion, and reduced GHG emissions have not materialized to date (Merlin, 2019) (See Chapter 5).

Education & Environmental Knowledge. A positive relationship was found between general and carbon-specific knowledge and the attitude towards carbon-specific behaviours in US consumers (Polonsky et al., 2012). One example, pertaining to students, found that the gain of environmental knowledge resulted in more environmentally favourable attitude among these high school students (Bradley et al., 1999). A comparison across states in the USA, for example, shows that environmental awareness can be a mitigating factor of territorial GHG emissions (Dietz et al., 2015). A 1% increase in 'environmentalism' – defined as the "environmental voting record of the state's Congressional delegation" (Dietz et al., 2015) – leads to a 0.45% decrease in emissions.

Environmental knowledge is not always directly translating into decreased ecological footprint (Csutora, 2012). While pro-environmental action is lagging behind, research shows that this is not caused by people undervaluing the environment but rather by people structurally underestimating how much others care (Bouman and Steg, 2019). Other evidence shows that there are multiple causal pathways through which a more educated population can effect emissions, some of which may be positive and others negative (Lutz et al., 2019). A more educated population is more productive and can drive higher economic growth and therefore emissions (Lenzen and Cummins, 2013). Moreover, education that is designed to specifically inform decision makers of the impacts of their decisions and provide behavioural nudges can be a way to reduce emissions (Duarte et al., 2016).

Status Competition. As part of a larger consumer society and consumer culture, based on consumer-oriented lifestyles, products frequently provide a source for identity and fulfilment (Stearns, 2001; Baudrillard, 2017; Jorgenson et al., 2019). People pursue cultural constructs such as status, comfort, convenience, hygiene, nutrition, and necessity. Consumption is, by and large, not an end in itself but a means to achieve some other end, and those ends are diverse and not necessarily connected to one another (Wilk, 2010). This shows that consumption patterns cannot be sufficiently understood without also considering the context, for example the cultural and social contexts leading to status competition and status-related consumption (Veblen, 2009; Schor and J.B., 2015; Wilk, 2017). Status seeking can work to reduce emissions when 'green products' such as an electric car or photovoltaics on the roof become a sign for high-status (Griskevicus Tybur, and Van Den Bergh, 2010). It also can work to increase emissions through visible and high-carbon intensive consumption items such a larger homes, fuel-inefficient SUVs cars, and long-distance vacations (Schor, 1998), driven by a notion of having 'to keep up with the Joneses'(Hamilton, 2011). This can lead to formation of new habits and needs, where products and services become normalized and are quickly perceived as needed, reinforced through social networks and advertisement, making it psychologically easy to convert a luxury item to a perceived necessity (Assadour, 2012). For example, the share of adults who consider a microwave a necessity was about one third in 1996 but had increased to more than two thirds in 2006, but retreated in importance during the recession years 2008-2009 (Morin and Taylor, 2009). Similar ups and downs have been observed for television sets, air conditioning, dishwasher or the clothes dryer. (Druckman and Jackson, 2009). What is considered a basic need and what is a luxury is subject to change over one's lifetime and in relation to others (Horowitz, 1988). This shows that the boundaries of public's luxury-versus-necessity perceptions are malleable (Morin and Taylor, 2009).

Inequality. Global inequality within and between countries has shifted over the last decades expanding consumption and consumer culture (Castilhos and Fonseca, 2016; Alvaredo et al., 2018; Short and Martínez, 2020). The rise of middle class income countries, mostly in Asia, eg. China, India, Indonesia and Vietnam, and the stagnating incomes of the middle classes in developed economies reduced between countries income differences; meanwhile the population under extreme poverty (threshold of 1.9 USD per person/day) is now concentrated in Sub-Saharan Africa and South Asia (Milanović, 2016). A major pulling apart between top and bottom incomes occurred in parallel within countries. Since 1980, the top 1% richest individuals in the world captured twice as much growth as the bottom 50% individuals (Friedman and Savage, 2017; Alvaredo et al., 2018). The influence of these dual inequality trends on lifestyles, new consumption patterns and carbon emissions at regional, local and global scale are large and have led to the fastest growth of global carbon emissions, in particular, for fast emerging economies (see section 2.2. and 2.3). Emissions remain highly concentrated, with the top 10% per capita emitters contributing to between 35-45% of global emissions, while bottom 50% emitters contribute to 13-15% of global emissions (Hubacek et al., 2017a). Furthermore, the top 1% of income earners by some estimates could have an average carbon footprint 175 times that of an average person in the bottom 10% (Otto et al., 2020). The top 10% high emitters live in all continents, and one third of them live in emerging countries (Chancel and Piketty, 2015; Semieniuk and Yakovenko, 2020; Hubacek et al., 2017a). Mitigation pathways need to consider how to minimize the impacts of inequality on climate change and the different mechanisms and effects coming into play between inequality of income and emissions (see 2.4.3) (Baek and Gweisah, 2013; Berthe and Elie, 2015; Hao et al., 2016; Grunewald et al., 2017).

Inequality trends catalyses impact at a demand level, mobilizing rapid lifestyles changes, symbolic consumption and ideals of material improvements and upward mobility (Castilhos et al., 2017) and emulation of high-carbon emissions intensive lifestyle of the wealthy (Gough, 2017). Decoupling energy use and emissions from income growth and, the decarbonisation of energy services have not counteracted these trends (see 2.4.1). Alternative options to deal with carbon inequality like sharing global carbon emissions among high emitters (Chakravarty et al., 2009; Chakravarty and Tavoni, 2013) or addressing the discourse of income distribution and the carbon intensity of high emitters lifestyles (Gössling, 2019; Otto et al., 2019; Hubacek et al., 2017b). are met with caution that such alternatives may necessitate difficult and hard to implement institutional changes (Semieniuk and Yakovenko, 2020). Growing inequality within countries may make re-composition of emission intensive consumption more difficult and, it may also exacerbate redistribution and social cohesion dilemmas (Gough, 2017; Römpke et al., 2019). Climate mitigation action has different motivational departures in unequal context. An emerging global `middle class' strengthens consumption at the margin as evidence by first-time purchases of white goods with likely impacts on energy demand (Wolfram et al., 2012), and with a warming climate, the increased use of air conditioning (Davis and Gertler, 2015). Inequality may affect the willingness of rich and poor to pay for environmental goods or accept policies to protect the environment (Baumgärtner et al., 2017). Unequal departure for action is strongly manifested in cities of all sizes in developing countries with low-income urban residents hardest hit in lock-in situations such as lack of access to transportation and jobs (Altshuler, 2013; Mattioli, 2017), lack of green spaces (Joassart-Marcelli et al., 2011), poor access to waste collection (King and Gutberlet, 2013) and to energy and clean water provision. The exacerbation of these conditions constraint the feasibility for achieving emissions reductions through lifestyle or behavioural changes alone (Oxfam, 2015; Baiocchi et al., 2010). High inequality limits mitigation efforts, and conversely advancing mitigation should not contribute to deepen existing inequalities (Rao and Min, 2018; Saheb et al., 2019). It is critically important to account for varying demands and affordability across heterogeneous household groups in access to quality energy, education, health, decent jobs and services, while recomposing consumption and balancing societal trade-offs via policies to boost the inclusion of low income and energy poor population groups (Pachauri et al., 2013). Further, there is a need to reduce inequalities and improve the capabilities people have to live the lives they value (Sen, 1999; Gough et al., 2011; Gough, 2017; Aranoff et al., 2019)

2.7 Emissions associated with existing and planned long-lived infrastructure

2.7.1 Introduction: clarification of concepts

Carbon lock-in can be understood as inertia in a system that limits the rate of transformation by a path-dependent process (Seto et al., 2016). For example, long lifetimes of infrastructures such as power plants, roads, buildings or industrial plants may influence the rate of transformation substantially and lock societies into carbon-intensive lifestyles and practices for many decades (Unruh, 2000, 2002; Unruh and Carrillo-Hermosilla, 2006; Grubler, 2012; Seto et al., 2016; Sovacool, 2016). Infrastructure stock evolution depends not only on technological and economic factors, but also on institutional and behavioural ones that are often mutually reinforcing. That is, physical infrastructure such as the built environment of urban areas can shape behaviour and practices of daily life, which in turn change the demand for such infrastructure and lock-in energy demand patterns (Creutzig et al., 2016; Makido et al., 2012; Banister et al., 1997; Shove and Trentmann, 2018; Seto et al., 2016).

There is a broad literature on carbon lock-in related to infrastructure that has analysed different geographical scales and sectors, with a strong focus on the power sector (Fisch-Romito et al., 2020). Available quantifications differ in the time frames of analysis that can be classified as backward-looking, static for a given year, or forward-looking using scenarios (Fisch-Romito et al., 2020). Quantifications also differ in the indicators used to describe carbon-lock in. Literature has assessed how delays in climate policy affect the evolution of fossil-fuel infrastructure stock in the short term (Bertram et al., 2015; McGlade et al., 2018; Kefford et al., 2018), overall mitigation costs (Luderer et al., 2016; Riahi et al., 2015), or the transition risks from premature retirements or underutilisation of existing assets (Iyer et al., 2015; van Soest et al., 2017; Lane et al., 2016; Farfan and Breyer, 2017; Cui et al., 2019; Malik et al., 2020; Wang et al., 2020a; Johnson et al., 2015; Luderer et al., 2016; Kefford et al., 2018; Fofrich et al., 2020; Pradhan et al., 2021). Only a few authors have relied on indicators related to institutional factors such as technology scale or employment (Erickson et al., 2015; Spencer et al., 2018). A complementary literature has explored how the sheer size of the world's fossil fuel reserves (and resources) and financial interest of owners of these could contribute to supply-side dynamics that sustain the use of fossil fuels (McGlade and Ekins, 2015; Heede and Oreskes, 2016; Jewell et al., 2013; Bauer et al., 2016; Jakob and Hilaire, 2015; Welsby et al., 2021).

One way of quantifying potential carbon lock-in is to estimate the future CO_2 emissions from existing and planned infrastructure (Davis et al., 2010; Davis and Socolow, 2014) based on historic patterns of use and decommissioning. Such estimates focus on CO_2 emissions from operating infrastructure and do not comprise any upstream or downstream emissions across the lifecycle, which are provided elsewhere in the literature (Müller et al., 2013; Fisch-Romito, 2021; Krausmann et al., 2020; Creutzig et al., 2016). Moreover, estimates tend to focus on energy, while, for example, the agricultural sector is usually not covered. Another strand of literature quantifies lock-in by estimating fossil-fuel related CO_2 emissions that are hard-to-avoid in future scenarios using integrated assessment models (Kriegler et al., 2018b; Luderer et al., 2018). The remainder of this chapter will assess potential carbon lock-in through those two related strands of literature.

2.7.2 Estimates of future CO_2 emissions from long-lived infrastructures

Table 2.6 summarizes studies that apply an accounting approach based on plant-level data to quantify future CO_2 emissions from long-lived fossil fuel infrastructure (Davis and Socolow, 2014; Smith et al., 2019; Rozenberg et al., 2015; Davis et al., 2010; Tong et al., 2019; Cui et al., 2019; Pfeiffer et al., 2018; Pradhan et al., 2021; Edenhofer et al., 2018). Differences between studies arise in the scope of the infrastructure covered (incl. resolution), the inclusion of new infrastructure proposals, the exact estimation methodology applied as well as their assessments of uncertainties. Other studies provide analysis with a sectoral focus (Vogl et al., 2021; Bullock et al., 2020) or with a regional focus on the power sector (Shearer et al., 2017, 2020; Tao et al., 2020; González-Mahecha et al., 2019; Grubert, 2020) .

Assuming variations in historic patterns of use and decommissioning, comprehensive estimates of cumulative future CO_2 emissions from *current* fossil fuel infrastructures are 720 (550-910) $GtCO_2$ (Smith et al., 2019) and 660 (460-890) (Tong et al., 2019) (Table 2.6, Figure 2.26) (*high confidence*). This is about the same size than the overall cumulative net CO_2 emissions until reaching net zero CO_2 of 510 (330-710) Gt in pathways that limit warming to 1.5°C with no or limited overshoot (Chapter 3). About 50% of cumulative future CO_2 emissions from *current* fossil fuel infrastructures come from the power sector and 70% of these (or about 40% of the total) are from coal plants only. Like global annual CO_2 emissions (Friedlingstein et al., 2020; Peters et al., 2020), future CO_2 emissions from fossil-fuel infrastructures have increased over time, i.e. future CO_2 emissions from fossil fuel infrastructure additions in a given year are still outgrowing "savings" from infrastructure retirements (Davis and Socolow, 2014; Tong et al., 2019). This could add further inertia to the system as it may require more and faster retirement of fossil-based infrastructures later and leads to higher costs for meeting the climate goals (e.g. Johnson et al., 2015; Bertram et al., 2015).

Estimates of total cumulative future CO_2 commitments from *proposed infrastructure* focus only on the power sector due to data availability (Table 2.6, Figure 2.26). Infrastructure proposals can be at various stages of development involving very different probabilities of implementation. About one third of the currently proposed projects are more probable as they are already under construction (Cui et al., 2019).

Pfeiffer et al. (2018) and Tong et al. (2019) assess the cumulated CO_2 emissions from proposed infrastructure in the entire power sector at 270 $GtCO_2$ and 190 $GtCO_2$ respectively. Estimates of CO_2 emissions implications for new coal power infrastructure plans are more frequent (Pfeiffer et al., 2018; Edenhofer et al., 2018; Cui et al., 2019; Tong et al., 2019) ranging between 100 and 210 $GtCO_2$. Differences across estimates of future CO_2 emissions from proposed power infrastructure mostly reflect substantial cancellations of coal infrastructure proposals in 2017 and 2018 (Tong et al., 2019).

Table 2.6 - Comparing cumulative future CO_2 emissions estimates from existing and proposed long-lived infrastructures by sector.

Future CO_2 emissions estimates are reported from the "year of dataset". Note that in some cases, the totals may not correspond to the sum of underlying sectors due to rounding (based on Tong et al., 2019)**. Initial estimates of future CO_2 emissions from fossil fuel infrastructures by Davis et al. (2010) are considerably lower than more recent estimates by Smith et al. (2019) and Tong et al. (2019) due to substantial growth in fossil energy infrastructure as represented by more recent data. Estimates presented here are rounded to two significant digits.**

		Davis et al. (2010)		**Davis and Socolow (2014)**		**Rozenberg et al (2015)**		**Edenhofer et al. (2018)**		**Pfeiffer et al. (2018)**		**Smith et al. (2019)**		**Tong et al. (2019)**		**Cui et al. (2019)**	
		$GtCO_2$	Year of dataset	$GtCO_2$	Year of dataset	Gt CO_2	Year of dataset	$GtCO_2$	Year of dataset	$GtCO_2$	Year of dataset	$GtCO_2$	Year of dataset	$GtCO_2$	Year of dataset	Gt CO_2	Year of dataset
Existing	Electricity	220	2009	310	2012	-	-	-	-	310	2016	350 (260-450)	2009[*]	360 (240-490)	2018	-	-
	Coal		2009	210	2012	-	-	190	2016	220	2016	-	-	260 (180-360)	2018	340	2017
	Gas, oil, and other fuels		2009	100	2012	-	-	-	-	88	2016	-	-	98 (65-140)	2018	-	-
	Industry	100	2009			-	-	-	-	-	-	150 (120-190)	2009	160 (110-220)	2017	-	-
	Transport	120	2009			-	-	-	-	-	-	92 (73-110)	2017	64 (53-75)	2017	-	-
	Residential, commercial, and other energy	53	2009			-	-	-	-	-	-	120 (91-160)	2009[*]	74 (52-110)	2018	-	-
	All Sectors	**500 (280-700)**				**660 (370-890)**	2013	-	-	-	-	**720 (550-910)**	-	**660 (460-890)**	-	-	-
Proposed	Electricity					-	-	-	-	270	2016	-	-	190 (140-230)	2018	-	-
	Coal					-	-	150	2016	210	2016	-	-	97 (74-120)	2018	180	2017
	Gas, oil, and other fuels					-	-	-	-	60	2016	-	-	91 (68-110)	2018	-	-
All Sectors + Proposed Electricity														**850 (600-1,100)**			

The global estimate of future CO_2 emissions from *current and planned* fossil-fuel infrastructures is 850 (600-1100) $GtCO_2$ (Tong et al., 2019). This already exceeds total cumulative net CO_2 emissions in pathways that limit warming to 1.5°C with no or limited overshoot (see above). It is about the same size than the total cumulative net CO_2 emissions of 890 (640-1160) $GtCO_2$ from pathways that limit *likely* warming to 2°C (Chapter 3). Hence, cumulative net CO_2 emissions to limit *likely* warming to 2°C or lower could already be exhausted by current and planned fossil fuel infrastructure (*medium confidence*) even though this estimate only covers a fraction of all infrastructure developments over the 21st century as present in mitigation pathways, does not cover all sectors (e.g. AFOLU) and does not include currently infrastructure development plans in transport, buildings, and industry due to a lack of data.

Hence, the Paris climate goals could move out of reach unless there are dedicated efforts to early decommissioning, and reduced utilization of existing fossil fuel infrastructures, cancellation of plans for new fossil fuel infrastructures, or compensation efforts by removing some of the CO_2 emissions from the atmosphere (Smith et al., 2019; Tong et al., 2019; Cui et al., 2019; Pradhan et al., 2021). For example, Fofrich et al. (2020) suggest in a multi-model study that coal and gas power infrastructure would need to be retired 30 (19-34) and 24 (21-26) years earlier than the historical averages of 39 and 36 years when following 1.5°C pathways and 23 (11-33) and 19 (11-16) years earlier when following 2°C pathways. Cui et al. (2019) arrive at more conservative estimates for coal power plants, but only consider the existing and currently proposed capacity. Premature retirement of power plants pledged by members of the Powering Past Coal Alliance would cut emissions by 1.6 $GtCO_2$, which is 150 times less than future CO_2 emissions from existing coal power plants (Jewell et al., 2019).

Few quantifications of carbon lock-in from urban infrastructure, in particular urban form, have been attempted, in part because they also relate to behaviours that are closely tied to routines and norms that co-evolve with "hard infrastructures" and technologies, as well as "soft infrastructure" such as social networks and markets (Seto et al., 2016). There are some notable exceptions providing early attempts (Guivarch and Hallegatte, 2011; Lucon et al., 2014; Erickson and Tempest, 2015; Driscoll, 2014; IPCC, 2014b; Creutzig et al., 2016). Creutzig et al. (2016) attempt a synthesis of this literature and estimate the total cumulative future CO_2 emissions from existing urban infrastructure at 210 Gt and from new infrastructures at 495 Gt for the period 2010-2030.

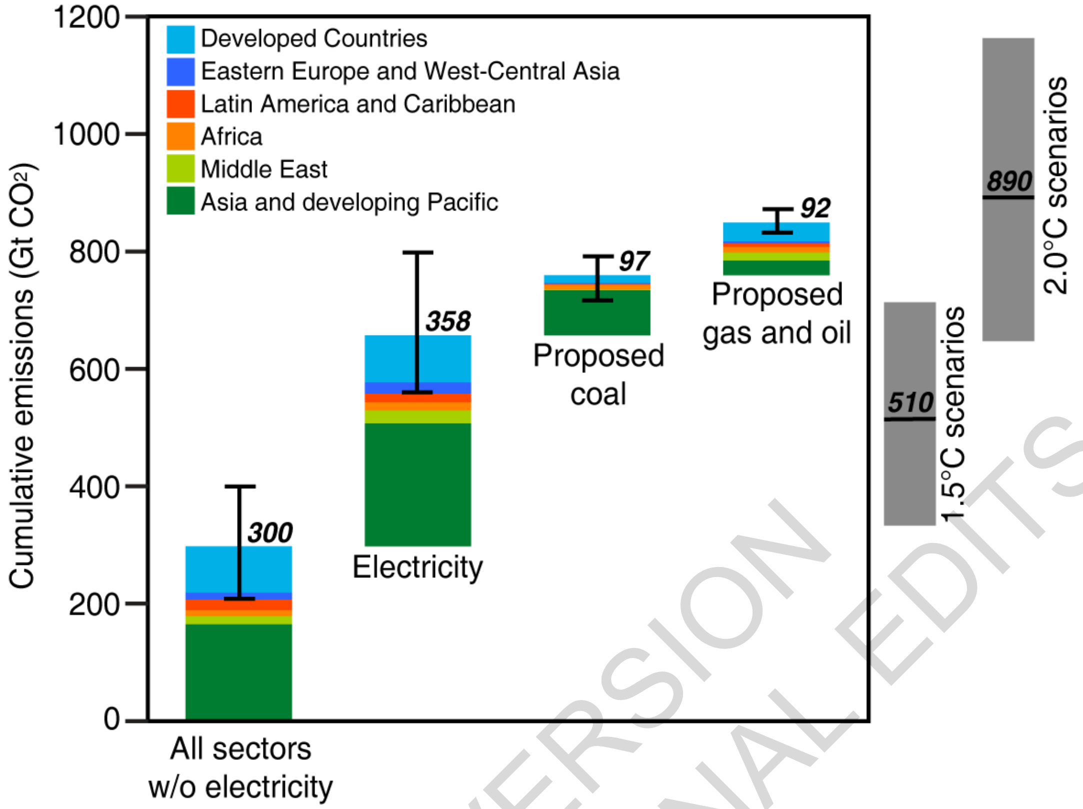

Figure 2.26 Future CO_2 emissions from existing and currently planned fossil fuel infrastructure in the context of Paris carbon budgets in $GtCO_2$ based on historic patterns of infrastructure lifetimes and capacity utilization. Future CO_2 emissions estimates of existing infrastructure for the electricity sector as well as all other sectors (industry, transport, buildings, other fossil fuel infrastructures) and of proposed infrastructures for coal power as well as gas and oil power. Grey bars on the right depict the range (5th – 95th percentile) in overall cumulative net CO_2 emissions until reaching net zero CO_2 in pathways that limit warming to 1.5°C with no or limited overshoot (1.5°C scenarios), and in pathways that limit *likely* warming to 2°C (2°C scenarios).

Source: Based on (Tong et al., 2019) and (Edenhofer et al., 2018).

2.7.3 Synthesis – Comparison with estimates of residual fossil fuel CO_2 emissions

A complementary strand of literature uses Integrated Assessment Models (IAMs) to assess the cumulative gross amount of unabated CO_2 emissions from fossil fuels across decarbonisation pathways that are not removed from the system even under strong (short- and long-term) climate policy ambition. Lower bound estimates for such a minimum amount of unabated residual CO_2 emissions across the 21st century that is not removed from the system even under very ambitious climate policy assumptions may be around 600-700 $GtCO_2$ (Kriegler et al., 2018b). This range increases to 650-1800 $GtCO_2$ (Table 2.7) as soon as a broader set of policy assumptions are considered including delayed action in scenarios that limit warming to 1.5°C and 2°C respectively (Luderer et al., 2018).

Notably, the lower end of residual fossil fuel emissions in IAM scenarios (Luderer et al., 2018) is remarkably similar to global estimates from the accounting studies of the previous section as shown in Table 2.6. Yet, there are important conceptual and interpretative differences that are also reflected in the very different distribution of reported future CO_2 emissions attached to current and future fossil fuel infrastructures (Table 2.7). Accounting studies start from granular, plant-based data for existing fossil fuel infrastructure and make statements about their future CO_2 emission assuming variations of historic patterns of use and decommissioning. Expansions to the future are limited to proposals for new infrastructures that we know of today. Scenario studies quantifying residual fossil fuel emissions start from aggregate infrastructure descriptions, but dynamically update those through new investment decisions in each time step across the 21st century based on the development of energy and energy service demands as well as technology availability, and guided by defined climate policy goals (or their absence).

In accounting studies, estimated of future CO_2 emissions from current fossil fuel infrastructures are dominated by the power sector with its large fossil fuel capacities today. In contrast, scenario studies highlight residual emissions from non-electric energy – particularly in the transport and industry sectors. Fossil-fuel infrastructure in the power sector can be much more easily retired than in those sectors, where there are fewer and more costly alternatives. IAMs therefore account for continued investments into fossil-based energy technologies in areas with limited decarbonisation potential, such as some areas of transportation (in particular aviation, shipping and road-based freight) or some industrial processes (such as cement production or feedstocks for chemicals). This explains the key discrepancies observable in Table 2.7. Overall, our assessment of these available lines of evidence therefore strongly emphasises the importance of decommissioning, as well as reduced utilization of existing power sector infrastructure as well as continued cancellation of new power sector infrastructures in order to limit warming to well below 2°C (*high confidence*) (Luderer et al., 2018; Kriegler et al., 2018b; Fofrich et al., 2020; Cui et al., 2019; Chen et al., 2019). This is important as the power sector is comparatively easy to decarbonise (IPCC, 2014a; Krey et al., 2014; Méjean et al., 2019; Davis et al., 2018) and it is crucial to make space for residual emissions from non-electric energy end-uses that are more difficult to mitigate (*high confidence*). Any further delay in climate policy substantially increases carbon lock-in and mitigation challenges as well as a dependence on carbon dioxide removal technologies for meeting the Paris climate goals (Kriegler et al., 2018b; Luderer et al., 2018).

Table 2.7 Residual (gross) fossil fuel emissions ($GtCO_2$) in climate change mitigation scenarios strengthening mitigation action after 2020 ("early strengthening"), compared to scenarios that keep NDC ambition level until 2030 and only strengthen thereafter.

Cumulative gross CO_2 emissions from fossil fuel and industry until reaching net zero CO_2 emissions are given in terms of the mean as well as minimum and maximum (in parentheses) across seven participating models: AIM/CGE, GCAM, IMAGE, MESSAGES, POLES, REMIND, WITCH. Scenario design prescribes a harmonised, global carbon price in line with long-term carbon budget. Delay scenarios follow the same price trajectory, but 10 years later. Carbon dioxide removal requirements represent ex-post calculations that subtract gross fossil fuel emissions from the carbon budget associated with the respective long-term warming limit. We take the carbon budget for limiting warming to 1.5°C with a 50% probability and to 2°C with a 67% probability (Canadell et al., 2021)**. Hence, carbon dioxide removal (CDR) requirements reflect a minimum amount of CDR for a given mitigation trajectory. Results are reported at 2 significant digits.**

Sources: (Luderer et al., 2018; Tong et al., 2019)

Future CO2 emissions from existing and planned fossil fuel infrastructure (accounting studies)			
		Tong et al. (2019)	
		$GtCO_2$	Year
Existing AND	Electricity	550 (380-730)	2018
Existing AND	Non-electric supply		
Existing	Industry	160 (110-220)	2017
Existing	Transportation	64 (53-75)	2017
Existing	Buildings	74 (52-110)	2018
Existing	All sectors and proposed electricity	850 (600-1,100)	

Residual fossil fuel emissions - cumulative gross CO_2 emissions from fossil fuel and industry until reaching net zero CO_2 emissions (in $GtCO_2$)					
		Early strengthening from (2020)		*Delayed strengthening from 2030*	
		Well below 2°C	Below 1.5°C in 2100	Well below 2°C	Below 1.5°C in 2100
Existing AND future instalments	Electricity	180 (140 - 310)	130 (90 - 160)	250 (220 - 340)	200 (190 - 230)
Existing AND future instalments	Non-electric supply	100 (42 - 130)	59 (27 - 83)	120 (55 - 150)	75 (40 - 100)
Existing AND future instalments	Industry	260 (160 - 330)	140 (86 - 180)	290 (200 - 370)	200 (130 - 250)
Existing AND future instalments	Transportation	310 (190 - 370)	170 (110 - 220)	310 (250 - 400)	200 (140 - 260)
Existing AND future instalments	Buildings	110 (75 - 110)	58 (35 - 77)	120 (80 - 150)	73 (51 - 93)
Existing AND future instalments	All sectors (2021 – net zero CO_2)	960 (730 - 1100)	570 (400 - 640)	1100 (900 - 1200)	770 (590 - 860)
Existing AND future instalments	All sectors (2021-2100)	1300 (970 - 1500)	850 (650 - 1100)	1400 (1200 - 1600)	1000 (860 - 1300)
	Implied minimum requirement for carbon dioxide removal until 2100	150 (0 – 350)	350 (150 – 600)	250 (50 – 450)	500 (360 – 800)

2.8 Climate and Non-Climate Policies and Measures and their Impacts on Emissions

2.8.1 Introduction

The key to achieving climate change mitigation targets includes crafting environmentally effective, economically efficient and socially equitable policies. For the purposes of this section, policies are defined broadly as actions to guide decisions to reach explicit goals and, accordingly, climate (mitigation) policies are the ones whose primary objective is to reduce GHG emissions. They include a range of domains from economic and institutional to R&D and social policies and are implemented by various instruments (e.g., market-based and regulatory in the economic domain) and measures (e.g., legal provisions and governance arrangements in the institutional domain) (see Chapter 13 and the Glossary about mitigation policies). Yet GHG emissions are also affected by policies enacted in various social, economic, and environmental areas to pursue primarily non-climatic objectives. This section presents succinct assessments of the outcomes and effectiveness of a few selected policy instruments applied in the last two decades targeting climate protection (Sections 2.8.2 and 2.8.3) and GHG emissions impacts of selected other policies primarily aiming improvements in environmental quality and natural resource management (Section 2.8.4).[12]

It is rather difficult, though not impossible, to discern the genuine impacts of climate and non-climate policies on GHG emissions. Most of current and past policies target only a small part of global emissions in a limited geographical area and/or from a small number of economic sectors. However, in addition to the targeted region or sector, policies and measures tend to affect GHG emissions in other parts of the world. Emissions leakage is the key channel by which such phenomena and complex interactions occur.[13] Uncertainties in impacts, synergies, and trade-offs between policies and measures also complicate the evaluation of emissions impacts. These make it challenging to identify the impacts of any specific policy or measure on emissions of any specific region or sector. Rigorous statistical analyses are necessary for building strong empirical evidence, but the experience with climate-related policy experiments to date is limited.

2.8.2 Comprehensive Multinational Assessments

Comprehensive multinational evaluations with wider regional and sectoral coverage enable the assessment of emissions impacts without distortions from emissions leakage. Among the wide range of climate policy instruments, pricing carbon such as a carbon tax or an emissions trading system has been one of the most widely used and effective options to reduce GHG emissions *(robust evidence, high agreement)*. In a comparison of 142 countries with and without carbon pricing, countries with a carbon price show an annual CO_2 emission growth rates of 2 percentage points lower than countries without such policies (Best et al., 2020). A more comprehensive evaluation of carbon prices shows that countries with a lower carbon pricing gap (a higher carbon price) tend to be more carbon-efficient, that is, they have a lower carbon intensity of GDP (OECD, 2018).[14] An empirical analysis of the effects of

FOOTNOTE[12] This section only reviews emission impacts of selected policy instruments. Other important aspects such as equity and cost-effectiveness are assessed in Chapter 13, presenting comprehensive evaluations of policies and measures.

FOOTNOTE[13] Refer to Chapter 13 on policies and institutions for detailed discussion of emissions leakages and complex interactions from policy mixes.

FOOTNOTE[14] The OECD (2018) measures carbon prices using the *effective carbon rate* (ECR), which is the sum of three components: specific taxes on fossil fuels, carbon taxes, and prices of tradable emissions permits. The environmental regulation and innovation on the carbon emissions of OECD countries during the period 1999–2014 indicates that a 1% increase in environmentally friendly patents reduced carbon emissions by 0.017%, and a 1% increase in environmental tax revenue per capita reduced carbon emissions by 0.03% (Hashmi and Alam, 2019).

Domestic and international climate legislation have also contributed to the reduction of GHG emissions. An empirical analysis of legislative activity in 133 countries over the period 1999–2016 based on panel data indicates that each new law reduced annual CO_2 emissions per unit of GDP by 0.78% nationally in the first three years and by 1.79% beyond three years. Additionally, climate laws as of 2016 were associated with an annual reduction in global CO_2 emissions of 5.9 $GtCO_2$ and 38 $GtCO_2$ cumulatively since 1999 (Eskander and Fankhauser, 2020). It is notable that 36 countries that accepted legally binding targets under the Kyoto Protocol all complied (Shishlov et al., 2016). It is impossible to disentangle precisely the contribution of individual mitigation policies, but it is clear that the participating countries, especially those in the OECD, did make substantial policy efforts with material impact (Grubb, 2016). An ex-post evaluation shows a significant impact of the Protocol on emissions reductions (Maamoun, 2019).

Renewable energy policies, such as Renewable Portfolio Standards and Feed-in-Tariff, have played an essential role in the massive expansion of renewable energy capacities, another key driver of GHG emissions reductions *(robust evidence, high agreement)*. The drivers of decreasing CO_2 emissions in a group of 18 developed economies that have decarbonised over the period 2005–2015 has been shown to be the displacement of fossil fuels by renewable energy and decreases in energy use (Le Quere et al., 2019). Renewable energy policies both at the EU and Member States level have played an essential role in abating GHG emissions (ICF International, 2016).

2.8.3 National, Sectoral, and Cross-Sectoral Policies

2.8.3.1 National and regional carbon pricing

Carbon prices (e.g., carbon taxes and GHG emissions trading schemes), are among the widely used climate policy instruments across the globe, together with technology support instruments (see IRENA (2018)). As of May 2020, there were 61 carbon pricing schemes in place or scheduled for implementation, consisting of 31 emissions trading schemes (ETSs) and 30 carbon tax regimes, covering 12 $GtCO_2$-eq or about 22% of annual global GHG emissions (World Bank, 2020). The performance of carbon pricing in practice varies by countries and sectors, and depends on the policy environment *(robust evidence, high agreement)*.

The European Union Emissions Trading Scheme (EU ETS), the longest-standing regional climate policy instrument to date, has reduced emissions, though the estimates of the amount vary by study, by country, and by sector; ranging from 3 to 28% (McGuinness and Ellerman, 2008; Ellerman et al., 2010; Abrell et al., 2011; Anderson and Di Maria, 2011; Egenhofer et al., 2011; Petrick and Wagner, 2014; Arlinghaus, 2015; Martin et al., 2016). The EU ETS avoided emitting about 1.2 $GtCO_2$ between 2008 and 2016 (3.8%), almost half of what EU governments promised to reduce under their Kyoto Protocol commitments (Bayer and Aklin, 2020).

China's emission trading pilots have resulted in a decline in carbon intensity in the pilot provinces by adjusting the industrial structure (Zhou et al., 2019). The Regional Greenhouse Gas Initiative (RGGI) in the USA has induced leakage in emissions through increases in electricity generation in surrounding non-RGGI areas, but it has led to the reduction of emissions by way of changes in the fuel mix from coal to gas (Fell and Maniloff, 2018). Actual emissions declined in six of the ten ETSs for which data

carbon pricing gap measures the difference between actual ECRs and benchmark rates. The carbon pricing gap indicates the extent to which polluters do not pay for the damage from carbon emissions.

is available, although other factors such as the 2009 recession, have had significant impacts on those emissions as well (Haites et al., 2018).

The evidence of environmental effectiveness of carbon taxes in Western European countries is varied depending on country and study *(robust evidence, high agreement)*. A significant impact is found in Finland but insignificant impacts are found in Denmark and the Netherlands, and there are mixed results for Sweden (Lin and Li, 2011; Brännlund et al., 2014). Only six of the 17 taxes, where data are available, have reduced actual emissions subject to the tax. Tax rates tend to be too low in many cases and the scale and frequency of the rate changes has not been sufficient to stimulate further emissions reductions (Haites et al., 2018).

2.8.3.2 Selected sectoral climate policy instruments

Many governments have implemented sector-specific policies, in addition to nationwide measures, to reduce GHG emissions *(high confidence)*. Examples of sectoral climate policies include carbon taxes on transportation fuels, low-carbon fuel standards, and regulation of coal power generation.

The implementation of a carbon tax and value-added tax on gasoline and diesel in Sweden resulted in significant reductions of CO_2 emissions in the transportation sector (Shmelev and Speck, 2018; Andersson, 2019). An assessment of a variety of carbon tax schemas across various sectors in the European Union shows a negative relationship between CO_2 emissions and a CO_2 tax (Hájek et al., 2019). In British Columbia (Canada), the carbon tax resulted in a decrease in demand for gasoline and a reduction in total GHG emissions (not exclusive to the transportation sector) estimated to be between 5 and 15% (Murray and Rivers, 2015; Rivers and Schaufele, 2015). Low Carbon Fuel Standards in California have contributed to reducing carbon emissions in the transportation sector by approximately 9.85–13.28% during 1997–2014 (Huseynov and Palma, 2018).

The power sector typically accounts for a large portion of countries' CO_2 emissions. Market-based regulation and government subsidies in China contributed to improving operational efficiency and reducing emissions (Zhao et al., 2015). In addition, the implementation of ultra-low emission standards also has resulted in a significant reduction in emissions from China's power plants (Tang et al., 2019). Mandatory climate and energy policies, including the California Global Warming Solutions Act, reduced CO_2 emissions by 2.7–25% of the average state-level annual emissions from the power sector over the period 1990–2014 in the USA. Mandatory GHG registry/reporting, electric decoupling and public benefit fund have been effective in further decreasing power sector emissions in the USA (Martin and Saikawa, 2017). In the UK electricity sector, a carbon price floor, combined with electricity market reform (competitive auctions for both firm capacity and renewable energy), displaced coal, whose share fell from 46% in 1995 to 7% in 2017, halving CO_2 emissions, while renewables grew from under 4% in 2008 to 22% by 2017 (Grubb and Newbery, 2018). See Chapter 13 for more.

An alternative approach to a carbon tax is an indirect emissions tax on fuels such as an excise tax, or on vehicles, based on the expected CO_2 intensity of new passenger vehicles. Vehicle purchase taxes can result in a reduction in GHG emissions through reducing the CO_2 emissions intensity of vehicles, while also discouraging new vehicle purchases (Aydin and Esen, 2018). For example, a vehicle tax policy in Norway resulted in a reduction of average CO_2 intensity per kilometre of 7.5 $gCO_2\ km^{-1}$ (Ciccone, 2018; Steinsland et al., 2018). Despite such evidence, studies of carbon pricing find that additional policies are often needed to stimulate sufficient emissions reductions in transportation *(medium confidence)* (Tvinnereim and Mehling, 2018).

Electric vehicles (EVs) powered by clean electricity can reduce GHG emissions and such policies are important for spurring adoption of such vehicles and GHG emission reductions (Kumar and Alok, 2020; Thiel et al., 2020). The extent to which EV deployment can decrease emissions by replacing internal combustion engine-based vehicles depends on the generation mix of the electric grid (Abdul-Manan, 2015; Nichols et al., 2015; Canals Casals et al., 2016; Hofmann et al., 2016; Choi et al., 2018; Teixeira and Sodré, 2018), although even with current grids EVs reduce emissions in almost all cases (Knobloch et al., 2020). Policy incentives for EV adoption can be an effective mechanism to increase EV sales (Langbroek et al., 2016) and may include charging discounts, purchase subsidies, regulations, and government leadership *(medium confidence)* (Bakker and Jacob Trip, 2013; Silvia and Krause, 2016; Teixeira and Sodré, 2018; Qiu et al., 2019; Santos and Davies, 2020). The presence of charging infrastructure and publicly available charging increases the adoption rate of EVs (Vergis and Chen, 2015; Javid et al., 2019). A comparison of EV adoption rates across 30 countries shows a positive correlation between charging stations and EV market share (Sierzchula et al., 2014). A rollout of 80,000 DC fast chargers across the United States is estimated to have resulted in a 4% reduction in emissions compared to a baseline of no additional fast chargers (Levinson and West, 2018). More recently, bans on internal combustion engine vehicles have provided a much more direct approach to stimulating the adoption of EVs and its supporting infrastructure; however, the efficacy of such measures depends on enforcement (Plötz et al., 2019).

Public transit can reduce vehicle travel and reduce GHG emissions by reducing the number of trips taken by private vehicles and the length of those trips *(medium confidence)*. Changes to the operation of public transportation systems (such as density of bus stops, distance from stops to households, duration and frequency of trip times, and lowering ridership costs) can result in a mode shift from private car trips to public transit trips (Cats et al., 2017; Choi, 2018; Carroll et al., 2019). These changes in the public transit system operation and network optimisation have been shown to have reduced GHG emissions in cases such as San Francisco, in which the cost optimisation of the transit network was estimated to decrease emissions by a factor of three (Cheng et al., 2018) and Barcelona, where the optimisation of the urban bus system was estimated to reduce GHG emissions by 50% (Griswold et al., 2017). For every 1% increase in investment in transit services and transit-oriented design, there is an estimated 0.16% reduction in private vehicle kilometres travelled per capita (McIntosh et al., 2014).

Bike and car sharing programmes can reduce GHG emissions *(medium confidence)*. Albeit a study of eight cities in the United States with larger bike share systems and higher ridership found that their potential to reduce total emissions is limited to <0.1% of total GHG emissions from the transportation sectors of these cities (Kou et al., 2020). The emissions reductions effects of car-sharing programmes depends on the specifics of programmes: the mode shift from public transit to car-sharing services can outweigh the decreases in GHG emissions associated with decreased cars on the road (Jung and Koo, 2018), whereas car-sharing programmes with electric vehicle fleets may reduce GHG emissions (Luna et al., 2020).

2.8.4 Emission Impacts of Other Related Policies

Policies other than those intended directly to mitigate GHG emissions can also influence these emissions. Policies to protect the stratospheric ozone layer is a case in point. Implementing the Montreal Protocol and its amendments, emissions of controlled ozone-depleting substances (ODSs) (those covered by the protocol) declined to a very low level of about 1.4 $GtCO_2$-eq yr^{-1} by 2010, avoiding GHG emissions of an estimated 13.3–16.7 $GtCO_2$-eq yr^{-1} (9.7–12.5 $GtCO_2$-eq yr^{-1} when accounting for the ozone depletion and hydrofluorocarbons (HFCs) offsets) (Velders et al., 2007). Yet fluorinated gases (F-gases), the substances introduced to substitute ODSs are also potent GHGs. See Section 2.2 for emissions data and Chapter 13 on current policies to mitigate HFCs and other F-gases. GHG implications of two other categories of non-climate policies are briefly assessed in this section.

2.8.4.1 Co-impacts of air quality, sector-specific and energy policies on climate mitigation

Co-impacts of local or regional air pollution abatement policies for climate mitigation are widely studied in the literature. Cross-border externalities of air pollution have also made these a focus of several international agreements (Mitchell et al., 2020). Evaluating the effectiveness of such treaties and policies is difficult because deriving causal inferences and accurate attribution requires accounting for several confounding factors, and direct and indirect spillovers (Isaksen, 2020). Nevertheless, several studies assess the effectiveness of such treaties and regulations (De Foy et al., 2016; Li et al., 2017a, 2017b; Morgenstern, 2018; Mardones and Cornejo, 2020). However, there is little ex-post empirical analysis and a greater focus on ex-ante studies in the literature.

At a local scale, air pollutants are often co-emitted with GHGs in combustion processes. Many air quality policies and regulations focus on local pollution from specific sources that can potentially either substitute or complement global GHG emissions in production and generation processes. Also, policies that reduce certain air pollutants, such as SO_2, have a positive radiative forcing effect (Navarro et al., 2016). The evidence on individual air pollution control regulation and policies for GHG emissions is therefore mixed *(medium evidence, medium agreement)*. Evidence from the USA suggests that increased stringency of local pollution regulation had no statistically detectable co-benefits or costs on GHG emissions (Brunel and Johnson, 2019). Evidence from China suggests that the effectiveness of policies addressing local point sources differed from those of non-point sources and the co-benefits for climate are mixed, though policies addressing large industrial point sources have been easier to implement and have had significant impact (Huang and Wang, 2016; Xu et al., 2016; van der A et al., 2017; Dang and Liao, 2019; Fang et al., 2019; Yu et al., 2019). Legislation to reduce emissions of air pollutants in Europe have significantly improved air quality and health but have had an unintended warming effect on the climate (Turnock et al., 2016).

Often, the realisation of potential co-benefits depends on the type of pollutant addressed by the specific policy, and whether complementarities between local pollution and global GHG emissions are considered in policy design (Rafaj et al., 2014; Li et al., 2017a) *(medium evidence, high agreement)*. Effective environmental regulations that also deliver co-benefits for climate mitigation require integrated policies (Schmale et al., 2014; Haines et al., 2017). Uncoordinated policies can have unintended consequences and even increase emissions (Holland et al., 2015). Many studies suggest that policies that target both local and global environmental benefits simultaneously may be more effective (Klemun et al., 2020) *(medium evidence, medium agreement)*. Furthermore, air pollution policies aimed at inducing structural changes, for example closure of polluting coal power plants or reducing motorised miles travelled, are more likely to have potential positive spillover effects for climate mitigation, as compared to policies incentivising end-of-pipe controls (Wang, 2021).

Other policies that typically have potential co-benefits for climate mitigation include those specific to certain sectors and are discussed in Chapters 5–11. Examples of such policies include those that encourage active travel modes, which have been found to have ancillary benefits for local air quality, human health, and GHG emissions (Fujii et al., 2018). Policies to reduce energy use through greater efficiency have also been found to have benefits for air quality and the climate (Tzeiranaki et al., 2019; Bertoldi and Mosconi, 2020) *(robust evidence, medium agreement)*. Important air quality and climate co-benefits of renewable or nuclear energy policies have also been found (Lee et al., 2017; Apergis et al., 2018; Sovacool and Monyei, 2021) *(medium evidence, medium agreement)*.

Policies specific to other sectors such as encouraging green building design can also reduce GHG emissions (Eisenstein et al., 2017). Evidence from several countries also show that replacing polluting solid biomass cooking with cleaner gas-burning or electric alternatives have strong co-benefits for health, air quality, and climate change (Anenberg et al., 2017; Singh et al., 2017; Tao et al., 2018) *(robust evidence, high agreement)*.

2.8.4.2 Climate impacts of agricultural, forestry, land use, and AFOLU-related policies

Policies on agriculture, forestry, and other land use (AFOLU), and AFOLU sector-related policies have had a long history in many developing and developed countries. Co-impacts of these policies on the climate have been only marginally studied, although their impacts might be quite important because the

AFOLU sector is responsible for 24% of total GHG emissions *(robust evidence, high agreement)*. The results of afforestation policies around the world and the contribution to CCS are also important.

Both private and governmental policies can have a major impact on the climate. Experience indicates that "climate proofing" a policy is likely to require some stimulus, resources, and expertise from agencies or organisations from outside the country. Stimulus and support for adaptation and mitigation can come from the UN system and from international development institutions (FAO, 2009). These findings are also valid for small/organic farmers vis-à-vis large-scale agro-industry. For example, small/medium and environmentally concerned farmers in Europe are often asking for more policies and regulations, and see it as necessary both from a climate perspective and to maintain competitiveness relative large agro-industrial complexes. Therefore, the need for governmental support for small producers in regulations encompasses all AFOLU sectors.

Forestry case: zero deforestation

Forest is generally defined as land spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10%, or trees able to reach these thresholds in situ (FAO, 1998). Zero-deforestation (i.e., both gross and net zero deforestation) initiatives generate results at multiple levels (Meijer, 2014). Efforts to achieve zero-deforestation (and consequently emissions) are announced by NGOs, companies, governments, and other stakeholder groups. NGOs engage through their campaigning, but also propose tools and approaches for companies (Leijten et al., 2020). The extent to which companies can actually monitor actions conducive to zero-deforestation pledges depends on their position in the supply chain. Beyond the business practices of participating companies, achieving long-term positive societal impacts requires upscaling from supply chains towards landscapes, with engagement of all stakeholders, and in particular small producers. The various success indicators for zero deforestation mirror the multiple levels at which such initiatives develop: progress towards certification, improved traceability, and legality are apparent output measures, whereas direct-area monitoring and site selection approaches target the business practices themselves.

Such efforts have led to the development of the High Carbon Stock (HCS) approach that combines carbon stock values with the protection of HCS areas (including peatlands and riparian zones) and areas important for the livelihoods of local communities (Rosoman et al., 2017). Long-term positive impacts, however, will need to be assessed with hindsight and focus on national and global statistics. Successful initiatives targeting zero deforestation at jurisdictional level would also need to improve the enforcement of forest laws and regulations (EII, 2015; Meyer and Miller, 2015).

Large-scale agribusiness, banks, and consumer goods companies dominate supply chain-focused zero-deforestation initiatives, but only the producers, including local communities and smallholders, can change the production circumstances (TFD, 2014). Producers shoulder much of the burden for meeting environmental requirements of pledges. And local communities and small producers are vulnerable to being cut out when supply chains reorient. The zero-deforestation pledges do not always devise programmes for introducing new sourcing strategies, and governments may have an important contribution to make here, particularly in safeguarding the interests of small producers.

Other than in Brazil and Indonesia, beyond individual supply chains, there is still little evidence on positive results of zero-deforestation commitments as information available for companies to judge their progress is scarce. Moreover, many zero-deforestation pledges set targets to be achieved by 2020 or 2030, and, consequently, many companies have not yet reported publicly on their progress. Similarly, only a few governments have yet shown progress in reducing deforestation, but the New York Declaration on Forests, the SDGs and the Paris Agreement were adopted relatively recently. The effectiveness of private-sector zero-deforestation pledges depends on the extent to which they can be supported by governmental action and foster a cooperative environment with the engagement of all stakeholders. Where the pledges are coordinated with regulation, multi-stakeholder dialogues, and technical and financial support, a true paradigm shift becomes possible. Many governments are still building the capacity to improve overall forest governance, but implementing ambitious international targets is likely to depend on technical and major financial support that has not yet been mobilised.

2.9 Knowledge Gaps

- Global GHG emissions estimates are published less frequently and with greater reporting lags than, for example, CO_2 from fossil fuel and industry. Data quality and reporting frequency remains an issue particularly in developing countries where the statistical infrastructure is not well developed. Efforts to compile a global GHG emissions inventory by country, sector, and across time that is annually updated based on the best-available inventory information, similar to on-going activities for CO_2, CH_4 or N_2O, could fill this gap. Uncertainties and their methodological treatment in GHG emissions estimates are still not comprehensively understood.
- There is a more fundamental data gap for F-gas emissions, where data quality in global inventories is poor due to considerable gaps in the underlying activity data – particularly in developing countries. Comprehensive tracking of F-gas emissions would also imply the inclusion of other gases not covered under the Paris Agreement such as chlorofluorocarbons, hydrochlorofluorocarbons and others.
- Currently, despite advances in terms of data availability, sectoral and spatial resolution, the results in consumption-based emission estimates are dependent on the database used, the level of sectoral aggregation and country resolution. More fine-grained data at spatial resolution as well as the product level would support to explore the mitigation options at the sub-national level, companies and households.
- Consumption-based emission accounts too suffer from lack of quantification of uncertainties at the subnational level and especially in data-scarce environments such as for developing countries. A better understanding of drivers that caused decoupling of emissions at the national and especially sub-national level are important to explore.
- Understanding how social-economic drivers modulate emission mitigation is crucial. Technological improvements (e.g. improved energy or land use intensity of the economy) have shown persistent pattern over the last few decades but gains have been outpaced by increases in affluence (GDP per capita) and population growth, leading to continued emissions growth. The key gap in knowledge therefore is how these drivers of emissions can be mitigated by demand management, alternative economic models, population control and rapid technological transition to different extent and in different settings. More research on decoupling and sustainability transformations would help to answer these questions. Key knowledge gaps also remain in role of trade, in particular, how supporting low-carbon technologies in developing and exporting countries can counteract the upward-driving effect of trade, and how to achieve decoupling without outsourcing emissions to others and often to less developed regions.
- Understanding of how inequality affects emissions is in a nascent stage. Less is known about the causal mechanisms by which different dimensions of inequality like income, socio-economic, spatial, socio-cultural-gender and ethnicity affect emissions. In particular, limited knowledge exists on the linkages between dimensions of inequality other than income or wealth and emissions arising from different service demands. Research gaps are apparent on how inequalities in living standards relate to emissions and how changes in inequalities between genders, social groups, and other marginalised communities impact emissions trends.
- Digitalisation of the economy are often quoted as providing new mitigation opportunities, but knowledge and evidences are yet limited- such as understanding of the role of smart apps and the potentials and influence of disruptive technologies at the demand and supply side on GHG emissions.
- Despite growing evidence of technological progress across a variety of mitigation areas and the availability of increasingly precise data sets, knowledge gaps remain on technological change

and innovation and evidence on speed of transitions to clarify what would make them fast or slow. Innovation is an inherently uncertain process and there will always be imperfect ex ante knowledge on technological outcomes and their effects on mitigation. The extent to which a low-carbon transition can proceed faster than historical examples is crucial to aid future mitigation. That depends on a better understanding of the speed of building, updating and replacing infrastructure. Additionally, how and whether financing for low-carbon technology investment in low and middle income countries can be delivered at low-cost and sustained over time are important questions. The emerging findings that small-scale technologies learn faster and are adopted more quickly needs to be tested against a broader set of cases and in particular against the large dispersion in data.

- Future CO_2 emissions from existing and planned infrastructure is not well understood and quantified outside the power sector. Further integration of bottom-up accounting and scenario approaches from integrated assessment seems promising. Comprehensive assessments of hard-to-abate residual fossil fuel emissions and their relationship to CO_2 removal activities are lacking, but will be important for informing net zero emissions strategies.
- Empirical evidence of emission impacts from climate policies, including carbon pricing, is not sufficient for unambiguous attribution assessment, mainly due to the limited experience with climate-related policy experiments to date. More attention to the methodology for comprehensive evaluation of climate policies and measures, such as effective carbon rates is apparent. Key knowledge gaps also exist on ex-post evaluations of climate and non-climate policies and measures for their impact on emissions, particularly at the global scale, considering national circumstances and priorities.

Frequently Asked Questions (FAQs)

FAQ 2.1 Are emissions still increasing or are they falling?

Global greenhouse gas (GHG) emissions continued to rise and reached 59±6.6 $GtCO_2$-eq in 2019, although the rate of growth has fallen compared to the previous decade. Still, emissions were higher than at any point in human history before**.** Emissions were around 12% and 54% higher than in 2010 and 1990, respectively. Average annual GHG emissions for 2009–2019 were higher compared to the periods 2000–2009 and 1990–1999, respectively. GHG emission growth slowed since 2010: while average annual GHG emission growth was 2.1% between 2000 and 2010, it was only 1.3% for 2010–2019. In order to stop the temperature increase, however, net emissions must be zero.

FAQ 2.2 Are there countries that have reduced emissions and grown economically at the same time?

About 24 countries that have reduced territorial CO_2 and GHG emissions for more than 10 years. Uncertainties in emission levels and changes over time prevents a precise assessment in some country cases. In the short observation period of 2010–2015, 43 out of 166 countries have achieved absolute decoupling of consumption-based CO_2 emissions from economic growth, which means that these countries experienced GDP growth while their emissions have stabilised or declined. A group of developed countries, such as some EU countries and the United States, and some developing countries, such as Cuba, have successfully achieved an absolute decoupling of consumption-based CO_2 emissions and GDP growth. Decoupling has been achieved at various levels of per capita income and per capita emissions. Overall, the absolute reduction in annual emissions achieved by some countries has been outweighed by growth in emissions elsewhere in the world.

FAQ 2.3 How much time do we have to act to keep global warming below 1.5 degrees?

If global CO_2 emissions continue at current rates, the remaining carbon budget for keeping warming to 1.5°C will likely be exhausted before 2030. Between 1850 and 2019, total cumulative CO_2 emissions from the fossil fuel industry (FFI) and agriculture, forestry, and other land use (AFOLU) were 2400 (±240 $GtCO_2$). Of these, about 410±30 $GtCO_2$ were added since 2010. This is about the same size as the remaining carbon budget for keeping global warming to 1.5°C and between one third and half the 1150±220 (1350, 1700) $GtCO_2$ for limiting global warming below 2°C with a 67% (50%, 33%) probability, respectively (Canadell et al., 2021). At current (2019) rates of emissions, it would only take 8 (2-15) and 25 (18-35) years to emit the equivalent amount of CO_2 for a 67^{th} percentile 1.5°C and 2°C remaining carbon budget, respectively. This highlights the dependence of 1.5°C pathways on the availability of substantial CO_2 removal capacities, as discussed in chapters 3, 4, and 12, but also Section 2.7 of this chapter.

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Chapter 3: Mitigation Pathways Compatible with Long-Term Goals

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Date of Draft: 27/11/2021

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Executive summary

Chapter 3 assesses the emissions pathways literature in order to identify their key characteristics (both in commonalities and differences) and to understand how societal choices may steer the system into a particular direction *(high confidence)*. More than 2000 quantitative emissions pathways were submitted to the IPCC's Sixth Assessment Report (AR6) database, out of which 1202 scenarios included sufficient information for assessing the associated warming consistent with WGI. Five Illustrative Mitigation Pathways (IMPs) were selected, each emphasizing a different scenario element as its defining feature: heavy reliance on renewables (IMP-Ren), strong emphasis on energy demand reductions (IMP-LD), extensive use of CDR in the energy and the industry sectors to achieve net negative emissions (IMP-Neg), mitigation in the context of broader sustainable development (IMP-SP), and the implications of a less rapid and gradual strengthening of near-term mitigation actions (IMP-GS).{3.2, 3.3}

Pathways consistent with the implementation and extrapolation of countries' current policies see GHG emissions reaching 52-60 $GtCO_2$-eq yr^{-1} by 2030 and to 46-67 $GtCO_2$-eq yr^{-1} by 2050, leading to a median global warming of 2.4°C to 3.5°C by 2100 (*medium confidence*). These pathways consider policies at the time that they were developed. The Shared Socioeconomic Pathways (SSPs) permit a more systematic assessment of future GHG emissions and their uncertainties than was possible in AR5. The main emissions drivers include growth in population, reaching 8.5-9.7 billion by 2050, and an increase in global GDP of 2.7-4.1% per year between 2015 and 2050. Final energy demand in the absence of any new climate policies is projected to grow to around 480 to 750 EJ yr^{-1} in 2050 (compared to around 390 EJ in 2015). *(medium confidence)* The highest emissions scenarios in the literature result in global warming of >5°C by 2100, based on assumptions of rapid economic growth and pervasive climate policy failures. (*high confidence*). {3.3}

Many pathways in the literature show how to likely limit global warming compared to preindustrial times to 2°C with no overshoot or to 1.5°C with limited overshoot. The likelihood of limiting warming to 1.5C with no or limited overshoot has dropped in AR6 compared to SR1.5 because global GHG emissions have risen since the time SR1.5 was published, leading to higher near-term emissions (2030) and higher cumulative CO_2 emissions until the time of net zero *(medium confidence)*. Only a small number of published pathways limit global warming to 1.5°C without overshoot over the course of the 21st century. {3.3, Annex III.II.3}

Cost-effective mitigation pathways assuming immediate actions to likely limit warming to 2°C are associated with net global GHG emissions of 30-49 $GtCO_2$-eq yr^{-1} by 2030 and 13-27 $GtCO_2$-eq yr^{-1} by 2050 *(medium confidence)*. This corresponds to reductions, relative to 2019 levels, of 12-46% by 2030 and 52-77% by 2050. Pathways that limit global warming to below 1.5°C with no or limited overshoot require a further acceleration in the pace of the transformation, with net GHG emissions typically around 21-36 $GtCO_2$-eq yr^{-1} by 2030 and 1-15 $GtCO_2$-eq yr^{-1} by 2050; thus reductions of 38–63% by 2030 and 75-98% by 2050 relative to 2019 levels. {3.3}

Pathways following current NDCs[1] until 2030 reach annual emissions of 47-57 $GtCO_2$-eq by 2030, thereby making it impossible to limit warming to 1.5°C with no or limited overshoot and strongly increasing the challenge to likely limit warming to 2°C *(high confidence)*. A high

FOOTNOTE [1] Current NDCs refers to the most recent nationally determined contributions submitted to the UNFCCC as well as those publicly announced with sufficient detail on targets, but not yet submitted, up to 11 October 2021, and reflected in studies published up to 11 October 2021.

overshoot of 1.5°C increases the risks from climate impacts and increases the dependence on large scale carbon dioxide removal from the atmosphere. A future consistent with current NDCs implies higher fossil fuel deployment and lower reliance on low carbon alternatives until 2030, compared to mitigation pathways with immediate action to likely limit warming to 2°C and below. To likely limit warming to 2°C after following the NDCs to 2030, the pace of global GHG emission reductions would need to accelerate quite rapidly from 2030 onward: to an average of 1.3-2.1 $GtCO_2$-eq per year between 2030 and 2050, which is similar to global CO_2 emission reductions in 2020 due to the COVID-19 pandemic, and around 70% faster than in immediate action pathways likely limiting warming to 2°C. Accelerating emission reductions after following an NDC pathway to 2030 would be particularly challenging because of the continued build-up of fossil fuel infrastructure that would be expected to take place between now and 2030. {3.5, 4.2}

Pathways accelerating actions compared to current NDCs that reduce annual GHG emissions to 47 (38-51) GtCO2-eq by 2030, or 3-9 GtCO2-eq below projected emissions from fully implementing current NDCs reduce the mitigation challenge for likely limiting warming to 2°C after 2030. *(medium confidence)*. The accelerated action pathways are characterized by a global, but regionally differentiated, roll-out of regulatory and pricing policies. Compared to NDCs, they see less fossil fuels and more low-carbon fuels until 2030, and narrow, but do not close the gap to pathways assuming immediate global action using all available least-cost abatement options. All delayed or accelerated action pathways likely limiting warming to below 2°C converge to a global mitigation regime at some point after 2030 by putting a significant value on reducing carbon and other GHG emissions in all sectors and regions. {3.5}

Mitigation pathways limiting warming to 1.5°C with no or limited overshoot reach 50% reductions of CO_2 in the 2030s, relative to 2019, then reduce emissions further to reach net zero CO_2 emissions in the 2050s. Pathways likely limiting warming to 2°C reach 50% reductions in the 2040s and net zero CO_2 by 2070s (*medium confidence*). {3.3, Cross-Chapter Box 3 in Chapter 3}

Peak warming in mitigation pathways is determined by the cumulative net CO_2 emissions until the time of net zero CO_2 and the warming contribution of other GHGs and climate forcers at that time *(high confidence)*. Cumulative net CO_2 emissions from 2020 to the time of net zero CO_2 are 510 (330-710) $GtCO_2$ in pathways that limit warming to 1.5°C with no or limited overshoot and 890 (640-1160) $GtCO_2$ in pathways likely limiting warming to 2.0°C. These estimates are consistent with the assessment of remaining carbon budgets by WGI after adjusting for differences in peak warming levels. {3.3, Box 3.4}

Rapid reductions in non-CO_2 GHGs, particularly methane, would lower the level of peak warming *(high confidence)*. Residual non-CO_2 emissions at the time of reaching net zero CO_2 range between 4-11 $GtCO_2$-eq yr-1 in pathways likely limiting warming to 2.0°C or below. Methane (CH_4) is reduced by around 20% (1-46%) in 2030 and almost 50% (26-64%) in 2050, relative to 2019. Methane emission reductions in pathways limiting warming to 1.5°C with no or limited overshoot are substantially higher by 2030, 33% (19-57%), but only moderately so by 2050, 50% (33-69%). Methane emissions reductions are thus attainable at relatively lower GHG prices but are at the same time limited in scope in most 1.5-2°C pathways. Deeper methane emissions reductions by 2050 could further constrain the peak warming. N_2O emissions are reduced too, but similar to CH_4, emission reductions saturate for more stringent climate goals. In the mitigation pathways, the emissions of cooling aerosols are reduced due to reduced use of fossil fuels. The overall impact on non-CO_2-related warming combines these factors. {3.3}

Net zero GHG emissions imply net negative CO_2 emissions at a level compensating residual non-CO_2 emissions. Only 30% of the pathways likely limiting warming to 2°C or below reach net zero GHG emissions in the 21st century. (*high confidence*). In those pathways reaching net zero GHGs, it is achieved around 10-20 years later than for net zero CO_2. (*medium confidence*). The reported quantity of residual non-CO_2 emissions depends on accounting: the choice of GHG metric. Reaching and sustaining global net zero GHG emissions, measured in terms of GWP-100, results in a gradual decline of temperature. (*high confidence*) {3.3, Cross-Chapter Box 3 in Chapter 3, Cross-Chapter Box 2 in Chapter 2}

Pathways likely limiting warming to 2°C and below exhibit substantial reductions in emissions from all sectors (*high confidence*). Projected CO_2 emissions reductions between 2019 and 2050 in 1.5°C pathways with no or limited overshoot are around 77% (31-96%) for energy demand, 115% for energy supply (90 to 167%), and 148% for AFOLU (94 to 387%). In pathways likely limiting warming to 2°C, projected CO_2 emissions are reduced between 2019 and 2050 by around 49% for energy demand, 97% for energy supply, and 136% for AFOLU. *(medium confidence)*{3.4}

Delaying or sacrificing emissions reductions in one sector or region involves compensating reductions in other sectors or regions if warming is to be limited (*high confidence*). Mitigation pathways show differences in the timing of decarbonization and when net zero CO_2 emissions are achieved across sectors and regions. At the time of global net zero CO_2 emissions, emissions in some sectors and regions are positive while others are negative; the ordering depends on the mitigation options available, the cost of those options, and the policies implemented. In cost-effective mitigation pathways, the energy supply sector typically reaches net zero CO2 before the economy as a whole, while the demand sectors reach net zero CO_2 later, if ever (*high confidence*). {3.4}

Pathways likely limiting warming to 2°C and below involve substantial reductions in fossil fuel consumption and a near elimination of the use of coal without CCS (*high confidence*). These pathways show an increase in low carbon energy, with 88% (69-97%) of primary energy coming from these sources by 2100. {3.4}

Stringent emissions reductions at the level required for 2°C and below are achieved through increased direct electrification of buildings, transport, and industry, resulting in increased electricity generation in all pathways (*high confidence*). Nearly all electricity in pathways likely limiting warming to 2°C or below is from low or no carbon technologies, with different shares of nuclear, biomass, non-biomass renewables, and fossil CCS across pathways. {3.4}

The measures required to likely limit warming to 2°C or below can result in large scale transformation of the land surface (*high confidence*). Pathways likely limiting warming to 2°C or below are projected to reach net zero CO_2 emissions in the AFOLU sector between 2020s and 2070, with an increase of forest cover of about 322 million ha (-67 to 890 million ha) in 2050 in pathways limiting warming to 1.5°C with no or limited overshoot. Cropland area to supply biomass for bioenergy (including BECCS) is around 199 (56-482) million ha in 2100 in pathways limiting warming to 1.5°C with no or limited overshoot. The use of bioenergy can lead to either increased or reduced emissions, depending on the scale of deployment, conversion technology, fuel displaced, and how/where the biomass is produced *(high confidence)*. {3.4}

Anthropogenic land CO_2 emissions and removals in IAM pathways cannot be directly compared with those reported in national GHG inventories (*high confidence*). Methodologies enabling a more like-for-like comparison between models' and countries' approaches would support more accurate assessment of the collective progress achieved under the Paris Agreement. {3.4, 7.2.2.5}

Pathways that likely limiting warming to 2°C or below involve some amount of CDR to compensate for residual GHG emissions remaining after substantial direct emissions reductions in all sectors and regions (*high confidence*). CDR deployment in pathways serves multiple purposes: accelerating the pace of emissions reductions, offsetting residual emissions, and creating the option for net negative CO_2 emissions in case temperature reductions need to be achieved in the long term (*high confidence*). CDR options in the pathways are mostly limited to BECCS, afforestation and DACCS. CDR through some measures in AFOLU can be maintained for decades but not in the very long term because these sinks will ultimately saturate (high confidence). {3.4}

Mitigation pathways show reductions in energy demand relative to reference scenarios, through a diverse set of demand-side interventions (*high confidence*). Bottom-up and non-IAM studies show significant potential for demand-side mitigation. A stronger emphasis on demand-side mitigation implies less dependence on CDR and, consequently, reduced pressure on land and biodiversity. {3.4, 3.7}

Limiting warming requires shifting energy investments away from fossil-fuels and towards low-carbon technologies (*high confidence*). The bulk of investments are needed in medium- and low-income regions. Investment needs in the electricity sector are on average 2.3 trillion USD2015 yr^{-1} over 2023-2052 for pathways limiting temperature to 1.5°C with no or limited overshoot, and 1.7 trillion USD2015 yr^{-1} for pathways likely limiting warming to 2°C. {3.6.1}

Pathways likely avoiding overshoot of 2°C warming require more rapid near-term transformations and are associated with higher up-front transition costs, but meanwhile bring long-term gains for the economy as well as earlier benefits in avoided climate change impacts *(high confidence)*. This conclusion is independent of the discount rate applied, though the modelled cost-optimal balance of mitigation action over time does depend on the discount rate. Lower discount rates favour earlier mitigation, reducing reliance on CDR and temperature overshoot. {3.6.1, 3.8}

Mitigation pathways likely limiting warming to 2°C entail losses in global GDP with respect to reference scenarios of between 1.3% and 2.7% in 2050; and in pathways limiting warming to 1.5°C with no or limited overshoot, losses are between 2.6% and 4.2%. Yet, these estimates do not account for the economic benefits of avoided climate change impacts *(medium confidence)*. In mitigation pathways likely limiting warming to 2°C, marginal abatement costs of carbon are about 90 (60-120) USD2015/tCO_2 in 2030 and about 210 (140-340) USD2015/tCO_2 in 2050; in pathways that limit warming to 1.5°C with no or limited overshoot, they are about 220 (170-290) USD2015/tCO_2 in 2030 and about 630 (430-990) USD2015/tCO_2 in 2050[2]. {3.6.1}

The global benefits of pathways likely limiting warming to 2°C outweigh global mitigation costs over the 21st century, if aggregated economic impacts of climate change are at the moderate to high end of the assessed range, and a weight consistent with economic theory is given to economic impacts over the long-term. This holds true even without accounting for benefits in other sustainable development dimensions or non-market damages from climate change (*medium confidence*). The aggregate global economic repercussions of mitigation pathways include the macroeconomic impacts of investments in low-carbon solutions and structural changes away from emitting activities, co-benefits and adverse side effects of mitigation, (avoided) climate change impacts, and (reduced) adaptation costs. Existing quantifications of global aggregate economic

FOOTNOTE[2] Numbers in parenthesis represent he interquartile range of the scenario samples.

impacts show a strong dependence on socioeconomic development conditions, as these shape exposure and vulnerability and adaptation opportunities and responses. (Avoided) impacts for poorer households and poorer countries represent a smaller share in aggregate economic quantifications expressed in GDP or monetary terms, whereas their well-being and welfare effects are comparatively larger. When aggregate economic benefits from avoided climate change impacts are accounted for, mitigation is a welfare-enhancing strategy. *(high confidence)* {3.6.2}

The economic benefits on human health from air quality improvement arising from mitigation action can be of the same order of magnitude as mitigation costs, and potentially even larger *(medium confidence)*. {3.6.3}

Differences between aggregate employment in mitigation pathways compared to reference scenarios are relatively small, although there may be substantial reallocations across sectors, with job creation in some sectors and job losses in others. The net employment effect (and its sign) depends on scenario assumptions, modelling framework, and modelled policy design. Mitigation has implications for employment through multiple channels, each of which impacts geographies, sectors and skill categories differently. (*medium confidence*) {3.6.4}

The economic repercussions of mitigation vary widely across regions and households, depending on policy design and level of international cooperation *(high confidence)*. Delayed global cooperation increases policy costs across regions, especially in those that are relatively carbon intensive at present (*high confidence*). Pathways with uniform carbon values show higher mitigation costs in more carbon-intensive regions, in fossil-fuels exporting regions and in poorer regions (*high confidence*). Aggregate quantifications expressed in GDP or monetary terms undervalue the economic effects on households in poorer countries; the actual effects on welfare and well-being are comparatively larger (*high confidence*). Mitigation at the speed and scale required to likely limit warming to 2°C or below implies deep economic and structural changes, thereby raising multiple types of distributional concerns across regions, income classes and sectors (*high confidence*). {3.6.1, 3.6.4}

The timing of mitigation actions and their effectiveness will have significant consequences for broader sustainable development outcomes in the longer term *(high confidence)*. Ambitious mitigation can be considered a precondition for achieving the Sustainable Development Goals, especially for vulnerable populations and ecosystems with little capacity to adapt to climate impacts. Dimensions with anticipated co-benefits include health, especially regarding air pollution, clean energy access and water availability. Dimensions with potential trade-offs include food, employment, water stress, and biodiversity, which come under pressure from large-scale CDR deployment, energy affordability/access, and mineral resource extraction. *(high confidence)* {3.7}

Many of the potential trade-offs of mitigation measures for other sustainable development outcomes depend on policy design and can thus be compensated or avoided with additional policies and investments or through policies that integrate mitigation with other SDGs *(high confidence)*. Targeted SDG policies and investments, for example in the areas of healthy nutrition, sustainable consumption and production, and international collaboration, can support climate change mitigation policies and resolve or alleviate trade-offs. Trade-offs can be addressed by complementary policies and investments, as well as through the design of cross-sectoral policies integrating mitigation with the Sustainable Development Goals of health, nutrition, sustainable consumption and production, equity and biodiversity. {3.7}

Decent living standards, which encompass many SDG dimensions, are achievable at lower energy use than previously thought *(high confidence)*. Mitigation strategies that focus on lower demands for energy and land-based resources exhibit reduced trade-offs and negative consequences for sustainable development relative to pathways involving either high emissions and climate impacts or those with high consumption and emissions that are ultimately compensated by large quantities of BECCS. {3.7}

Different mitigation pathways are associated with different feasibility challenges, though appropriate enabling conditions can reduce these challenges. Feasibility challenges are transient and concentrated in the next two to three decades *(high confidence)*. They are multi-dimensional, context-dependent and malleable to policy, technological and societal trends. {3.8}

Mitigation pathways are associated with significant institutional and economic feasibility challenges rather than technological and geophysical. The rapid pace of technological development and deployment in mitigation pathways is not incompatible with historical records. Institutional capacity is rather a key limiting factor for a successful transition. Emerging economies appear to have highest feasibility challenges in the short to medium term. {3.8}

Pathways relying on a broad portfolio of mitigation strategies are more robust and resilient *(high confidence)*. Portfolios of technological solutions reduce the feasibility risks associated with the low carbon transition. {3.8}

3.1 Introduction

3.1.1 Assessment of mitigation pathways and their compatibility with long-term goals

Chapter 3 takes a long-term perspective on climate change mitigation pathways. Its focus is on the implications of long-term targets for the required short- and medium-term system changes and associated greenhouse gas (GHG) emissions. This focus dictates a more global view and on issues related to path-dependency and up-scaling of mitigation options necessary to achieve different emissions trajectories, including particularly deep mitigation pathways that require rapid and fundamental changes.

Stabilizing global average temperature change requires to reduce CO_2 emissions to net zero. Thus, a central cross-cutting topic within the Chapter is the timing of reaching net zero CO_2 emissions and how a "balance between anthropogenic emissions by sources and removals by sinks" could be achieved across time and space. This includes particularly the increasing body of literature since the IPCC Special Report on Global Warming of 1.5°C (SR1.5) which focuses on net zero CO_2 emissions pathways that avoid temperature overshoot and hence do not rely on net negative CO_2 emissions. The chapter conducts a systematic assessment of the associated economic costs as well as the benefits of mitigation for other societal objectives, such as the Sustainable Development Goals (SDGs). In addition, the Chapter builds on SR1.5 and introduces a new conceptual framing for the assessment of possible social, economic, technical, political, and geophysical "feasibility" concerns of alternative pathways, including the enabling conditions that would need to fall into place so that stringent climate goals become attainable.

The structure of the Chapter is as follows: Section 3.2 introduces different types of mitigation pathways as well as the available modelling. Section 3.3 explores different emissions trajectories given socio-economic uncertainties and consistent with different long-term climate outcomes. A central element in this section is the systematic categorization of the scenario space according to key characteristics of the mitigation pathways (including e.g., global average temperature change, socio-economic development, technology assumptions, etc.). In addition, the section introduces selected Illustrative Mitigation Pathways (IMPs) that are used across the whole report. Section 3.4 conducts a sectoral analysis of the mitigation pathways, assessing the pace and direction of systems changes across sectors. Among others, this section aims at the integration of the sectoral information across WGIII AR6 chapters through a comparative assessment of the sectoral dynamics in economy-wide systems models compared to the insights from bottom-up sectoral models (from Chapters 6-11). Section 3.5 focuses on the required timing of mitigation actions, and implication of near-term choices for the attainability of a range of long-term climate goals. After having explored the underlying systems transitions and the required timing of the mitigation actions, Section 3.6 assesses the economic implications, mitigation costs and benefits; and Section 3.7 assesses related co-benefits, synergies, and possible trade-offs for sustainable development and other societal (non-climate) objectives. Section 3.8 assumes a central role in the Chapter and introduces a multi-dimensional feasibility metric that permits the evaluation of mitigation pathways across a range of feasibility concerns. Finally, methods of the assessment and knowledge gaps are discussed in Section 3.9, followed by Frequently Asked Questions.

3.1.2 Linkages to other Chapters in the Report

Chapter 3 is linked to many other chapters in the report. The most important connections exist with Chapter 4 on mitigation and development pathways in the near to mid-term, with the sectoral chapters (Chapters 6-11), with the chapters dealing with cross-cutting issues (e.g., feasibility), and finally also with WGI and WGII AR6.

Within the overall framing of the AR6 report, Chapter 3 and Chapter 4 provide important complementary views of the required systems transitions across different temporal and spatial scales. While Chapter 3 focuses on the questions concerning the implications of the long-term objectives for the medium-to-near-term transformations, Chapter 4 comes from the other direction, and focuses on current near-term trends and policies (such as the Nationally Determined Contributions - NDCs) and their consequences with regards to GHG emissions. The latter chapter naturally focuses thus much more on the regional and national dimensions, and the heterogeneity of current and planned policies. Bringing together the information from these two chapters enables the assessment of whether current and planned actions are consistent with the required systems changes for the long-term objectives of the Paris Agreement.

Important other linkages comprise the collaboration with the "sectoral" Chapters 6-11 to provide an integrated cross-sectoral perspective. This information (including information also from the sectoral chapters) is taken up ultimately also by Chapter 5 on demand/services and Chapter 12 for a further assessment of sectoral potential and costs.

Linkages to other chapters exist also on the topic of feasibility, which are informed by the policy, the sectoral and the demand chapters, the technology and finance chapters, as well as Chapter 4 on national circumstances.

Close collaboration with WGI permitted the use of AR6-calibrated emulators, which assure full consistency across the different working groups. Linkages to WGII concern the assessment of macro-economic benefits of avoided impacts that are put into the context of mitigation costs as well as co-benefits and trade-offs for sustainable development.

3.1.3 Complementary use of large scenario ensembles and a limited set of Illustrative Mitigation Pathways (IMPs)

The assessment of mitigation pathways explores a wide scenario space from the literature within which seven Illustrative Pathways (IPs) are explored. The overall process is indicated in Figure 3.5a.

For a comprehensive assessment, a large ensemble of scenarios is collected and made available through an interactive AR6 scenario database. The collected information is shared across the chapters of AR6 and includes more than 3000 different pathways from a diverse set of studies. After an initial screening and quality control, scenarios were further vetted to assess if they sufficiently represented historical trends (Annex III). Subsequently, the climate consequences of each scenario were assessed using the climate emulator (leading to further classification). The assessment in Chapter 3 is however not limited to the scenarios from the database, and wherever necessary other literature sources are also assessed in order to bring together multiple lines of evidence.

In parallel, based on the overall AR6 assessment seven illustrative pathways (IP) were defined representing critical mitigation strategies discussed in the assessment. The seven pathways are composed of two sets: (i) one set of five Illustrative Mitigation Pathways (IMPs) and (ii) one set of two reference pathways illustrative for high emissions. The IMPs are on the one hand representative of the scenario space but help in addition to communicate archetypes of distinctly different systems transformations and related policy choices. Subsequently, seven scenarios were selected from the full database that fitted these storylines of each IP best. For these scenarios are more strict vetting criteria were applied. The selection was done by first applying specific filters based on the storyline followed by a final selection (see Box 3.1 and Figure 3.5 a).

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Box 3.1 Illustrative Mitigation Pathways

The literature shows a wide range of possible emissions trajectories, depicting developments in the absence of new climate policies or showing pathways consistent with the Paris Agreement. From the literature, a set of five Illustrative Mitigation Pathways (IMPs) was selected to denote implications of choices on socio-economic development and climate policies, and the associated transformations of the main GHG emitting sectors (see Figure 3.5b). The IMPs include a set of transformative pathways that illustrates how choices may lead to distinctly different transformations that may keep temperature increase to below 2°C or 1.5°C. These pathways illustrate the implications of a focus on renewable energy such as solar and wind; reduced energy demand; extensive use of CDR in the energy and the industry sectors to achieve net negative emissions and reliance on other supply-side measures; strategies that avoid net-negative carbon emissions, and gradual strengthening. In addition, one IMP explores how climate policies consistent with keeping temperature to 1.5˚C can be combined with a broader shift towards sustainable development. These IMPs are used in various chapters, exploring for instance their implications for different sectors, regions, and innovation characteristics (see Figure 3.5b).

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3.2 What are mitigation pathways compatible with long-term goals?

3.2.1 Scenarios and emission pathways

Scenarios and emission pathways are used to explore possible long-term trajectories, the effectiveness of possible mitigation strategies, and to help understand key uncertainties about the future. A **scenario** is an integrated description of a possible future of the human–environment system (Clarke et al. 2014), and could be a qualitative narrative, quantitative projection, or both. Scenarios typically capture interactions and processes driving changes in key driving forces such as population, GDP, technology, lifestyles, and policy, and the consequences on energy use, land use, and emissions. Scenarios are not predictions or forecasts. An **emission pathway** is a modelled trajectory of anthropogenic emissions (Rogelj et al. 2018a) and, therefore, a part of a scenario.

There is no unique or preferred method to develop scenarios, and future pathways can be developed from diverse methods, depending on user needs and research questions (Turnheim et al. 2015; Trutnevyte et al. 2019a; Hirt et al. 2020). The most comprehensive scenarios in the literature are qualitative narratives that are translated into quantitative pathways using models (Clarke et al. 2014; Rogelj et al. 2018a). Schematic or illustrative pathways can also be used to communicate specific features of more complex scenarios (Allen et al. 2018). Simplified models can be used to explain the mechanisms operating in more complex models (e.g., Emmerling et al. (2019)). Ultimately, a diversity of scenario and modelling approaches can lead to more robust findings (Gambhir et al. 2019; Schinko et al. 2017).

3.2.1.1 Reference scenarios

It is common to define a reference scenario (also called a baseline scenario). Depending on the research question, a reference scenario could be defined in different ways (Grant et al. 2020): 1) a hypothetical world with no climate policies or climate impacts (Kriegler et al. 2014b), 2) assuming current policies or pledged policies are implemented (Roelfsema et al. 2020), or 3) a mitigation scenario to compare sensitivity with other mitigation scenarios (Kriegler et al. 2014a; Sognnaes et al. 2021).

No-climate-policy reference scenarios have often been to compare with mitigation scenarios (Clarke et al. 2014). A no-climate-policy scenario assumes that no future climate policies are implemented, beyond what is in the model calibration, effectively implying that the carbon price is zero. No-climate-policy reference scenarios have a broad range depending on socioeconomic assumptions and model characteristics, and consequently are important when assessing mitigation costs (Riahi et al. 2017; Rogelj et al. 2018b). As countries move forward with climate policies of varying stringency, no-climate-policy baselines are becoming increasingly hypothetical (Hausfather and Peters 2020). Studies clearly show current policies are having an effect, particularly when combined with the declining costs of low carbon technologies (IEA 2020a; UNEP 2020; Roelfsema et al. 2020; Sognnaes et al. 2021), and, consequently, realised trajectories begin to differ from earlier no-climate-policy scenarios (Burgess et al. 2020). High-end emission scenarios, such as RCP8.5 and SSP5-8.5, are becoming less likely with climate policy and technology change (see Box 3.3), but high-end concentration and warming levels may still be reached with the inclusion of strong carbon or climate feedbacks (Pedersen et al. 2020; Hausfather and Peters 2020).

3.2.1.2 Mitigation scenarios

Mitigation scenarios explore different strategies to meet climate goals and are typically derived from reference scenarios by adding climate or other policies. Mitigation pathways are often developed to meet a predefined level of climate change, often referred to as a backcast. There are relatively few IAMs that include an endogenous climate model or emulator due to the added computational complexity, though exceptions do exist. In practice, models implement climate constraints by either iterating carbon price assumptions (Strefler et al. 2021b) or by adopting an associated carbon budget (Riahi et al. 2021). In both cases, other GHGs are typically controlled by CO2-equivalent pricing. A large part of the AR5 literature has focused on forcing pathways towards a target at the end of the century (van Vuuren et al. 2007, 2011; Clarke et al. 2009; Blanford et al. 2014; Riahi et al. 2017), featuring a temporary overshoot of the warming and forcing levels (Geden and Löschel 2017). In comparison, many recent studies explore mitigation strategies that limit overshoot (Johansson et al. 2020; Riahi et al. 2021). An increasing number of IAM studies also explore climate pathways that limit adverse side-effects with respect to other societal objectives, such as food security (van Vuuren et al. 2019; Riahi et al. 2021) or larger sets of sustainability objectives (Soergel et al. 2021a).

3.2.2 The utility of Integrated Assessment Models

Integrated Assessment Models (IAMs) are critical for understanding the implications of long-term climate objectives for the required near-term transition. For doing so, an integrated systems perspective including the representation of all sectors and GHGs is necessary. IAMs are used to explore the response of complex systems in a formal and consistent framework. They cover broad range of modelling frameworks (Keppo et al. 2021). Given the complexity of the systems under investigation, IAMs necessarily make simplifying assumptions and therefore results need to be interpreted in the context of these assumptions. IAMs can range from economic models that consider only carbon dioxide emissions through to detailed process-based representations of the global energy system, covering separate regions and sectors (such as energy, transport, and land use), all GHG emissions and air pollutants, interactions with land and water, and a reduced representation of the climate system. IAMs are generally driven by economics and can have a variety of characteristics such as partial-, general, or non-equilibrium, myopic or perfect foresight, be based on optimization or simulation, have exogenous or endogenous technological change, amongst many other characteristics. IAMs take as input socioeconomic and technical variables and parameters to represent various systems. There is no unique way to integrate this knowledge into a model, and due to their complexity, various simplifications and omissions are made for tractability. IAMs therefore have various advantages and disadvantages which need to be weighed up when interpreting IAM outcomes. Annex III contains an overview of the different types of models and their key characteristics.

Most IAMs are necessarily broad as they capture long-term dynamics. IAMs are strong in showing the key characteristics of emission pathways and are most suited to questions related to short- versus long-term trade-offs, key interactions with non-climate objectives, long-term energy and land-use characteristics, and implications of different overarching technological and policy choices (Rogelj et al. 2018a; Clarke et al. 2014). While some IAMs have an high level of regional and sectoral detail, for questions that require higher levels of granularity (e.g., local policy implementation) specific region and sector models may be better suited. Utility of the IAM pathways increases when the quantitative results are contextualized through qualitative narratives or other additional types of knowledge to provide deeper insights (Geels et al. 2016a; Weyant 2017; Gambhir et al. 2019).

IAMs have a long history in addressing environmental problems, particularly in the IPCC assessment process (van Beek et al. 2020). Many policy discussions have been guided by IAM-based quantifications, such as the required emission reduction rates, net zero years, or technology deployment rates required to meet certain climate outcomes. This has led to the discussion whether IAM scenarios have become performative, meaning that they act upon, transform or bring into being the scenarios they describe (Beck and Mahony 2017, 2018). Transparency of underlying data and methods is critical for scenario users to understand what drives different scenario results (Robertson 2020). A number of community activities have thus focused on the provision of transparent and publicly accessible databases of both input and output data (Riahi et al. 2012; Huppmann et al. 2018; Krey et al. 2019; Daioglou et al. 2020) as well as the provision of open-source code, and increased documentation (Annex III). Transparency is needed to reveal conditionality of results on specific choices in terms of assumptions (e.g., discount rates) and model architecture. More detailed explanations of underlying model dynamics would be critical to increase the understanding of what drives results (Bistline et al. 2020; Butnar et al. 2020; Robertson 2020).

Mitigation scenarios developed for a long-term climate constraint typically focus on cost-effective mitigation action towards a long-term climate goal. Results from IAM as well as sectoral models depend on model structure (Mercure et al. 2019), economic assumptions (Emmerling et al. 2019), technology assumptions (Pye et al. 2018), climate/emissions target formulation (Johansson et al. 2020), and the extent to which pre-existing market distortions are considered (Guivarch et al. 2011). The vast majority of IAM pathways do not consider climate impacts (Schultes et al. 2021). Equity hinges upon ethical and normative choices. As most IAM pathways follow the cost-effectiveness approach, they do not make any additional equity assumptions. Notable exceptions include (Tavoni et al. 2015; Pan et al. 2017; van den Berg et al. 2020; Bauer et al. 2020). Regional IAM results need thus to be assessed with care, considering that emissions reductions are happening where it is most cost-effective, which needs to be separated from the fact who is ultimately paying for the mitigation costs. Cost-effective pathways can provide a useful benchmark, but may not reflect real-world developments (Trutnevyte 2016; Calvin et al. 2014a). Different modelling frameworks may lead to different outcomes (Mercure et al. 2019). Recent studies have shown that other desirable outcomes can evolve with only minor deviations from cost-effective pathways (Neumann and Brown 2021; Bauer et al. 2020). IAM and sectoral models represent social, political, and institutional factors only in a rudimentary way. This assessment is thus relying on new methods for the ex-post assessment of feasibility concerns (Jewell and Cherp 2020; Brutschin et al. 2021). A literature is emerging that recognises and reflects on the diversity and strengths/weaknesses of model-based scenario analysis (Keppo et al. 2021).

The climate constraint implementation can have a meaningful impact on model results. The literature so far included many temperature overshoot scenarios with heavy reliance on long-term CDR and net negative CO_2 emissions to bring back temperatures after the peak (Johansson et al. 2020; Rogelj et al. 2019b). New approaches have been developed to avoid temperature overshoot. The new generation of scenarios show that CDR is important beyond its ability to reduce temperature, but is essential also for offsetting residual emissions to reach a net zero CO_2 emissions (Rogelj et al. 2019b; Johansson et al. 2020; Riahi et al. 2021; Strefler et al. 2021b).

Many factors influence the deployment of technologies in the IAMs. Since AR5, there has been fervent debate on the large-scale deployment of Bioenergy with Carbon Capture and Storage (BECCS) in scenarios (Geden 2015; Fuss et al. 2014; Smith et al. 2016; Anderson and Peters 2016; van Vuuren et al. 2017; Galik 2020; Köberle 2019). Hence, many recent studies explore mitigation pathways with limited BECCS deployment (Grubler et al. 2018; Soergel et al. 2021a; van Vuuren et al. 2019; Riahi et al. 2021). While some have argued that technology diffusion in IAMs occurs too rapidly (Gambhir et al. 2019), others argued that most models prefer large-scale solutions resulting in a relatively slow phase-out of fossil fuels (Carton 2019). While IAMs are particularly strong on supply-side representation, demand-side measures still lag in detail of representation despite progress since AR5 (Grubler et al. 2018; van den Berg et al. 2019; Lovins et al. 2019; O'Neill et al. 2020b; Hickel et al. 2021; Keyßer and Lenzen 2021). The discount rate has a significant impact on the balance between near-term and long-term mitigation. Lower discount rates <4% (than used in IAMs) may lead to more near-term emissions reductions – depending on the stringency of the target (Emmerling et al. 2019; Riahi et al. 2021). Models often use simplified policy assumptions (O'Neill et al. 2020b) which can affect the deployment of technologies (Sognnaes et al. 2021). Uncertainty in technologies can lead to more or less short-term mitigation (Grant et al. 2021; Bednar et al. 2021). There is also a recognition to put more emphasis on what drives the results of different IAMs (Gambhir et al. 2019) and suggestions to focus more on what is driving differences in result across IAMs (Nikas et al. 2021). As noted by Weyant (2017) (p.131), "IAMs can provide very useful information, but this information needs to be carefully interpreted and integrated with other quantitative and qualitative inputs in the decision-making process."

3.2.3 The scenario literature and scenario databases

IPCC reports have often used voluntary submissions to a scenario database in its assessments. The database is an ensemble of opportunity, as there is not a well-designed statistical sampling of the hypothetical model or scenario space: the literature is unlikely to cover all possible models and scenarios, and not all scenarios in the literature are submitted to the database. Model inter-comparisons are often the core of scenario databases assessed by the IPCC (Cointe et al. 2019; Nikas et al. 2021). Single model studies may allow more detailed sensitivity analyses or address specific research questions. The scenarios that are organised within the scientific community are more likely to enter the assessment process via the scenario database (Cointe et al. 2019), while scenarios from different communities, in the emerging literature, or not structurally consistent with the database may be overlooked. Scenarios in the grey literature may not be assessed even though they may have greater weight in a policy context.

One notable development since IPCC AR5 is the Shared Socioeconomic Pathways (SSPs), conceptually outlined in (Moss et al. 2010) and subsequently developed to support integrated climate research across the IPCC Working Groups (O'Neill et al. 2014). Initially, a set of SSP narratives were developed, describing worlds with different challenges to mitigation and adaptation (O'Neill et al. 2017a): SSP1 (sustainability), SSP2 (middle of the road), SSP3 (regional rivalry), SSP4 (inequality) and SSP5 (rapid growth). The SSPs have now been quantified in terms of energy, land-use change, and emission pathways (Riahi et al. 2017), for both no-climate-policy reference scenarios and mitigation scenarios that follow similar radiative forcing pathways as the RCPs assessed in AR5 WGI. Since then the SSPs have been successfully applied in 1000s of studies (O'Neill et al. 2020b) including some critiques on the use and application of the SSP framework (Rosen 2021; Pielke and Ritchie 2021). A selection of the quantified SSPs are used prominently in IPCC AR6 WGI as they were the basis for most climate modelling since AR5 (O'Neill et al. 2016). Since 2014, when the first set of SSP data was made available, there has been a divergence between scenario and historic trends

(Burgess et al. 2020). As a result, the SSPs require updating (O'Neill et al. 2020b). Most of the scenarios in the AR6 database are SSP-based and consider various updates compared to the first release (Riahi et al. 2017).

3.2.4 The AR6 scenario database

To facilitate this assessment, a large ensemble of scenarios has been collected and made available through an interactive WGIII AR6 scenario database. The collection of the scenario outputs is coordinated by Chapter 3 and expands upon the IPCC SR1.5 scenario explorer (Huppmann et al. 2018; Rogelj et al. 2018a). A complementary database for national pathways has been established by Chapter 4. Annex III contains full details on how the scenario database was compiled.

The AR6 scenario database contains 3131 scenarios (see Figure 3.5a). After an initial screening and quality control, scenarios were further vetted to assess if they sufficiently represented historical trends (Annex III). Of the initial 2266 scenarios with global scope, 1686 scenarios passed the vetting process and are assessed in this Chapter. The scenarios that did not pass the vetting are still available in the database. The vetted scenarios were from over 50 different model families, or over 100 when considering all versions of the same family (Figure 3.1). The scenarios originated from over 15 different model intercomparison projects, with very few scenarios originating from individual studies (Figure 3.2). Because of the uneven distribution of scenarios from different models and projects, uncorrected statistics from the database can be misleading.

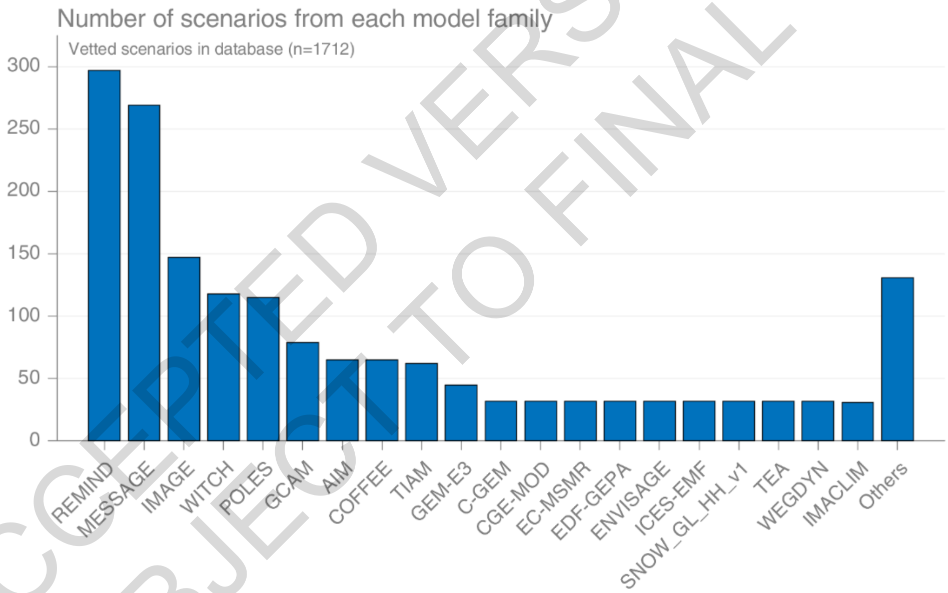


Figure 3.1 Scenario counts from each model family defined as all versions under the same model's name.

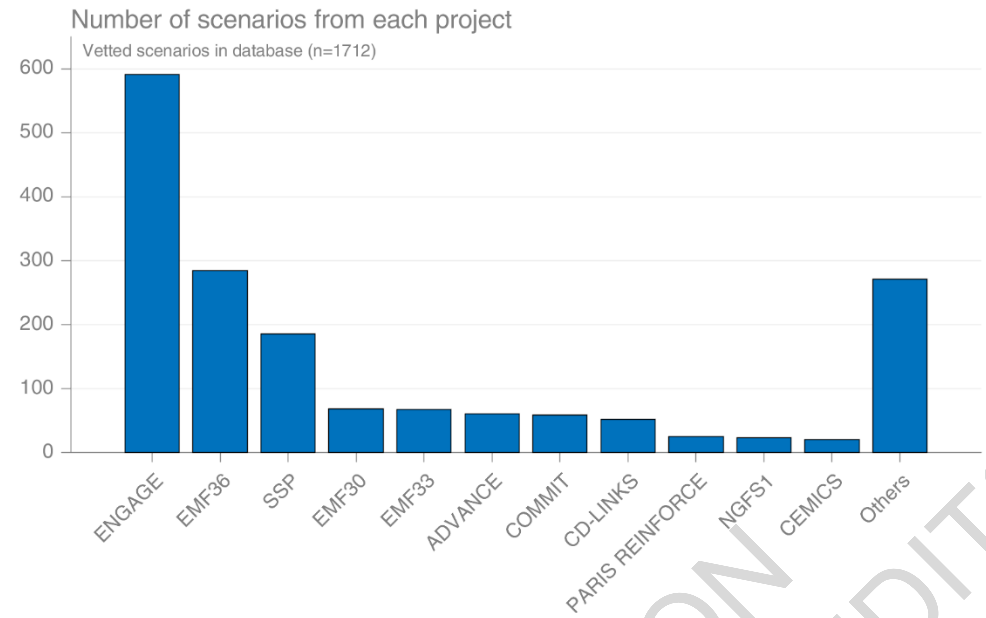


Figure 3.2 Scenario counts from each named project.

Each scenario with sufficient data is given a temperature classification using climate model emulators. Three emulators were used in the assessment: FAIR (Smith et al. 2018), CICERO-SCM (Skeie et al. 2021), MAGICC (Meinshausen et al. 2020). Only the results of MAGICC are shown in this chapter as it adequately covers the range of outcomes. The emulators are calibrated against the behaviour of complex climate models and observation data, consistent with the outcomes of AR6 WGI AR6 (WGI cross-chapter Box 7.1). The climate assessment is a three-step process of harmonization, infilling and a probabilistic climate model emulator run (Annex III.2.5.1). Warming projections until the year 2100 were derived for 1574 scenarios, of which 1202 passed vetting, with the remaining scenarios having insufficient information (Table 3.1 and Figure 3.3). For scenarios that limit warming to 2°C or below, the SR15 classification was adopted in AR6, with more disaggregation provided for higher warming levels (Table 3.1). These choices can be compared with the selection of common global warming levels (GWL) of 1.5°C, 2°C, 3°C and 4°C to classify climate change impacts in the WGII assessment.

Table 3.1 Classification of emissions scenarios into warming levels using MAGICC

Description	**Subset**	**WGI SSP**	**WGIII IP**	**Scenarios**
C1: Below 1.5°C with no or limited overshoot	<1.5°C peak warming with ≥33% chance and < 1.5°C end of century warming with >50% chance	SSP1-1.9 -,	SP, LD, Ren	**97**
C2: Below 1.5°C with high overshoot	<1.5°C peak warming with <33% chance and < 1.5°C end of century warming with >50% chance			**133**
C3: Likely below 2°C	<2°C peak warming with >67% chance	SSP2-2.6	GS, Neg	**311**
C4: Below 2ºC	<2°C peak warming with >50% chance			**159**
C5: Below 2.5°C	<2.5°C peak warming with >50% chance			**212**

C6: Below 3°C	<3°C peak warming with >50% chance	SSP2-4.5	Mod-Act	**97**
C7: Below 4°C	<4°C peak warming with >50% chance	SSP3-7.0	Cur-Pol	**164**
C8: Above 4°C	>4°C peak warming with ≥50% chance	SSP5-8.5		**29**

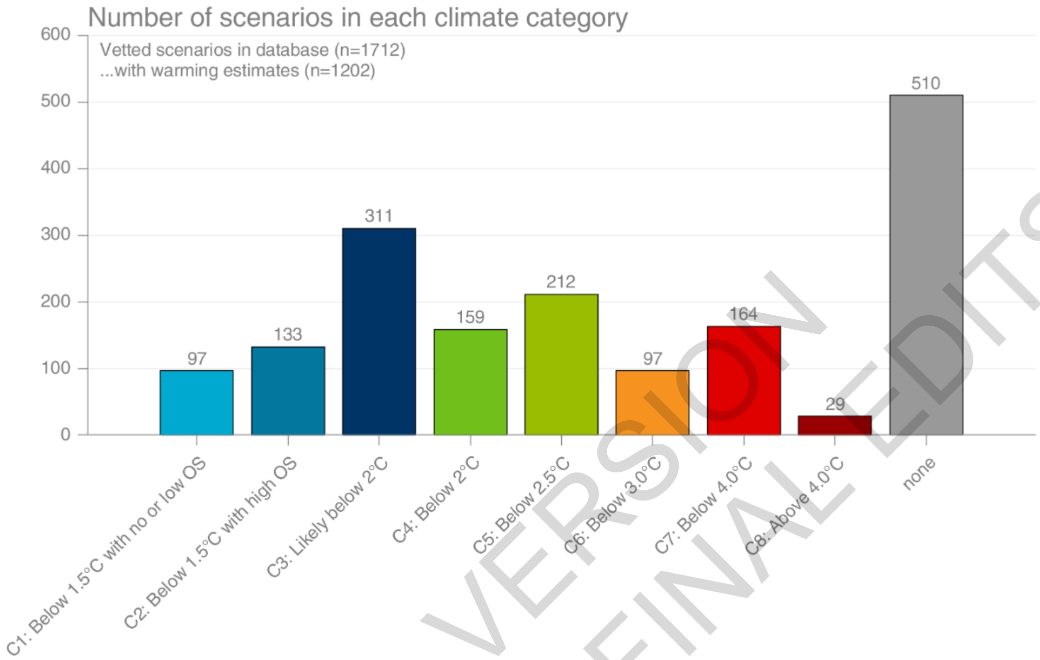


Figure 3.3 Of the 1686 scenarios that passed vetting, 1202 had sufficient data available to be classified according to temperature, with an uneven distribution across warming levels.

In addition to the temperature classification, each scenario is assigned to one of the following policy categories: (P0) diagnostic scenarios – 100 of 1686 vetted scenarios; (P1) scenarios with no globally coordinated policy and either (P1a) no climate mitigation efforts – 119, (P1b) current national mitigation efforts – 59, (P1c) Nationally Determined Contributions (NDCs) – 110, or (P1d) other non-standard assumptions – 104; (P2) globally coordinated climate policies with immediate (i.e. before 2030) action – 73, (P2a) without any transfer of emission permits – 435, (P2b) with transfers – 70; or (P2c) with additional policy assumptions – 55; (P3) globally coordinated climate policies with delayed (i.e. from 2030 onwards or after 2030) action, preceded by (P3a) no mitigation commitment or current national policies – 7, (P3b) NDCs – 376, (P3c) NDCs and additional policies – 18 and (P3d) other non-standard regional assumptions – 0; (P4) Cost-Benefit Analysis (CBA) – 2. The policy categories were identified using text pattern matching on the scenario metadata and calibrated on the best-known scenarios from model intercomparisons, with further validation against the related literature, reported emission and carbon price trajectories, and exchanges with modellers. If the information available is enough to qualify a policy category number but not sufficient for a subcategory, then only the number is retained (e.g., P2 instead of P2a/b/c). A suffix added after P0 further qualifies a diagnostic scenario as one of the other policy categories.To demonstrate the diversity of the scenarios, the vetted scenarios were classified into different categories along the dimensions of population, GDP, energy, and cumulative emissions (Figure 3.4). The number of scenarios in each category provides some insight into the current literature, but this does not indicate a higher probability of that category occurring in reality. For population, the majority of scenarios are consistent with the SSP2 'middle of the road' category, with very few scenarios exploring the outer extremes. GDP has a slightly larger variation, but overall, most scenarios are around the SSP2 socioeconomic assumptions. The level of CCS and CDR is expected to change depending on the extent of mitigation, but there remains extensive use of both CDR and CCS in scenarios. CDR is dominated by bioenergy with CCS (BECCS) and sequestration on land, with relatively few scenarios using Direct Air Capture with Carbon Storage (DACCS) and even less with Enhanced Weathering and other technologies (not shown). In terms of energy consumption, final energy has a much smaller range than primary energy as conversion losses are not included in final energy. Both mitigation and reference scenarios are shown, so there is a broad spread in different energy carriers represented in the database. Bioenergy has a number of scenarios at around 100EJ, representing a constraint used in many model intercomparisons.

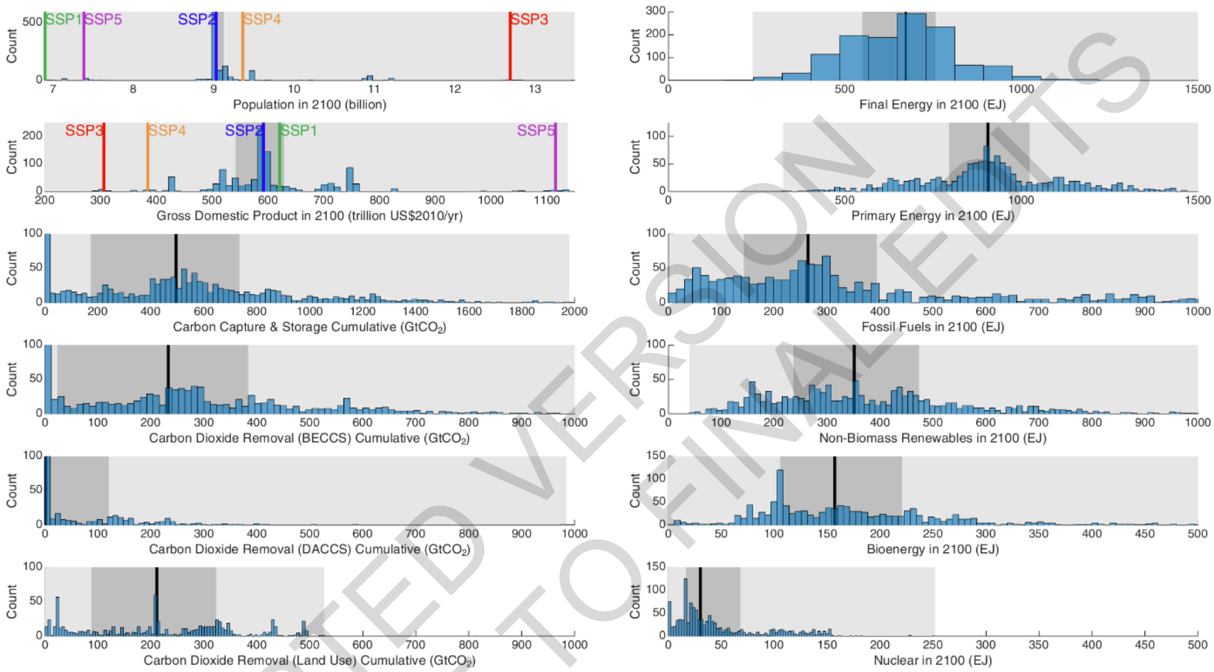


Figure 3.4 Histograms for key categories in the AR6 scenario database. Only scenarios that passed vetting are shown. For population and GDP, the SSP input data are also shown. The grey shading represents the 0-100% range (light grey), 25-75% range (dark grey), and the median is a black line. The figures with white areas are outside of the scenario range, but the axis limits are retained to allow comparability with other categories. Each subfigure potentially has different x- and y-axis limits. Each figure also potentially contains different numbers of scenarios, depending on what was submitted to the database.

Source: AR6 scenarios database.

3.2.5 Illustrative Mitigation Pathways

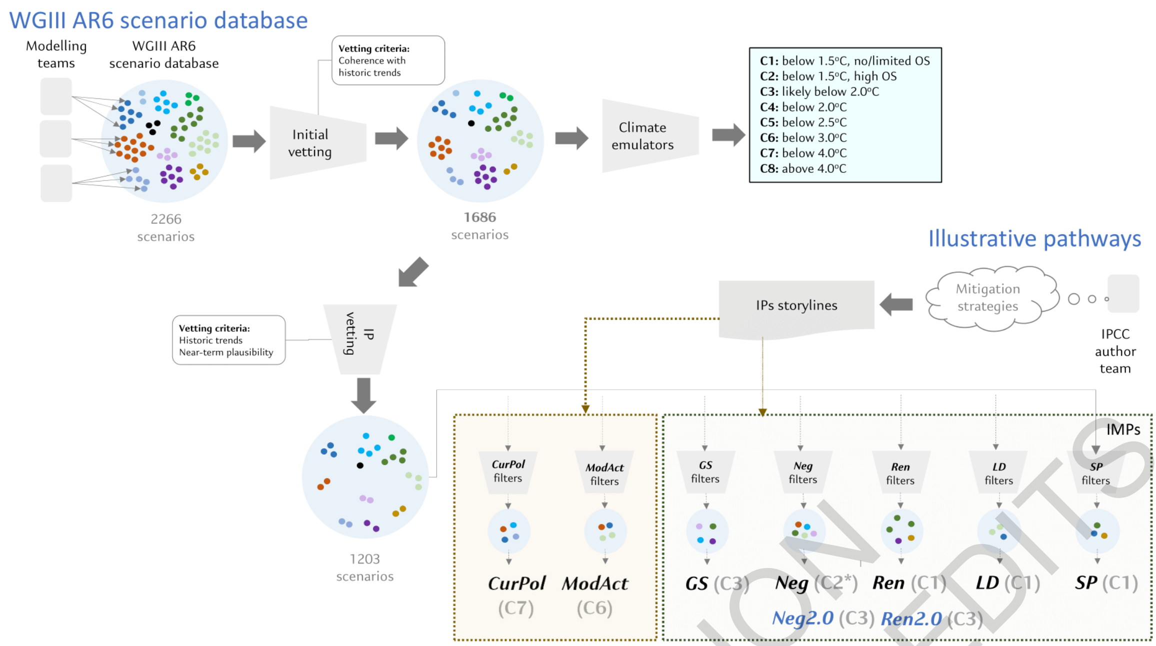
Successive IPCC Ars have used scenarios to illustrate key characteristics of possible climate (policy) futures. In IPCC AR5 four RCPs made the basis of climate modelling in WGI and WGII, with WGIII assessing over 1,000 scenarios spanning those RCPs (Clarke et al. 2014). Of the over 400 hundred scenarios assessed in SR15, four scenarios were selected to highlight the trade-off between short-term emission reductions and long-term deployment of BECCS (Rogelj et al. 2018a), referred to as ‘Illustrative Pathways’. AR6 WGI and WGII rely on the scenarios selected for CMIP6, called ScenarioMIP (O’Neill et al. 2016), to assess warming levels. IPCC AR6 WGIII uses in addition to the full set of scenarios also selected Illustrative Mitigation Pathways (IMPs).

In WGIII, IMPs were selected to denote the implications of different societal choices for the development of future emissions and associated transformations of main GHG emitting sectors (see Box 3.1 and Figure 3.5a). The most important function of the IMPs is to illustrate key themes that form a common thread in the report, both with a storyline and a quantitative illustration. The storyline describes the key characteristics that define an IMP. The quantitative versions of the IMPs provide numerical values that are internally consistent and comparable across chapters of the report. The quantitative IMPs have been selected from the AR6 scenario database. No assessment of the likelihood of each IMP has been made.

The selected scenarios (IPs) are divided into two sets (Figure 3.5 and Figure 3.6): two reference pathways illustrative of high emissions and five Illustrative Mitigation Pathways (IMPs). The narratives are explained in full in Annex III. The two reference pathways explore the consequences of current policies and pledges: Current Policies (***CurPol***) and Moderate Action (***ModAct***). The ***CurPol*** pathway explores the consequences of continuing along the path of implemented climate policies in 2020 and only a gradual strengthening after that. The scenario illustrates the outcomes of many scenarios in the literature that project the outcomes of current policies. The ***ModAct*** pathway explores the impact of implementing the Nationally Determined Contributions as formulated in 2020 and some further strengthening after that. In line with current literature, these two reference pathways lead to an increase in global mean temperature of more than 2°C (see Section 3.3).

The Illustrative Mitigation Pathways properly explore different pathways consistent with meeting the long-term temperature goals of the Paris Agreement. They represent five different pathways that emerge from the overall assessment. The IMPs consist of pathways with: gradual strengthening of current policies (***GS***), extensive use of net negative emissions (***Neg***), renewables (***Ren***), low demand (***LD***), and shifting pathways (***SP***). Each of these pathways can be implemented with different levels of ambition. In the IMP framework, ***GS*** is consistent with staying likely below 2°C (C3), ***Neg*** shows a strategy that also stays likely below 2°C level but returns to nearly 1.5°C by the end of the century (hence indicated as C2*). The other variants that can limit warming to 1.5°C (C1) were selected. In addition to these IMPs, sensitivity cases that explore alternative warming levels (C3) for ***Neg*** and ***Ren*** are assessed (***Neg-2.0*** and ***Ren-2.0***).

Panel A



Panel B

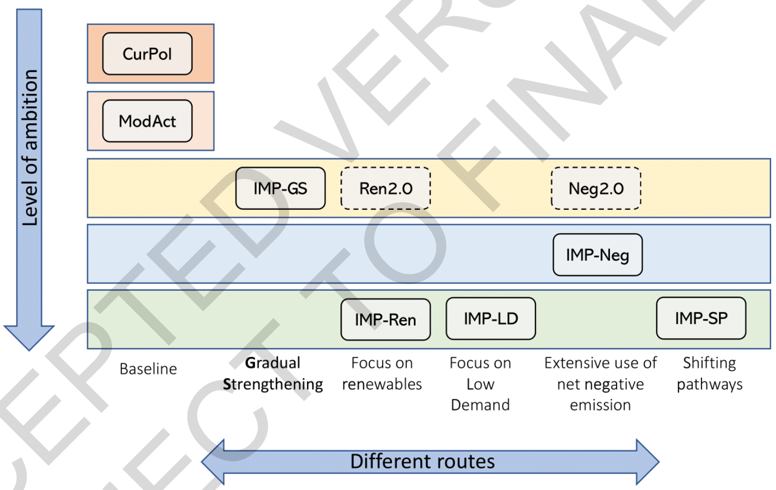


Figure 3.5 Panel A: Process for creating the AR6 scenario database and selecting the illustrative (mitigation) pathways. The compiled scenarios in the AR6 scenarios database were vetted for consistency with historical statistics and subsequently a temperature classification was added using climate model emulators. The illustrative (mitigation) pathways were selected from the full set of pathways based on storylines of critical mitigation strategies that emerged from the assessment. Panel B: An overview of the Illustrative Pathways selected for use in IPCC AR6 WGIII, consisting of pathways illustrative of higher emissions, Current Policies (*CurPol*) and Moderate Action (*ModAct*), and Illustrative Mitigation Pathways (IMPs): gradual strengthening of current policies (*GS*), extensive use of net negative emissions (*Neg*), renewables (*Ren*), low demand (*LD*), and shifting pathways (*SP*).

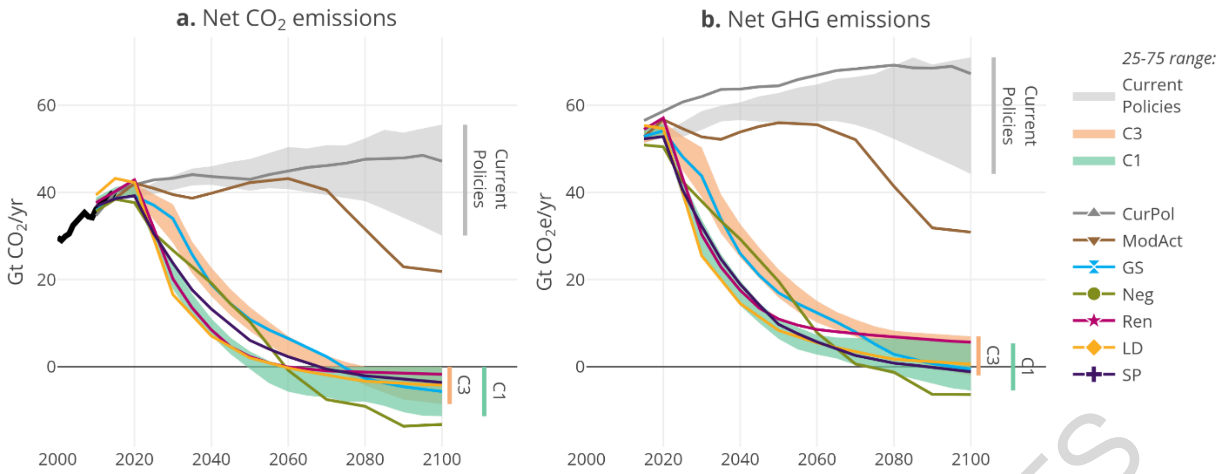


Figure 3.6 Overview of the net CO_2 emissions and Kyoto GHG emissions for each IMP

The IMPs are selected to have different mitigation strategies, which can be illustrated looking at the energy system and emission pathways (Figure 3.7 and Figure 3.8). The mitigation strategies show the different options in emission reduction (Figure 3.7). Each panel shows the key characteristics leading to total GHG emissions, consisting of residual (gross) emissions (fossil CO_2 emissions, CO_2 emissions from industrial processes, and non-CO_2 emissions) and removals (net land-use change, bioenergy with carbon capture and storage, and direct air carbon capture and storage), in addition to avoided emissions through the use of carbon capture and storage on fossil fuels. The ***Neg*** and ***GS*** scenarios were shown to illustrate scenarios with a significant role of CDR. The energy supply (Figure 3.8) shows the phase-out of fossil fuels in the ***LD***, ***Ren*** and ***SP*** cases, but a less substantial decrease in the ***Neg*** case. The ***GS*** case needs to make up its slow start by 1) rapid reductions mid-century and 2) massive reliance on net negative emissions by the end of the century. The ***CurPol*** and ***ModAct*** cases both result in relatively high emissions, showing a slight increase and stabilization compared to current emissions, respectively.

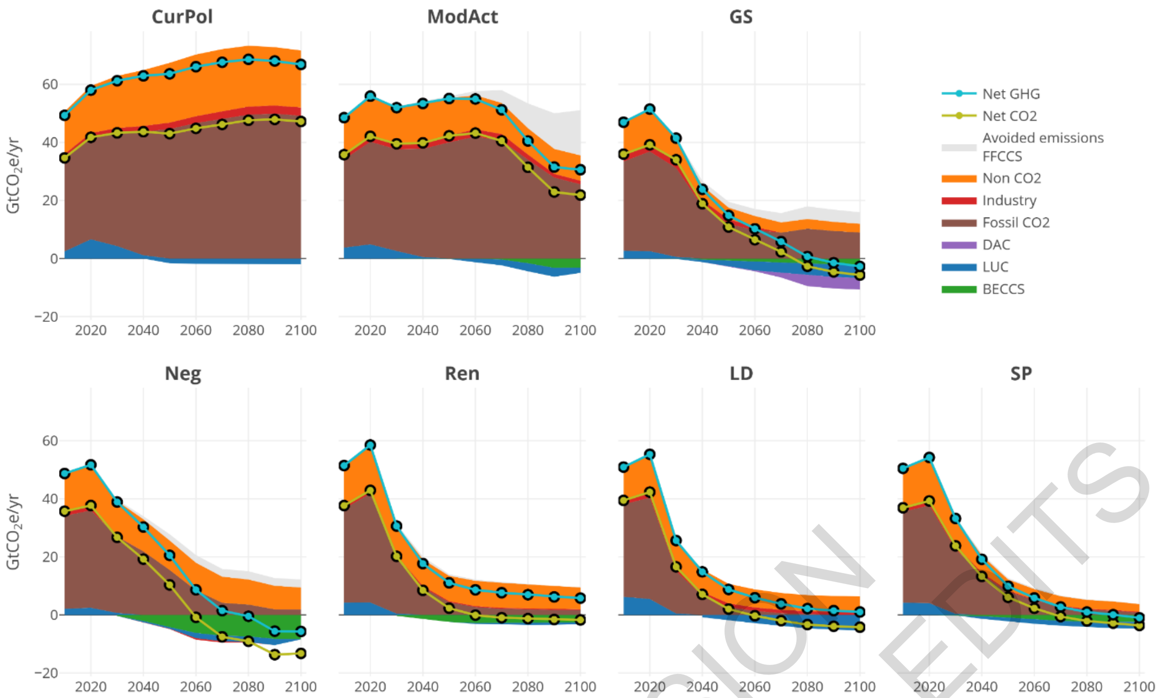


Figure 3.7 The residual fossil fuel and industry emissions, net land-use change, CDR, and non-CO_2 emissions (using AR6 GWP100) for each of the seven illustrative pathways. Fossil CCS is also shown, though this does not lead to emissions to the atmosphere.

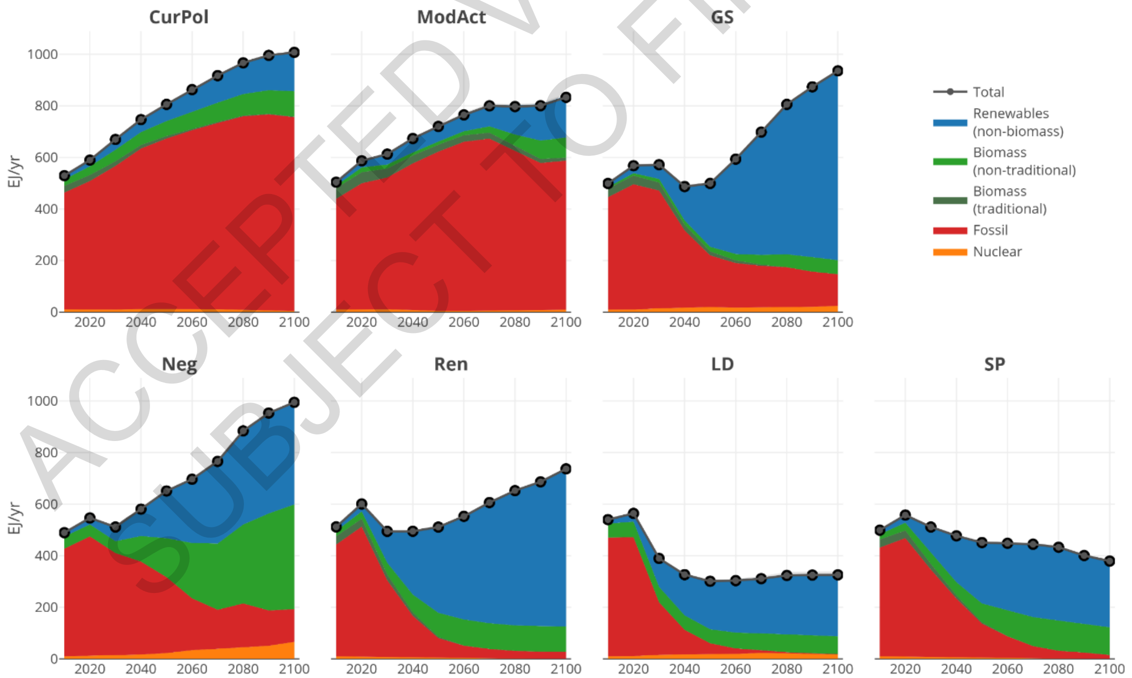


Figure 3.8 The energy system in each of the illustrative pathways.

3.3 Emission pathways, including socio-economic, carbon budget and climate responses uncertainties

3.3.1 Socio-economic drivers of emissions scenarios

Greenhouse gas emissions mainly originate from the use and transformation of energy, agriculture, land use (change) and industrial activities. The future development of these sources is influenced by trends in socio-economic development, including population, economic activity, technology, politics, lifestyles, and climate policy. Trends for these factors are not independent, and scenarios provide a consistent outlook for these factors together (see Section 3.2). Marangoni et al. (2017) show that in projections, assumptions influencing energy intensity (e.g., structural change, lifestyle and efficiency) and economic growth are the most important determinants of future CO_2 emissions from energy combustion. Other critical factors include technology assumptions, preferences, resource assumptions and policy (van Vuuren et al. 2008). As many of the factors are represented differently in specific models, the model itself is also an important factor – providing a reason for the importance of model diversity (Sognnaes et al. 2021). For land use, Stehfest et al. (2019) show that assumptions on population growth are more dominant given that variations in per capita consumption of food are smaller than for energy. Here, we only provide a brief overview of some key drivers. We focus first on so-called reference scenarios (without stringent climate policy) and look at mitigation scenarios in detail later. We use the SSPs to discuss trends in more detail. The SSPs were published in 2017, and by now, some elements will have to be updated (O'Neill et al. 2020b). Still, the ranges represent the full literature relatively well.

Historically, population and GDP have been growing over time. Scenario studies agree that further global population growth is likely up to 2050, leading to a range of possible outcomes of around 8.5-11 billion people (see Figure 3.9). After 2050, projections show a much wider range. If fertility drops below replacement levels, a decline in the global population is possible (as illustrated by SSP1 and SSP5). This typically includes scenarios with rapid development and investment in education. However, median projections mostly show a stabilisation of the world population (e.g., SSP2), while high-end projections show a continued growth (e.g., SSP3). The UN Population Prospects include considerably higher values for both the medium projection and the high end of the range than the SSP scenarios (KC and Lutz 2017; UN 2019). The most recent median UN projection reaches almost 11 billion people in 2100. The key differences are in Africa and China: here, the population projections are strongly influenced by the rate of fertility change (faster drop in SSPs). Underlying, the UN approach is more based on current demographic trends while the SSPs assume a broader range of factors (including education) driving future fertility.

Economic growth is even more uncertain than the population projections (Figure 3.9). The average growth rate of GDP was about 2.8% per year (constant USD) in the 1990-2019 period (The World Bank 2021). In 2020, the Covid-19 crisis resulted in a considerable drop in GDP (estimated around 4-5%) (IMF 2021). After a recovery period, most economic projections assume growth rates to converge back to previous projections, although at a lower level (IMF 2021; OECD 2021) (see also Box 3.2). In the long-term, assumptions on future growth relate to political stability, the role of the progress of the technology frontier and the degree to which countries can catch up (Johansson et al. 2013). The SSP scenarios cover an extensive range, with low per capita growth in SSP3 and SSP4 (mostly in developing countries) and rapid growth in SSP1 and SSP5. At the same, however, also scenarios outside the range have some plausibility – including the option of economic decline (Kallis et al. 2012) or much faster economic development (Christensen et al. 2018). The OECD long-term projection is at the global level reasonably consistent with SSP2. Equally important economic parameters include income distribution (inequity) and the type of growth (structural change, i.e., services vs manufacturing industries). Some projections (like SSP1) show a considerable convergence of income levels within and across countries, while in other projections, this does not occur (e.g., SSP3). Most scenarios reflect the suggested inverse relationship between the assumed growth rate for income and population growth (Figure 3.9e). SSP1 and SSP5 represent examples of scenarios with relatively low population increase and relatively high-income increase over the century. SSP3 represents an example of the opposite – while SSP2 and SSP4 are placed more in the middle. Nearly all scenarios assessed here do not account for climate impacts on growth (mostly for methodological reasons). As discussed in Section 3.5 these impacts can be considerable. An emerging area of literature emphasises the possibility of stabilisation (or even decline) of income levels in developed countries, arguing that such a trend would be preferred or even needed for environmental reasons (Anderson and Larkin 2013; Kallis et al. 2020; Hickel and Kallis 2020; Keyßer and Lenzen 2021; Hickel et al. 2021) (see also Chapter 5). Such scenarios are not common among IAM outcomes, that are more commonly based on the idea that decarbonisation can be combined with economic growth by a combination of technology, lifestyle and structural economic changes. Still, such scenarios could result in a dramatic reduction of energy and resource consumption (see further).

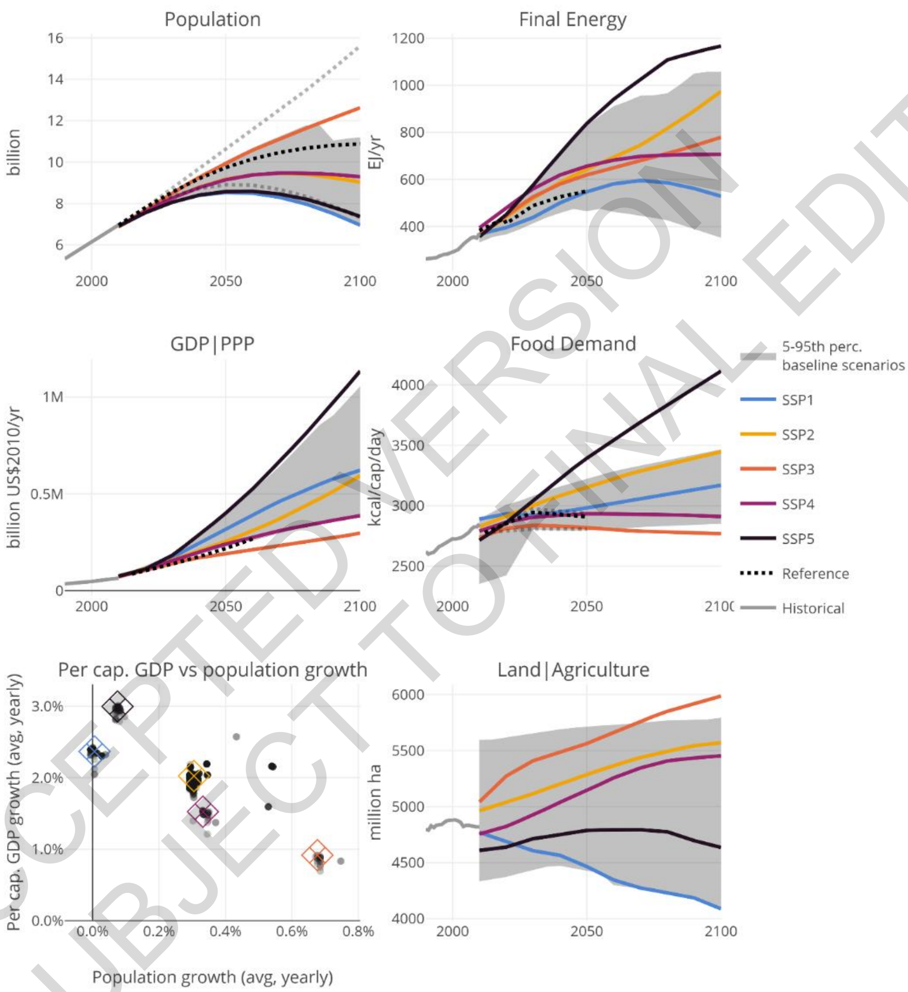


Figure 3.9 Trends in key scenarios characteristics and driving forces as included in the SSP scenarios (showing 5-95th percentiles of the reference scenarios as included in the database in grey shading). Reference (dotted lines) refers to UN low, medium and high population scenario (UN 2019), OECD Long-term economic growth scenario (OECD 2021), the scenarios from IEA's World Energy Outlook (IEA 2019), and the scenarios in the FAO assessment (FAO 2018)

Scenarios show a range of possible energy projections. In the absence of climate policy, most scenarios project the final energy demand to continue to grow to around 650-800 EJ yr^{-1} in 2100 (based on the scenario database). Some projections show a very high energy demand up to 1000 EJ yr^{-1} (comparable to SSP5). The scenario of the IEA lies within the SSP range but near the SSP1 projection. However, it should be noted that the IEA scenario includes current policies (most reference scenarios do not) and many scenarios published before 2021 did not account for the Covid-19 crisis. Several researchers discuss the possibility of decoupling material and energy demand from economic growth in the literature, mainly in developed countries (Kemp-Benedict 2018) (decoupling here refers to either a much slower increase in demand or even a decrease). In the scenario literature, this is reflected by scenarios with very low demand for final energy based on increased energy efficiency and less energy-intensive lifestyles (e.g., SSP1 and the LED scenario) (Grubler et al. 2018; van Vuuren et al. 2018). While these studies show the feasibility of such pathways, their energy efficiency improvement rates are considerably above the historic range of around 2% (Haberl et al. 2020).

(Vrontisi et al. 2018; Roelfsema et al. 2020; Sognnaes et al. 2021)(IEA 2021a; Höhne et al. 2021)(Jeffery et al. 2018; Gütschow et al. 2018)(Giarola et al. 2021)(Sognnaes et al. 2021)(Höhne et al. 2021)(Höhne et al. 2021)These scenarios also show clear differences in food consumption and the amount of land used for agriculture. Food demand in terms of per capita caloric intake is projected to increase in most scenarios. However, it should be noted that there are large differences in dietary composition across the scenarios (from more meat-intensive in scenarios like SSP5 to a decrease in meat consumptions in other scenarios such as SSP1). Land use projections also depend on assumed changes in yield and the population scenarios. Typically, changes in land use are less drastic than some other parameters (in fact, the 5-95th database range is almost stable). Agriculture land is projected to increase in SSP3, SSP2, and SSP4 – more-or-less stable in SSP5 and is projected to decline in SSP1.

3.3.2 Emission pathways and temperature outcomes

3.3.2.1 Overall mitigation profiles and temperature consequences

Figure 3.10 shows the GHG and CO_2 emission trajectories for different temperature categories as defined in Section 3.2 (the temperature levels are calculated using simple climate models, consistent with the outcomes of the recent WGI assessment, Cross-Chapter Box 7.1). It should be noted that most scenarios currently in the literature do not account for an impact of Covid-19 (see Box 3.2). The higher categories (C6 and C7) mostly included scenarios with no or modest climate policy. Because of the progression of climate policy, it is becoming more common that reference scenarios incorporate implemented climate policies. Modelling studies typically implement current or pledged policies up until 2030 (Vrontisi et al. 2018; Roelfsema et al. 2020; Sognnaes et al. 2021) with some studies focusing also on the policy development in the long term (IEA 2021a; Höhne et al. 2021). (Jeffery et al. 2018; Gütschow et al. 2018)Based on the assessment by Chapter 4, reference pathways consistent with the implementation and extrapolation of current policies are associated with increased GHG emissions from 59 (53-65) $GtCO_2$-eq yr^{-1} in 2019 to 52-60 $GtCO_2$-eq yr^{-1} by 2030 and to 46-67 $GtCO_2$-eq yr^{-1} by 2050 (see Figure 3.6). Pathways with these near-term emissions characteristics, lead to a median global warming of 2.4°C to 3.5°C by 2100 (see also further in this section). These pathways consider policies at the time that they were developed. A recent model comparison that harmonised socioeconomic, technological, and policy assumptions (Giarola et al. 2021) found a 2.2-2.9°C median temperature rise in 2100 for current and stated policies, with the results sensitive to the model used and the method of implementing policies (Sognnaes et al. 2021). Scenario inference and construction methods using similar policy assumptions leads to a median range of 2.9-3.2°C in 2100 for current policies and 2.4-2.9°C in 2100 for 2030 pledges (Höhne et al. 2021). The median spread of 1°C across these studies (2.2-3.2°C) indicates the deep uncertainties involved with modelling temperature outcomes of 2030 policies through to 2100. (Höhne et al. 2021)

The lower categories include increasingly stringent assumed climate policies. For all scenario categories, except the highest category, emissions peak in the 21st century. For the lowest categories, the emissions peak is mostly before 2030. In fact, for scenarios in the category that avoids temperature overshoot for the 1.5ºC scenario (C1 category), GHG emissions are reduced already to almost zero around the middle of the century. Typically, CO_2 emissions reach net zero about 10-20 years before total GHG emissions reach net zero. The main reason is that scenarios reduce non-CO_2 greenhouse gas emissions less than CO2 due to a limited mitigation potential (see 3.3.2.2). The figure also shows that many scenarios in the literature with a temperature outcome below 2 ˚C show net negative emissions. There are, however, also exceptions in which more immediate emission reductions limits the need for CDR. The IMPs illustrate alternative pathways to reach the C1-C3 temperature levels.

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Box 3.2 Impact of Covid-19 on long-term emissions

The reduction in CO_2 emissions of the Covid-19 pandemic in 2020 was estimated to be about 6% (see section 4.2.2.4 and Table S4.2) lower than 2019 levels (BP 2021, Crippa et al. 2021, IEA 2021, Le Quéré et al. 2021; Friedlingstein et al. 2020; Forster et al. 2020; Liu et al. 2020c). Near-real-time monitoring estimates show a rebound in emissions levels, meaning 2021 emissions levels are expected to be higher than 2020 (Le Quéré et al. 2021). The longer-term effects are uncertain but so far do not indicate a clear structural change for climate policy related to the pandemic. The increase in renewable shares in 2020 could stimulate a further transition, but slow economic growth can also slow down (renewable) energy investments. Also, lifestyle changes during the crisis can still develop in different directions (working from home, but maybe also living further away from work). Without a major intervention, most long-term scenarios project that emission will start to follow a similar pathway as earlier projections (although at a reduced level) (IEA 2020b; Kikstra et al. 2021a; Rochedo et al. 2021). If emissions reductions are limited to only a short time, the adjustment of pathways will lead to negligible outcomes in the order of 0.01K (Forster et al. 2020; Jones et al. 2021). At the same time, however, the large amount of investments pledged in the recovery packages could provide a unique opportunity to determine the long-term development of infrastructure, energy systems and land use (Hepburn et al. 2020; Pianta et al. 2021; Andrijevic et al. 2020b). Near-term alternative recovery pathways have been shown to have the potential to influence carbon price pathways, and energy investments and electrification requirements under stringent mitigation targets (Kikstra et al. 2021a; Rochedo et al. 2021; Bertram et al. 2021; Pollitt et al. 2021; Shan et al. 2021). Most studies suggest a noticeable reduction in 2030 emissions. However, much further reductions would be needed to reach the emission levels consistent with mitigation scenarios that would likely stay below 2ºC or lower (see Chapter 4). At the moment, the share of investments in greenhouse gas reduction is relatively small in most recovery packages, and no structural shifts for climate policies are observed linked to the pandemic. Finally, most of the scenarios analysed in this Chapter do not include the 2020 emissions reduction related to the Covid-19 pandemic. The effect of the pandemic on the pathways will likely be very small. The assessment of climate mitigation pathways in this chapter should be interpreted as being almost exclusively based on the assumption of a fast recovery with limited persistent effects on emissions or structural changes.

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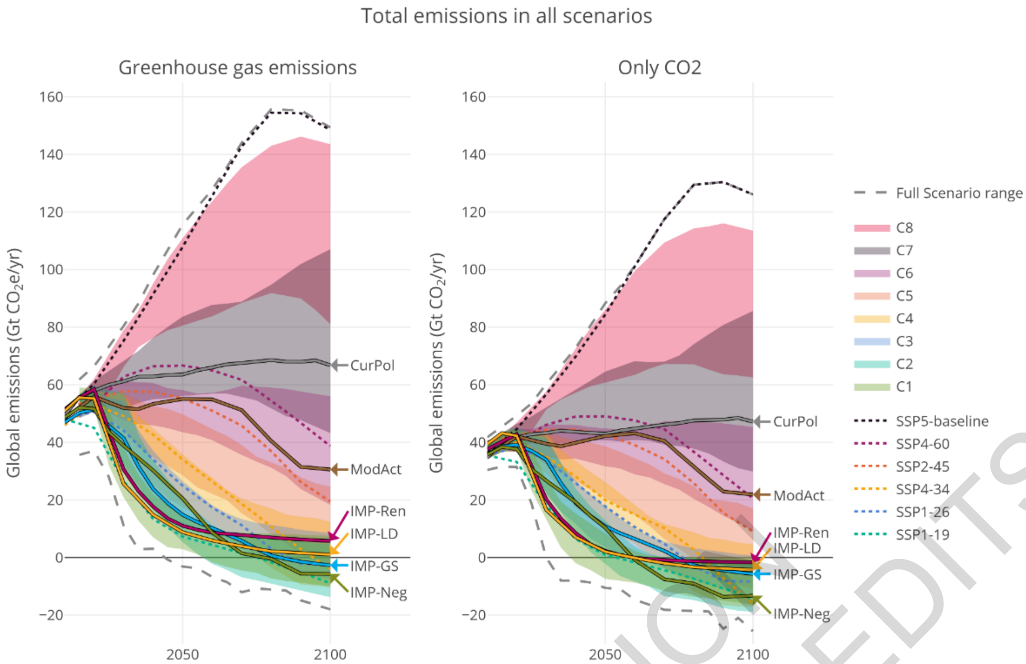

Figure 3.10 Total emission profiles in the scenarios based on climate category for GHGs (AR6 GWP-100) and CO_2. The IMPs are also indicated

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Box 3.3 The likelihood of high-end emission scenarios

At the time the Representative Concentration Pathways (RCPs) were published, they included 3 scenarios that could represent emission developments in the absence of climate policy: RCP4.5, RCP6 and RCP8.5, described as, respectively, low, medium and high-end scenarios in the absence of strong climate policy (van Vuuren et al. 2011). RCP8.5 was described as representative of the top 5% scenarios in the literature. The SSPs-based set of scenarios covered the RCP forcing levels adding a new low scenario (at 1.9 W/m2). Hausfather and Peters (2020) pointed out that since 2011, the rapid development of renewable energy technologies and emerging climate policy have made it considerably less likely that emissions could end up as high as RCP8.5. Still, emission trends in developing countries track RCP8.5 Pedersen et al. (2020), and high land-use emissions could imply that emissions would continue to do so in the future, even at the global scale (Schwalm et al. 2020). Other factors resulting in high emissions include higher population or economic growth as included in the SSPs (see subsection 3.3.1) or rapid development of new energy services. Climate projections of RCP8.5 can also result from strong feedbacks of climate change on (natural) emission sources and high climate sensitivity (see WGI Chapter 7), and therefore their median climate impacts might also materialise while following a lower emission path (e.g., Hausfather and Betts (2020)). The discussion also relates to a more fundamental discussion on assigning likelihoods to scenarios, which is extremely difficult given the deep uncertainty and direct relationship with human choice. However, it would help to appreciate certain projections (e.g., Ho et al. (2019)). All-in-all, this means that high-end scenarios have become considerably less likely since AR5 but cannot be ruled out. It is important to realize that RCP8.5 and SSP5-8.5 do not represent a typical ‘business-as-usual projection but are only useful as high-end, high-risk scenarios. Reference emission scenarios (without additional climate policy) typically end up in C5-C7 categories included in this assessment.

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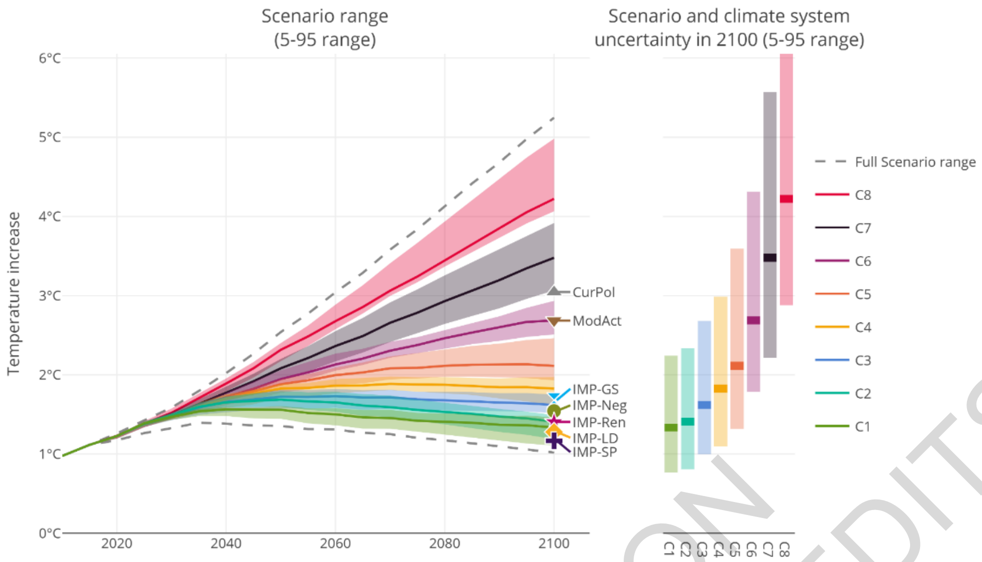

Figure 3.11: Global mean temperature outcome of the ensemble of scenarios included in the climate categories C1-C7 (based on RCM calibrated to the WGI assessment, both in terms of future and historic warming). The left panel shows the ranges of scenario uncertainty (shaded area) with the P50 RCM probability (line). The right panel shows the P5 to P95 range of RCM climate uncertainty (C1-C7 is explained in Table 3.1) and the P50 (line) and P66 (dashed line).

Figure 3.11 shows the possible consequences of the different scenario categories for global mean temperature calculated using a reduced complexity model calibrated to the IPCC WGI assessment (see Annex III and WGI report). For the C5-C7 categories (containing most of the reference and current policy scenarios), the global mean temperature is expected to increase throughout the century (and further increase will happen after 2100 for C6 and C7). While warming would likely be in the range from 2.2-3.8 ˚C – warming above 5˚C cannot be excluded. The highest emissions scenarios in the literature combine assumptions about rapid long-term economic growth and pervasive climate policy failures, leading to a reversal of some recent trends (see box 3.3). For the categories C1-C4, a peak in global mean temperature is reached mid-century for most scenarios in the database, followed by a small (C3/C4) or more considerable decline (C1/C2). There is a clear distinction between the scenarios with no or limited overshoot (typically <0.1 ˚C, C1) compared to those with high overshoot (C2): in emissions, the C1 category is characterised by steep early reductions and a relatively small contribution of net negative emissions (like ***LD*** and ***Ren***) (Figure 3.10). In addition to the temperature caused by the range of scenarios in each category (main panel), also climate uncertainties contribute to a range of temperature outcomes (including uncertainties regarding the carbon cycle, climate sensitivity, and the rate of change, see WGI). The bars on the right of Figure 3.11 show the uncertainty range for each category (combining scenario and uncertainty). While the C1 category more likely than not leads to warming below 1.5 ˚C by the end of the century, even with such a scenario, warming above 2ºC cannot be excluded (95th percentile). The uncertainty range for the highest emission categories (C7) implies that these scenarios could lead to a warming above 6ºC.

3.3.2.2 The role of carbon dioxide and other greenhouse gases

The trajectory of future CO_2 emissions plays a critical role in mitigation, given CO_2 long-term impact and dominance in total greenhouse gas forcing. As shown in Figure 3.12, CO_2 dominates total greenhouse gas emissions in the high emissions scenarios but is also reduced most, going from scenarios in the highest to lower categories. In C4 and below, most scenarios exhibit net negative CO_2 emissions in the second half of the century compensating for some of the residual emissions of non-CO_2 gases as well as reducing overall warming from an intermediate peak. Still, early emission reductions and further reductions in non-CO_2 emissions can also lead to scenarios without net negative emissions in 2100, even in C1 and C3 (shown for the 85-95th percentile). In C1, avoidance of significant overshoot implies that immediate gross reductions are more relevant than long-term net negative emissions (explaining the lower number than in C2) but carbon dioxide removal is still playing a role in compensating for remaining positive emissions in hard-to-abate sectors.

Figure 3.12 Upper left: The role of CO_2 and other greenhouse gases. Emission in CO_2-eq in 2100 (using AR6 GWP-100) (other = halogenated gases) and upper right: Cumulative CO_2 emissions in the 2020-2100 period. The lower left and right panel show the development of CH4 and N2O emissions over time. Energy emissions include the contribution of BECCS. For both energy and AFOLU sectors, the positive and negative values represent the cumulated annual balances. In both panels, the three bars per scenario category represent the lowest 5-15th percentile, the average value and the highest 5-15th percentile. These illustrate the range of scenarios in each category. The definition of C1-C7 can be found in Table 3.1

CH_4 and N_2O emissions are also reduced from C7 to C1, but this mostly occurs between C7 and C5. The main reason is the characteristics of abatement potential: technical measures can significantly reduce CH_4 and N_2O emissions at relatively low costs to about 50% of the current levels (e.g., by reducing CH_4 leaks from fossil fuel production and transport, reducing landfill emissions gazing, land management and introducing measure related to manure management, see also Chapter 7 and 11). However, technical potential estimates becomes exhausted even if the stringency of mitigation is increased (Harmsen et al. 2019a,b; Höglund-Isaksson et al. 2020). Therefore, further reduction may come from changes in activity levels, such as switching to a less meat-intensive diet reducing livestock (Stehfest et al. 2009; Willett et al. 2019; Ivanova et al. 2020) (see also Chapter 7). Other non-CO_2 GHG emissions (halogenated gases) are reduced to low levels for scenarios below 2.5°C.

Short-lived climate forcers (SLCFs) also play an important role in climate change, certainly for short-term changes (see Figure SPM.2, WGI) (Shindell et al. 2012). These forcers consist of 1) substances contributing to warming, such as methane, black carbon and tropospheric ozone and 2) substances contributing to cooling (other aerosols, such as related to sulphur emissions). Most SLCFs are also air pollutants, and reducing their emissions provides additional co-benefits (Shindell et al. 2017a,b; Hanaoka and Masui 2020). In the case of the first group, emission reduction thus leads to both air pollution and climate benefits. For the second, group there is a possible trade-off (Shindell and Smith 2019; Lund et al. 2020). As aerosol emissions are mostly associated with fossil fuel combustion, the benefits of reducing CO_2 could, in the short term, be reduced as a result of lower aerosol cooling. There has been an active discussion on the exact climate contribution of SLCF focused policies in the literature. This discussion partly emerged from different assumptions on possible reductions in the absence of ambitious climate policy and the uncertain global climate benefit from aerosol (black carbon) (Rogelj et al. 2014). The latter is now assessed to be smaller than originally thought (Smith et al. 2020b; Takemura and Suzuki 2019) (see also WGI Chapter 6, Section 6.4). Reducing SLCF emissions is critical to meet long-term climate goals and might help reduce the rate of climate change in the short term. Deep SLCF emission reductions also increase the remaining carbon budget for a specific temperature goal (Rogelj et al. 2015a; Reisinger et al. 2021) (see Box 3.4). A more detailed discussion can be found in WGI Chapter 5 and 6.

For accounting of emissions and the substitution of different gases as part of a mitigation strategy, typically, emission metrics are used to compare the climate impact of different gases. Most policies currently use Global Warming Potentials with a 100-year time horizon as this is also mandated for emissions reporting in the Paris Rulebook (for a wider discussion of GHG metrics, see Box 2.2 in Chapter 2 and WGI, Chapter 7, Section 7.6). Alternative metrics have also been proposed, such as those using a shorter or longer time horizon or those that focus directly on the consequences of reaching a certain temperature target (Global Temperature Change Potential, GTP), allowing a more direct comparison with cumulative CO_2 emissions (Allen et al. 2016; Lynch et al. 2020) or focusing on damages (Global Damage Potential) (an overview is given in Chapter 2, and Cross-Chapter Box 3). Depending on the metric, the value attributed to reducing short-lived forcers like methane can be lower in the near term (e.g., in the case of GTP) or higher (GWP with short reference period). For most metrics, however, the impact on mitigation strategies is relatively small, among others, due to the marginal abatement cost curve of methane (low costs for low to medium mitigation levels; expensive for high levels). The timing of reductions across different gases impacts warming and the co-benefits (Harmsen et al. 2016; Cain et al. 2019). Nearly all scenarios in the literature use GWP-100 in cost-optimisation, reflecting the existing policy approach; the use of GWP-100 deviates from cost-optimal mitigation pathways by at most a few percent for temperature goals of likely below 2°C and lower (see Box 2.2 in Chapter 2).

Cumulative CO_2 emissions and temperature goals

The dominating role of CO_2 and its long lifetime in the atmosphere and some critical characteristics of the earth system implies that there is a strong relationship between cumulative CO_2 emissions and temperature outcomes (MacDougall and Friedlingstein 2015; Meinshausen et al. 2009; Allen et al. 2009; Matthews et al. 2009). This is illustrated in Figure 3.13 that plots the cumulative CO_2 emissions against the projected outcome for global mean temperature, both until a temperature peak and full century. The deviations from in linear relationship in Figure 3.13 are mostly caused by different non-CO_2 emission and forcing levels (see also Rogelj et al. (2015b)). This means that reducing non-CO_2 emissions can play an important role in limiting peak warming: the smaller the residual non-CO2 warming, the larger the carbon budget. This impact on carbon budgets can be substantial for stringent warming limits. For 1.5°C pathways, variations in non-CO_2 warming across different emission scenarios have been found to vary the remaining carbon budget by approximately 220 $GtCO_2$ (see WGI Chapter 5, Subsection 5.5.2.2). In addition to reaching net zero CO_2 emissions, a strong reduction in methane emissions is the most critical component in non-CO_2 mitigation to keep the Paris climate goals in reach (van Vuuren et al. 2018; Collins et al. 2018) (see also WGI, Chapter 5, 6 and 7). It should be noted that the temperature categories (C1-C7) generally aligned with the horizontal axis, except for the end-of-century values for C1 and C2 that coincide.

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Box 3.4 Consistency of remaining carbon budgets in the WGI assessment and cumulative CO_2 emissions in WGIII mitigation pathways

Introduction

The WGI assessment has shown that the increase in global mean temperature has a near-linear relationship with cumulative CO_2 emissions (Chapter 5, Section 5.5, Box 5.3). Consistently, WGI has confirmed that net zero CO_2 emissions are required to halt CO_2-induced warming. This permits the estimation of carbon budgets consistent with specific temperature goals. In Chapter 3, we present the temperature outcomes and cumulative CO_2 emissions associated with different warming levels for around 1200 scenarios published in the literature and which were classified according to different warming levels (see Section 3.2 and Annex III, Part II.2.5). In this box, we discuss the consistency of the assessments presented here and in IPCC WGI. The box summarises how the remaining carbon budgets assessed by WGI relate to the remaining cumulative CO_2 emissions until the time of net zero CO_2 emissions in mitigation pathways (Table 3.2, Table SPM1) assessed by WGIII.

In its assessment, WGI uses a framework in which the various components of the remaining carbon budget are informed by various lines of evidence and assessed climate system characteristics. WGIII, instead, uses around 1200 emission scenarios with estimated warming levels that cover the scenario range presented in WGI but also contain many more intermediate projections with varying emission profiles and a combination of CO_2 emissions and other greenhouse gases. In order to assess their climate outcomes, climate model emulators are used. The emulators are reduced complexity climate models that are provided by WGI, and which are calibrated to the WGI assessment of future warming for various purposes (a detailed description of the use of climate model emulators in the WGI and WGIII assessments can be found in Cross-chapter Box 7.1 in the WGI report, with the connection of WGI and WGII discussed in Annex III.2.5.1).

Remaining carbon budgets estimated by WGI

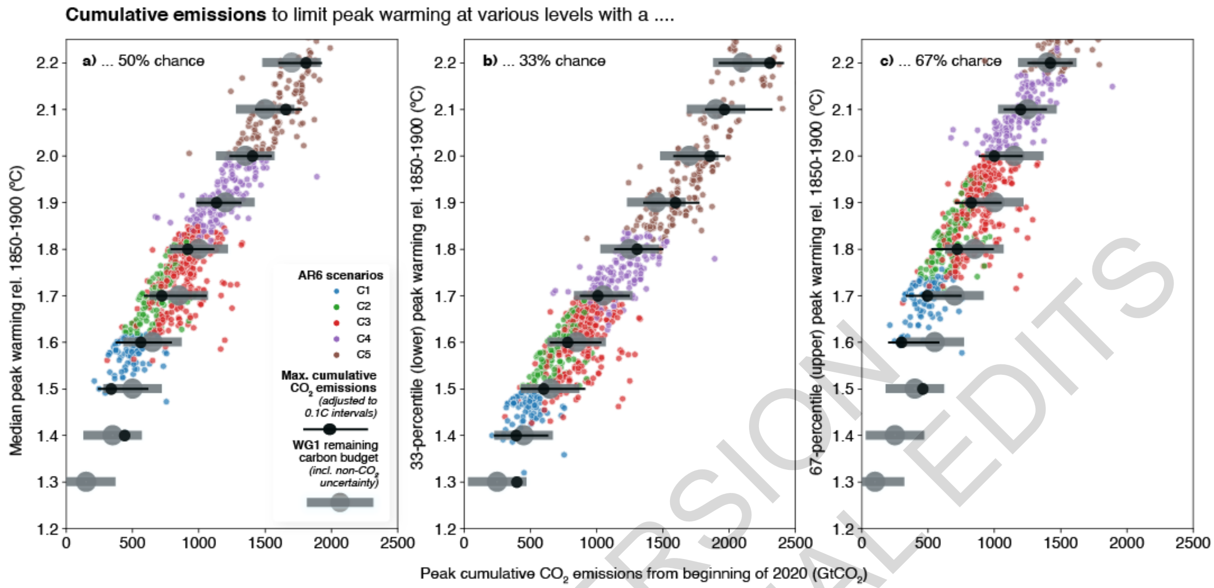
WGI estimated the remaining carbon budgets from their assessment of (i) the transient climate response to cumulative emissions of carbon dioxide (TCRE), and estimates of (ii) the historical human-induced warming, (iii) the temperature change after reaching net zero CO_2 emissions, (iv) the contribution of future non-CO_2 warming (derived from the emissions scenarios assessed in the Special Report on 1.5°C Warming using WGI-calibrated emulators), and (v) the earth system feedbacks (WGI Chapter 5.5, Box 5.2). For a given warming level, WGI assessed the remaining carbon budget from the beginning of 2020 onwards. These are 650 / 500 / 400 $GtCO_2$ for limiting warming to 1.5°C with 33% / 50% / 67% chance and 1350 / 1150 $GtCO_2$ for limiting warming to 2°C with 50% / 67% chance. The estimates are subject to considerable uncertainty related to historical warming, future non-CO_2 forcing, and poorly quantified climate feedbacks. For instance, variation in non-CO_2 emissions across scenarios are estimated to either increase or decrease the remaining carbon budget estimates by 220 $GtCO_2$. The estimates of the remaining carbon budget assume that non-CO_2 emissions are reduced consistently with the tight temperature targets for which the budgets are estimated.

Cumulative CO_2 emissions until net zero estimated by WGIII

WGIII provides estimates of cumulative net CO_2 emissions (from 2020 inclusive) until the time of reaching net zero CO_2 emissions (henceforth called "peak cumulative CO_2 emissions") and until the end of the century for eight temperature classes that span a range of warming levels. The numbers can be found in Table 3.2 (330-710 $GtCO_2$ for C1; 540-930 for C2 and 640-1160 for C3).

Comparing the WGI remaining carbon budgets and remaining cumulative CO_2 emissions of the WGIII scenarios

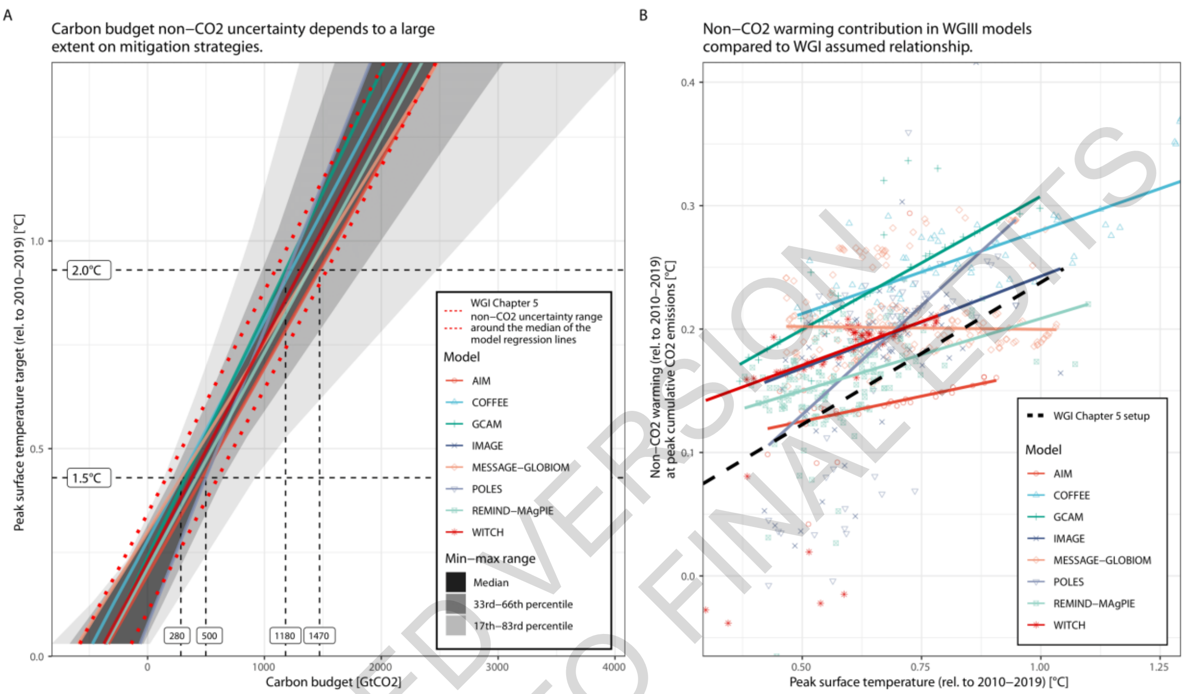
A comparison between WGI and WGIII findings requires recognising that, unlike in WGI, cumulative emissions in WGIII are not provided for a specific peak warming threshold or level but are instead provided for a set of scenarios in a category, representing a specific range of peak temperature outcomes (for instance the C4 category contains scenarios with a median peak warming anywhere between approximately 1.8°C and up to 2°C). When accounting for this difference, the WGI and WGIII findings are very consistent for temperature levels below 2ºC. Figure 1 compares the peak temperatures and associated cumulative CO_2 emissions (i.e., peak cumulative CO_2 emissions) for the WGIII scenarios to the remaining carbon budgets assessed by WGI. This shows only minor differences between the WGI and WGIII approaches.



Box 3.4 Figure 1: Cumulative CO_2 emissions from AR6 scenario categories (coloured dots), adjusted for distinct 0.1°C warming levels (black bars) in comparison to the WGI remaining carbon budgets (grey bars). The cumulative carbon emissions for the AR6 scenarios are shown for the median peak warming (panel a), the 33rd-percentile peak warming (panel b) and the upper 67th-percentile peak warming (panel c) calculated with the WGI-calibrated emulator MAGICC7 (IPCC AR6 WGI, Cross-Chapter Box 7.1). The adjustment to the nearest 0.1°C intervals is made using WGI TCRE (at the relevant percentile, e.g., the 67th-percentile TCRE is used to adjust the 67th-percentile peak warming), with the 5% to 95% range of adjusted scenarios provided by the black bar. The WGI remaining carbon budget is shown, including the WGI estimate of at least a ±220 GtCO2 uncertainty due to non-CO_2 emissions variations across scenarios (grey bars). For median peak warming (panel a) projections below 2°C relative to 1850-1900, the WGIII assessment of cumulative carbon emissions tends to be slightly smaller than the remaining carbon budgets provided by WGI but well within the uncertainties. Note that only a few scenarios in WGIII limit warming to below 1.5°C with a 50% chance, thus statistics for that specific threshold have low confidence.

After correcting for the categorisation, some (small) differences between the WGI and WGIII numbers arise from remaining differences between the outcomes of the climate emulators and their set-up (see Cross-Chapter Box 7.1 in IPCC WGI AR6) and the differences in the underlying scenarios. Moreover, the WGI assessment estimated the non-CO_2 warming at the time of net zero CO_2 emissions based on a relationship derived from the SR1.5 scenario database with historical emission estimates as in Meinshausen et al. (2020) (WGI chapter 5). The WGIII assessment uses the same climate emulator with improved historical emissions estimates (Nicholls et al. 2021) (WGI Cross-Chapter Box 7.1). Annex III.2.5.1 further explores the effects of these factors on the relationship between non-CO_2 warming at peak cumulative CO_2 and peak surface temperature.

Estimates of the remaining carbon budgets thus vary with the assumed level of non-CO_2 emissions, which are a function of policies and technology development. The linear relationship used in the WGI assessment between peak temperature and the warming as a result of non-CO_2 emissions (based on the SR1.5 data) is shown in the right panel of Figure 2 (dashed line). In the WG3 approach, the non-CO_2 warming for each single scenario is based on the individual scenario characteristics. This shown in the same figure by plotting the outcomes of scenario outcomes of a range models (dots). The lines show the fitted data for individual models, emphasizing the clear differences across models and the relationship with peak warming (policy level). In some scenarios stringent non-CO_2 emission reductions provide an option to reach more stringent climate goals with the same carbon budget. This is especially the case for scenarios with a very low non-CO_2 warming, for instance as a result of methane reductions through diet change. The left panel shows how these differences impact estimates of the remaining carbon budget. While the WGIII AR6 scenario database includes a broad range of non-CO_2 emission projections the overall range is still very consistent with the WGI relationship and the estimated uncertainty with a ±220 $GtCO_2$ range (see also panel B of Figure II.2 in Annex III.2.5).



Box 3.4 Figure 2: Panel A) Differences in regressions of the relationship between peak surface temperature and associated cumulative CO_2 emissions from 2020 derived from scenarios of eight integrated assessment model frameworks. The coloured lines show the regression at median for scenarios of the 8 modelling frameworks, each with more than 20 scenarios in the database and a detailed land-use representation. The red dotted lines indicate the non-CO_2 uncertainty range of WGI Chapter 5 (± 220 GtCO2), here visualised around the median of the 8 model framework lines. Carbon budgets from 2020 until 1.5C (0.43K above 2010-2019 levels) and 2.0C (0.93K above 2010-2019 levels) are shown for minimum and maximum model estimates at the median, rounded to the nearest 10$GtCO_2$. Panel B) Shows the relationship between the estimated non-CO2 warming in mitigation scenarios that reach net zero and the associated peak surface temperature outcomes. The coloured lines show the regression at median for scenarios of the 8 modelling frameworks with more than 20 scenarios in the database and a detailed land-use representation. The black dashed line indicates the non-CO2 relationship based on the scenarios and climate emulator setup as was assessed in WGI Chapter 5.

Overall, the slight differences between the cumulative emissions in WGIII and the carbon budget in WGI are because the non-CO_2 warming in the WGIII AR6 scenarios is slightly lower than in the SR1.5 scenarios that are used for the budget estimates in WGI (Annex III.2.5.1). In addition, improved consistency with Cross-Chapter Box 7.1 in WGI results in a non-CO2 induced temperature difference of about ~0.05K between the assessments. Re-calculating the remaining carbon budget using the WGI methodology combined with the full WGIII AR6 scenario database results in a reduction of the estimated remaining 1.5C carbon budget by about 100 $GtCO_2$ (-20%), and a reduction of ~40 $GtCO_2$ (-3%) for 2C. Accounting also for the categorisation effect, the difference between the WGI and WGIII estimates is found to be small and well within the uncertainty range (Figure 1). This means that the cumulative CO_2 emissions presented in WGIII and the WGI carbon budgets are highly consistent.

A detailed comparison of the impact of different assessment steps, i.e., the new emulators, scenarios, and harmonisation methods, has been made and is presented in Annex III.

Policy implications

The concept of a finite carbon budget means that the world needs to get to net zero CO_2, no matter whether global warming is limited to 1.5°C or well below 2°C (or any other level). Moreover, exceeding the remaining carbon budget will have consequences by overshooting temperature levels. Still, the relationship between the timing of net zero and temperature targets is a flexible one, as discussed further in Cross-Chapter Box 3. It should be noted that national level inventory as used by UNFCCC for the land use, land-use change and forestry sector are different from the overall concept of anthropogenic emissions employed by IPCC WG1. For emissions estimates based on these inventories, the remaining carbon budgets must be correspondingly reduced by approximately 15%, depending on the scenarios (Grassi et al., 2021) (see also Chapter 7).

One of the uncertainties of the remaining carbon budget is the level of non-CO_2 emissions which is a function of policies and technology development. This represents a point of leverage for policies rather than an inherent geophysical uncertainty. Stringent non-CO_2 emission reductions hence can provide – to some degree – an option to reach more stringent climate goals with the same carbon budget.

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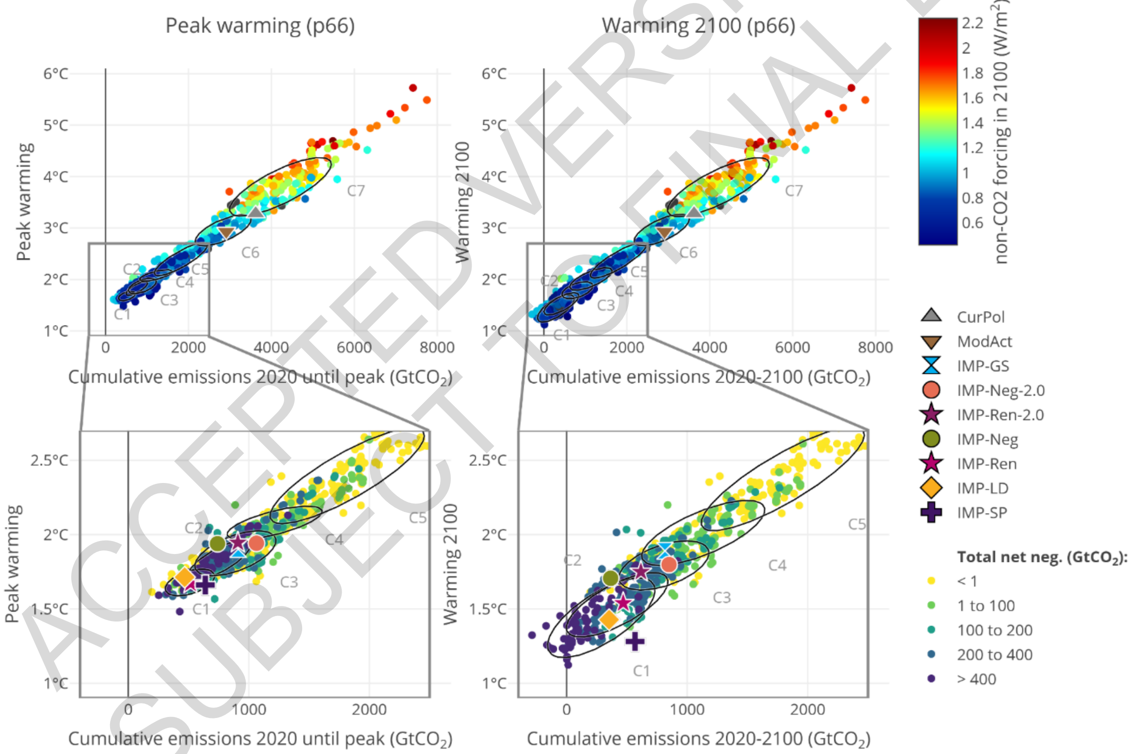

Figure 3.13: The near-linear relationship between cumulative CO_2 emissions and temperature. The left panel shows cumulative emissions until net zero emission is reached. The right panel shows cumulative emissions until the end of the century, plotted against peak and end-of-century temperature, respectively. Both are shown as a function of non-CO_2 forcing and cumulative net negative CO_2 emissions. Position temperature categories (circles) and IPs are also indicated, including two 2°C sensitivity cases for *Neg* (Neg-2.0) and *Ren* (Ren-2.0).

The near-linear relationship implies that cumulative CO_2 emissions are critically important for climate outcomes (Collins et al. 2013). The maximum temperature increase is a direct function of the cumulative emissions until net zero CO_2 emissions is reached (the emission budget) (Figure 3.13, left side). The end-of-century temperature correlates well with cumulative emissions across the century (right panel). For long-term climate goals, positive emissions in the first half of the century can be offset by net removal of CO_2 from the atmosphere (net negative emissions) at the cost of a temporary overshoot of the target (Tokarska et al. 2019). The bottom panels of Figure 3.13 show the contribution of net negative CO_2 emissions.

Focusing on cumulative emissions, the right-hand panel of Figure 3.12 shows that for high-end scenarios (C6-C7), most emissions originate from fossil fuels, with a smaller contribution from net deforestation. For C5 and lower, there is also a negative contribution to emissions from both AFOLU emissions and energy systems. For the energy systems, these negative emissions originate from bio-energy-and-carbon-capture-and-storage (BECCS), while for AFOLU, they originate from re- and afforestation. For C3-C5, reforestation has a larger CDR contribution than BECCS, mostly due to considerably lower costs (Rochedo et al. 2018). For C1 and C2, the tight carbon budgets imply in many scenarios more CDR use (Riahi et al. 2021). Please note that net negative emissions are not so relevant for peak temperature targets, and thus the C1 category, but CDR can still be used to offset the remaining positive emissions (Riahi et al. 2021). While positive CO_2 emissions from fossil fuels are significantly reduced, inertia and hard-to-abate sectors imply that in many C1-C3 scenarios, around 800-1000 $GtCO_2$ of net positive cumulative CO_2 emissions remain. This is consistent with literature estimates that current infrastructure is associated with 650 $GtCO_2$ (best estimate) if operated until the end of its lifetime (Tong et al. 2019). These numbers are considerably above the estimated carbon budgets for 1.5 °C estimated in WGI, hence explaining CDR reliance (either to offset emissions immediately or later in time).

Creating net negative emissions can thus be an important part of a mitigation strategy to offset remaining emissions or compensate for emissions earlier in time. As indicated above, there are different ways to potentially achieve this, including re- and afforestation and BECCS (as often covered in IAMs) but also soil carbon enhancement, direct air carbon capture and storage (DACCS) and ocean alkalinization (see Chapter 12). Except for reforestation, these options have not been tested at large scale and often require more R&D. Moreover, the reliance on CDR in scenarios has been discussed given possible consequences of land use related to biodiversity loss and food security (BECCS and afforestation), the reliance on uncertain storage potentials (BECCS and DACCS), water use (BECCS), energy use (DACCS), the risks of possible temperature overshoot and the consequences for meeting sustainable development goals (Venton 2016; Peters and Geden 2017; Smith et al. 2016; van Vuuren et al. 2017; Anderson and Peters 2016; Honegger et al. 2021). In the case of BECCS, it should be noted that bio-energy typically is associated with early-on positive CO_2 emissions and net-negative effects are only achieved in time (carbon debt), and its potential is limited (Cherubini et al. 2013; Hanssen et al. 2020) (most IAMs have only a very limited representation of these time dynamics). Several scenarios have therefore explored how reliance on net negative CO_2 emissions can be reduced or even avoided by alternative emission strategies (Grubler et al. 2018; van Vuuren et al. 2018) or early reductions by more stringent emission reduction in the short-term (Rogelj et al. 2019b; Riahi et al. 2021). A more in-depth discussion of land-based mitigation options can be found in Chapter 7. It needs to be emphasized that even in strategies with net negative CO_2 emissions, the emission reduction via more conventional mitigation measures (efficiency improvement, decarbonisation of energy supply) is much larger than the CDR contribution (Tsutsui et al. 2020).

3.3.2.3 The timing of net zero emissions

In addition to the constraints on change in global mean temperature, the Paris Agreement also calls for reaching a balance of sources and sinks of GHG emissions (Art. 4). Different interpretations of the concept related to balance have been published (Rogelj et al. 2015c; Fuglestvedt et al. 2018). Key concepts include that of net zero CO_2 emissions (anthropogenic CO_2 sources and sinks equal zero) and net zero greenhouse gas emission (see also Annex I Glossary and Box 3.3). The same notion can be used for all GHG emissions, but here ranges also depend on the use of equivalence metrics (Chapter 2, Box 2.2). Moreover, it should be noted that while reaching net zero CO_2 emissions typically coincides with the peak in temperature increase; net zero GHG emissions (based on GWP-100) implies a decrease in global temperature (Riahi et al. 2021) and net zero GHG emission typically requires negative CO_2 emissions to compensate for the remaining emissions from other GHGs. Many countries have started to formulate climate policy in the year that net zero emissions (either CO_2 or all greenhouse gases) are reached – although, at the moment, formulations are often still vague (Rogelj et al. 2021). There has been increased attention on the timing of net zero emissions in the scientific literature and ways to achieve it.

Figure 3.14 shows that there is a relationship between the temperature target, the cumulative CO_2 emissions budget, and the net zero year for CO_2 emissions (left) and the sum of greenhouse gases (right) for the scenarios published in the literature. In other words, the temperature targets from the Paris Agreement can, to some degree, be translated into a net zero emission year (Tanaka and O'Neill 2018). There is, however, a considerable spread. In addition to the factors influencing the emission budget (see WGI and section 3.3.2.2), this is influenced by the emission trajectory until net zero is reached, decisions related to temperature overshoot and non-CO_2 emissions (especially for the moment CO_2 reaches net zero emissions). Scenarios with limited or no net negative emissions and rapid near-term emission reductions can allow small positive emissions (e.g., in hard-to-abate-sectors). They may therefore have a later year that net zero CO_2 emissions are achieved. High emissions in the short-term, in contrast, require an early net zero year.

For the scenarios in the C1 category (warming below 1.5°C (50% probability) with limited overshoot), the net zero year for CO_2 emissions is typically around 2035-2070 For scenarios in C3 (likely limiting warming to below 2°C), CO_2 emissions reach net zero around 2060-2100. Similarly, also the years for net zero GHG emissions can be calculated (see right graph). The GHG net zero emissions year is typically around 10-20 years later than the carbon neutrality. Residual non-CO_2 emissions at the time of reaching net zero CO_2 range between 4-11 $GtCO_2$-eq in pathways that *likely* limit warming to 2.0°C or below. In pathways likely limiting warming to 2°C, methane is reduced by around 20% (1-46%) in 2030 and almost 50% (26-64%) in 2050, and in pathways limiting warming to 1.5°C with no or limited overshoot by around 33% (19-57) in 2030 and a similar 50% (33-69%) in 2050. Emissions reduction potentials assumed in the pathways become largely exhausted when limiting warming to below 2°C. N_2O emissions are reduced too, but similar to CH4, emission reductions saturate for stringent climate goals. In the mitigation pathways, the emissions of cooling aerosols are reduced due to reduced use of fossil fuels. The overall impact on non-CO_2-related warming combines these factors.
In cost-optimal scenarios, regions will mostly achieve net zero emissions as a function of options for emission reduction, CDR, and expected baseline emission growth (van Soest et al. 2021b). This typically implies relatively early net zero emission years in scenarios for the Latin America region and relatively late net zero years for Asia and Africa (and average values for OECD countries). However, an allocation based on equity principles (such as responsibility, capability and equality) might result in different carbon neutrality years, based on the principles applied – with often earlier net zero years for the OECD (Fyson et al. 2020; van Soest et al. 2021b). Therefore, the emission trajectory until net zero emissions is a critical determinant of future warming (see Section 3.5). The more CO_2 is emitted until 2030, the less CO_2 can be emitted after that to stay below a warming limit (Riahi et al. 2015). As discussed before, also non-CO_2 forcing plays a key role in the short term.

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Cross-Chapter Box 3: Understanding net zero CO_2 and net zero GHG emissions

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This cross-chapter box surveys scientific, technical and policy aspects of net zero carbon dioxide (CO_2) and net zero greenhouse gas (GHG) emissions, with a focus on timing, the relationship with warming levels, and sectoral and regional characteristics of net zero emissions. Assessment of net zero GHG emissions additionally requires consideration of non-CO_2 gases and choice of GHG emission metrics used to aggregate emissions and removals of different GHGs (Cross-Chapter Box 2 in Chapter 2; Cross-Chapter Box 7 in Chapter 10). The following considers net zero CO_2 and GHG emissions globally, followed by regional and sectoral dimensions.

Net zero CO_2

Reaching net zero CO_2 emissions globally is necessary for limiting global warming to any level. At the point of net zero CO_2, the amount of CO_2 human activity is putting into the atmosphere equals the amount of CO_2 human activity is removing from the atmosphere (see Glossary). Reaching and sustaining net zero CO_2 emissions globally stabilizes CO_2-induced warming. Reaching net zero CO_2 emissions and then moving to net negative CO_2 emissions globally leads to a peak and decline in CO_2-induced warming (WGI AR6 Chapter 5.5, 5.6).

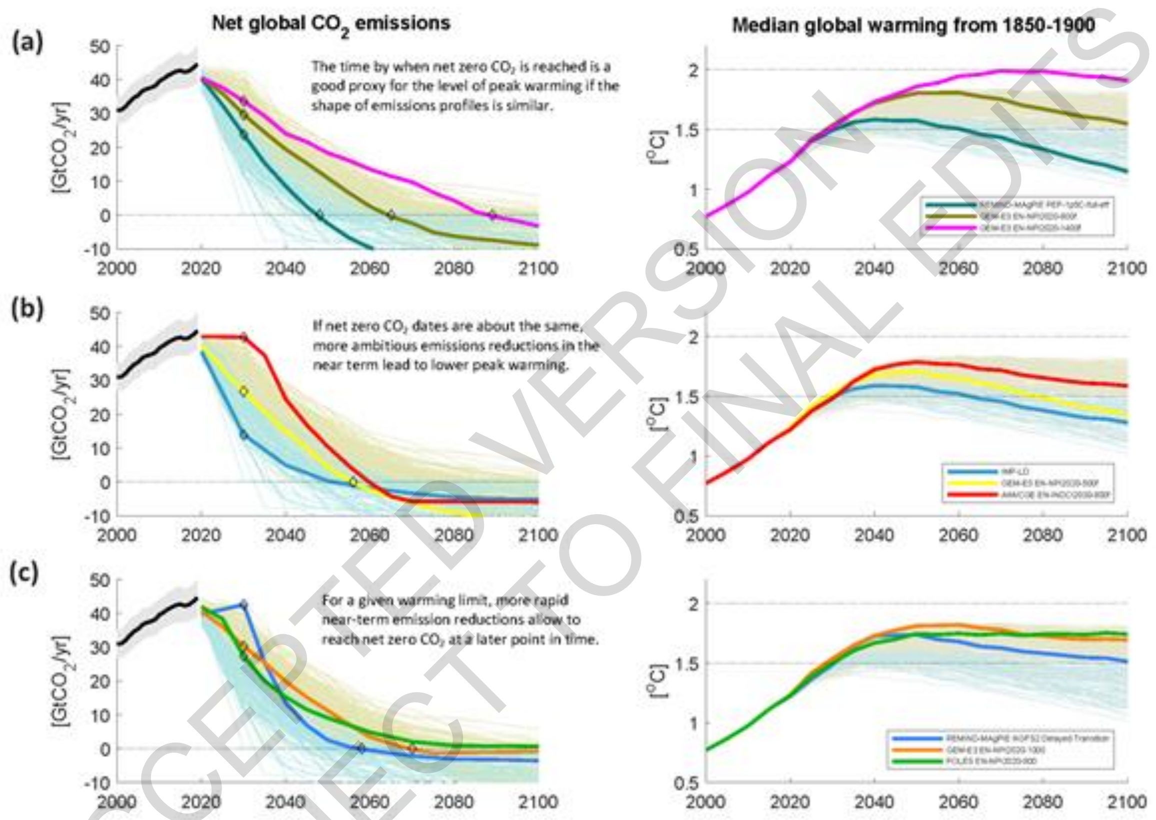
Limiting warming to 1.5°C or *likely* to 2°C requires deep, rapid, and sustained reductions of other greenhouse gases including methane alongside rapid reductions of CO_2 emissions to net zero. This ensures that the warming contributions from non-CO_2 forcing agents as well as from CO_2 emissions are both limited at low levels. WGI estimated remaining carbon budgets until the time of reaching net zero CO_2 emissions for a range of warming limits, taking into account historical CO_2 emissions and projections of the warming from non-CO_2 forcing agents (WGI AR6 Chapter 5.5, Cross-chapter box 3).

The earlier global net zero CO_2 emissions are reached, the lower the cumulative net amount of CO_2 emissions and human-induced global warming, all else being equal (Figure 1a in this Box)**.** For a given net zero date, a variation in the shape of the CO_2 emissions profile can lead to a variation in the cumulative net amount of CO_2 emissions until the time of net zero CO_2 and as a result to different peak warming levels. For example, cumulative net CO_2 emissions until the time of reaching net zero CO_2 will be smaller, and peak warming lower, if emissions are reduced steeply and then more slowly compared to reducing emissions slowly and then more steeply (Figure 1b in this Box).

Net zero CO_2 emissions are reached between 2050-2055 (2035-2070) in global emissions pathways limiting warming to 1.5°C with no or limited overshoot, and between 2070-2075 (2060-…) in pathways *likely* limiting warming to 2°C as reported in the AR6 scenario database (median five-year interval and 5^{th}-95^{th} percentile ranges)[3]. The variation of non-CO_2 emissions in 1.5-2°C pathways varies the available remaining carbon budget which can move the time of reaching net zero CO_2 in these pathways forward or backward[4]. The shape of the CO_2 emissions reduction profile

FOOTNOTE [3] A small fraction of pathways in the AR6 scenarios database that likely limit warming to 2°C (9%) or are as likely as not to limit warming to 2°C (14%) do not reach net-zero CO_2 emissions during the 21st century. This is not inconsistent with the fundamental scientific requirement to reach net-zero CO_2 emissions for a stable climate, but reflects that in some pathways, concurrent reductions in non-CO_2 emissions temporarily compensate for on-going warming from CO_2 emissions. These would have to reach net-zero CO_2 emissions eventually after 2100 to maintain these warming limits. For the two classes of pathways, the 95th percentile cannot be deduced from the scenario database as more than 5% of them do not reach net zero CO2 by 2100.

FOOTNOTE [4] WGI Chapter 5.5 estimates a variation of the remaining carbon budget by ± 220 $GtCO_2$ due to variations of the non-CO_2 warming contribution in 1.5-2°C pathways. This translates to a shift of the timing of also affects the time of reaching net zero CO_2 (Figure 1c in this Box). Global emission pathways that more than halve CO_2 emissions from 2020 to 2030 can follow this rapid reduction by a more gradual decline towards net zero CO_2 and still limit warming to 1.5°C with no or limited overshoot, reaching the point of net zero after 2050. The literature since SR1.5 included a larger fraction of such pathways than were available at the time of SR1.5. This is the primary reason for the small backward shift in the median estimate of reaching global net zero CO_2 emissions in 1.5°C pathways collected in the AR6 scenario database compared to SR1.5. This does not mean that the world is assessed to have more time to rapidly reduce current emissions levels compared to SR1.5. The assessment of emissions reductions by 2030 and 2040 in pathways limiting warming to 1.5°C with no or limited overshoot has not changed substantially. It only means that the exact timing of reaching net zero CO_2 after a steep decline of CO_2 emissions until 2030 and 2040 can show some variation, and the SR1.5 median value of 2050 is still close to the middle of the current range (Figure 1c in this Box).



Cross-Chapter Box 3 Figure 1: Selected global CO_2 emissions trajectories with similar shape and different net zero CO_2 date (Panel a), different shape and similar net zero CO_2 date (Panel b), and similar peak warming, but varying shapes and net zero CO_2 dates (Panel c). Funnels show pathways limiting warming to 1.5°C with no or limited overshoot (light blue) and likely limiting warming to 2°C (beige). Historic CO_2 emissions from Chapter 2.2 (EDGAR v6).

Pathways coinciding with emissions levels projected from the implementation of current NDCs would result in substantially (>0.1°C) exceeding 1.5°C. They would have to reach net zero CO_2

net zero CO_2 by about ±10 years, assuming global CO_2 emissions decrease linearly from current levels of around 40 $GtCO_2$ to net zero.

around 5-10 years later[5] than in pathways with no or limited overshoot in order to reach the net negative emissions that would then be required to return warming to 1.5°C by 2100. Those high overshoot pathways have higher transient warming and higher reliance on net-negative CO_2 emissions towards the end of the 21st century. As they need to reach net zero CO_2 only a few years later, with 2030 CO_2 emission levels being around twice as high, they imply post-2030 CO_2 emissions reduction rates that are almost double that of pathways limiting warming to 1.5°C with no or limited overshoot (Section 3.5).

Pathways following emissions levels projected from the implementation of current NDCs until 2030 would have to reach net zero CO_2 around 10 years earlier[6] than cost-effective pathways to likely limit warming to 2°C. While cost-effective pathways take around 50-55 years to reach net zero CO_2 emissions, those pathways would only have 35-40 years left for transitioning to net zero CO_2 from 2030 onwards, close to the transition times that 1.5°C pathways are faced with today. Current CO_2 emissions and 2030 emission levels projected under the current NDCs are in a similar range**.** (3.5, 4.2)

Net zero GHG emissions

The amount of CO_2-equivalent emissions and the point when net zero GHG emissions are reached in multi-GHG emissions pathways depends on the choice of GHG emissions metric. Various GHG emission metrics are available for this purpose[7]. GWP100 is the most commonly used metric for reporting CO_2-equivalent emissions and is required for emissions reporting under the Rulebook of the Paris Agreement. (Cross-Chapter Box 2 in Chapter 2, Annex II section 9, Annex I)

For most choices of GHG emissions metric, reaching net zero GHG emissions requires net negative CO_2 emissions in order to balance residual CH_4, N_2O and F-gas emissions. Under foreseen technology developments, some CH_4, N_2O and F-gas emissions from, e.g., agriculture and industry will remain over the course of this century. Net negative CO_2 emissions will therefore be needed to balance these remaining non-CO_2 GHG emissions to obtain net zero GHG emissions at a point in time after net zero CO_2 has been reached in emissions pathways. Both the amount of net negative CO_2 emissions and the time lag to reaching net zero GHG depend on the choice of GHG emission metric.

Reaching net zero GHG emissions globally in terms of GWP100 leads to a reduction in global warming from an earlier peak. This is due to net negative CO_2 emissions balancing the GWP100-equivalent emissions of short lived GHG emissions, which by themselves do not contribute to further warming if sufficiently declining (Fuglestvedt et al. 2018; Rogelj et al. 2021). Hence, 1.5-2°C

FOOTNOTE [5] Pathways following emissions levels of current NDCs to 2030 and then returning median warming to below 1.5°C in 2100 reach net zero during 2055-2060 (2045-2070) (median five year interval and 5th-95th percentile range).

FOOTNOTE [6] Pathways that follow emission levels projected from the implementation of current NDCs until 2030 and that still likely limit warming to 2°C reach net zero CO2 emissions during 2065 - 2070 (2060 - ...) compared with 2075 - 2080 (2060 - …) in cost-effective pathways acting immediately to likely limit warming to 2°C (median five year interval and 5th-95th percentile range). See Footnote 1 for the lack of 95th percentile. (Chapter 3.3 Table 3.1.)

FOOTNOTE [7] Defining net zero GHG emissions for a basket of greenhouse gases (GHGs) relies on a metric to convert GHG emissions including methane (CH_4), nitrous oxide (N_2O), fluorinated gases (F-gases), and potentially other gases, to CO_2-equivalent emissions. The choice of metric ranges from Global Warming Potentials (GWPs) and Global Temperature change Potentials (GTP) to economically-oriented metrics. All metrics have advantages and disadvantages depending on the context in which they are used (Cross-Chapter Box 2 in Chapter 2).

emissions pathways in the AR6 scenario database that reach global net zero GHG emissions in the second half of the century show warming being halted at some peak value followed by a gradual decline towards the end of the century (WGI Chapter 1 Box 1.4).

Global net zero GHG emissions measured in terms of GWP100 are reached between 2095-2100 (2055 - ...)[8] in emission pathways limiting warming to 1.5°C with no or limited overshoot (median and 5th-95th percentile)**.** Around 50% of pathways limiting warming to 1.5°C with no or limited overshoot and 70% of pathways limiting likely warming to 2°C do not reach net zero GHG emissions in terms of GWP100 before 2100. These pathways tend to show less reduction in warming after the peak than pathways that reach net zero GHG emissions. For the subset of pathways that reach net zero GHG emissions before 2100, including 90% of pathways that return warming to 1.5°C by 2100 after a high (>0.1°C) overshoot, the time lag between reaching net zero CO2 and net zero GHG is 11-14 (6-40) years and the amount of net negative CO2 emissions deployed to balance non-CO2 emissions at the time of net zero is -6 to -7 (-10 to -4) GtCO2 (range of medians and lowest 5th to highest 95 percentile across the four scenario classes that limit median warming to 2°C or lower). (section 3.3, Table 3.1)

Sectoral and regional aspects of net zero

The timing of net zero CO_2 or GHG emissions may differ across regions and sectors. Achieving net zero emissions globally implies that some sectors and regions must reach net zero CO_2 or GHG ahead of the time of global net zero CO_2 or GHG if others reach it later. Similarly, some sectors and regions would need to achieve net negative CO_2 or GHG emissions to compensate for continued emissions by other sectors and regions after the global net zero year. Differences in the timing to reach net zero emissions between sectors and regions depend on multiple factors, including the potential of countries and sectors to reduce GHG emissions and undertake carbon dioxide removal, the associated costs, and the availability of policy mechanisms to balance emissions and removals between sectors and countries (Fyson et al. 2020; Strefler et al. 2021a; van Soest et al. 2021b). A lack of such mechanisms could lead to higher global costs to reach net zero emissions globally, but less interdependencies and institutional needs (Fajardy and Mac Dowell 2020). Sectors will reach net zero CO_2 and GHG emissions at different times if they are aiming for such targets with sector-specific policies or as part of an economy-wide net zero emissions strategy integrating emissions reductions and removals across sectors. In the latter case, sectors with large potential for achieving net-negative emissions would go beyond net zero to balance residual emissions from sectors with low potential which in turn would take more time compared to the case of sector-specific action. Global pathways project global AFOLU emissions to reach global net zero CO_2 the earliest, around 2030-2035 in pathways likely to limit warming to 2°C and below, by rapid reduction of deforestation and enhancing carbon sinks on land, although net zero GHG emissions from global AFOLU are typically reached 30 years later, if at all. The ability of global AFOLU CO_2 emissions to reach net zero as early as in the 2030s in modelled pathways hinges on optimistic assumptions about the ability to establish global cost-effective mechanisms to balance emissions reductions and removals across regions and sectors. These assumptions have been challenged in the literature and the Special Report on Climate Change and Land (IPCC SRCCL).

The adoption and implementation of net zero CO_2 or GHG emission targets by countries and regions also depends on equity and capacity criteria. The Paris Agreement recognizes that peaking of emissions will occur later in developing countries (Article 4.1). Just transitions to net zero CO_2 or GHG could be expected to follow multiple pathways, in different contexts. Regions may decide about net zero pathways based on their consideration of potential for rapid transition to low-carbon development pathways, the capacity to design and implement those changes, and perceptions of equity within and across countries. Cost-effective pathways from global models have been shown to

FOOTNOTE [8] The 95th percentile cannot be deduced from the scenario database as more than 5% of pathways do not reach net zero GHG by 2100 (Chapter 3.3 Table 3.1.), hence denoted by -…

distribute the mitigation effort unevenly and inequitably in the absence of financial support mechanisms and capacity building (Budolfson et al. 2021), and hence would require additional measures to become aligned with equity considerations (Fyson et al. 2020; van Soest et al. 2021b). Formulation of net zero pathways by countries will benefit from clarity on scope, roadmaps and fairness (Rogelj et al. 2021; Smith 2021). Achieving net zero emission targets relies on policies, institutions and milestones against which to track progress. Milestones can include emissions levels, as well as markers of technological diffusion.

The accounting of anthropogenic carbon dioxide removal on land matters for the evaluation of net zero CO_2 and net zero GHG strategies. Due to the use of different approaches between national inventories and global models, the current net CO_2 emissions are lower by 5.5 $GtCO_2$, and cumulative net CO_2 emissions in modelled 1.5-2°C pathways would be lower by 104-170 GtCO2, if carbon dioxide removals on land are accounted based on national GHG inventories. National GHG inventories typically consider a much larger area of managed forest than global models, and on this area additionally consider the fluxes due to human-induced global environmental change (indirect effects) to be anthropogenic, while global models consider these fluxes to be natural. Both approaches capture the same land fluxes, only the accounting of anthropogenic vs. natural emission is different. Methods to convert estimates from global models to the accounting scheme of national GHG inventories will improve the use of emission pathways from global models as benchmarks against which collective progress is assessed. (7.2.2.5, Cross-Chapter Box 3 in this chapter)

Net zero CO_2 and carbon neutrality have different meanings in this assessment, as is the case for net zero GHG and GHG neutrality. They apply to different boundaries in the emissions and removals being considered. Net zero (GHG or CO_2) refers to emissions and removals under the direct control or territorial responsibility of the reporting entity. In contrast, (GHG or carbon) neutrality includes anthropogenic emissions and anthropogenic removals within and also those beyond the direct control or territorial responsibility of the reporting entity. At the global scale, net zero CO_2 and carbon neutrality are equivalent, as is the case for net zero GHG and GHG neutrality. The term "climate neutrality" is not used in this assessment because the concept of climate neutrality is diffuse, used differently by different communities, and not readily quantified.

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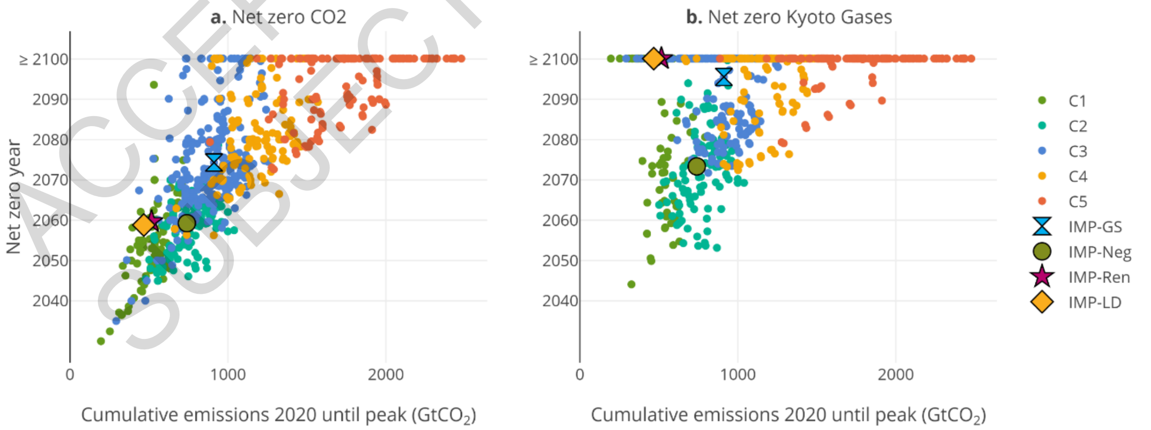

Figure 3.14: Net zero year for CO_2 and all GHGs (based on AR6 GWP-100) as a function of remaining carbon budget and temperature outcomes (not that stabilize (near) zero are also included in determining the net zero year)

Table 3.2 summarizes the key characteristics for all temperature categories in terms of cumulative CO_2 emissions, near-term emission reductions, and the years of peak emission and net zero CO_2 and GHG emissions. The table shows again that many pathways in the literature likely limit global warming to 2°C or limit warming to 1.5°C with limited overshoot compared to preindustrial levels.

Cumulative net CO_2 emissions from the year 2020 until the time of net zero CO_2 in pathways that limit warming to 1.5°C with no or limited overshoot are 510 (330-710) $GtCO_2$ and in pathways *likely* to limit warming to below 2.0°C 890 (640-1160) $GtCO_2$ (see also Cross-Chapter Box 3 in this chapter). Mitigation pathways *likely* to limit global warming to 2°C compared to pre-industrial levels are associated with net global GHG emissions of 40 (32–55) $GtCO_2$-eq yr^{-1} by 2030 and 20 (13-26) $GtCO_2$-eq yr^{-1} in 2050. These correspond to GHG emissions reductions of 21 (1-42) % by 2030, and 64 (53-77) % by 2050 relative to 2019 emission levels. Pathways that limit global warming to below 1.5°C with no or limited overshoot require a further acceleration in the pace of the transformation, with GHG emissions reductions of 43 (34–60) % by 2030 and 84 (74–98) % in 2050 relative to modelled 2019 emission levels. The likelihood of limiting warming to below 1.5°C with no or limited overshoot of the most stringent mitigation pathways in the literature (C1) has declined since SR1.5. This is because emissions have risen since 2010 by about 9 $GtCO_2$ yr^{-1}, resulting in relatively higher near-term emissions of the AR6 pathways by 2030 and slightly later dates for reaching net zero CO_2 emissions compared to SR1.5

Given the larger contribution of scenarios in the literature that aim to reduce net-negative emissions, emission reductions are somewhat larger in the short-term compared to similar categories in the IPCC SR1.5. At the same time, the year of net zero emissions is somewhat later (but only if these rapid, short-term emission reductions are achieved). The scenarios in the literature in C1-C3 show a peak in global emissions before 2025. Not achieving this requires a more rapid reduction after 2025 to still meet the Paris goals (see Section 3.5).

Table 3.2 GHG, CO_2 emissions and warming characteristics of different mitigation pathways submitted to the AR6 scenarios database and as categorized in the climate assessment.

p50 (p5-p95) [0] Global Mean Surface Air Temperature change			GHG emissions Gt CO_2-eq/yr			GHG emissions reductions from 2019 % [5]			Emissions milestones [6,7]				Cumulative CO_2 emissions Gt CO_2 [9]		Cumulative net-negative CO_2 emissions Gt CO_2	Temperature change 50% probability [10] °C		Likelihood of staying below (%) [11]			Time when specific temeprature levels are reached (with a 50% probability)		
Category [1, 2, 3, 4] [# pathways]	Category description	WG1 SSP & IPs alignment	2030	2040	2050	2030	2040	2050	Peak CO_2 emissions	Peak GHG emissions	net-zero CO_2 [% net-zero pathways]	net-zero GHGs [8] [% net-zero pathways]	2020 to netzero CO_2	2020-2100	year of net-zero CO_2 to 2100	at peak warming	2100	<1.5°C	<2.0°C	<3.0°C	1.5°C	2.0°C	3.0°C
C1 [97]	Below 1.5°C with no or limited overshoot	SP, LD Ren, SSP1-1.9	31 (21-36)	17 (6-23)	9 (1-15)	43 (34-60)	69 (58-90)	84 (73-98)	2020-2025 [100%] (2020-2025)	2020-2025 [100%] (2020-2025)	2050-2055 [100%] (2020-2025)	2095-2100 [52%] (2050-...)	510 (330-710)	320 (-210-570)	-200 (-560-0)	1.6 (1.3-1.6)	1.3 (0.8-1.5)	38 (33-73)	90 (86-98)	100 (99-100)	2030-2035 [90%] (2030-...)	...-... [0%] (...-...)	...-... [0%] (...-...)
C2 [133]	Below 1.5°C with high overshoot	Neg	42 (31-55)	25 (16-34)	14 (5-21)	23 (0-44)	55 (40-71)	75 (62-91)	2020-2025 [100%] (2020-2030)	2020-2025 [100%] (2020-2030)	2055-2060 [100%] (2045-2070)	2070-2075 [87%] (2055-...)	720 (540-930)	400 (-90-620)	-330 (-620--30)	1.7 (1.4-1.8)	1.4 (0.8-1.5)	24 (15-58)	82 (71-95)	100 (99-100)	2030-2035 [100%] (2030-2035)	...-... [0%] (...-...)	...-... [0%] (...-...)
C3 [311]	Likely below 2°C	SSP2-2.6	44 (32-55)	29 (20-36)	20 (13-26)	21 (1-42)	46 (34-63)	64 (53-77)	2020-2025 [100%] (2020-2030)	2020-2025 [100%] (2020-2030)	2070-2075 [91%] (2060-...)	...-... [30%] (2075-...)	890 (640-1160)	800 (500-1140)	-40 (-280-0)	1.7 (1.4-1.8)	1.6 (1.1-1.8)	20 (13-66)	76 (68-97)	99 (98-100)	2030-2035 [100%] (2030-2040)	...-... [0%] (...-...)	...-... [0%] (...-...)
C3a [204]	Immediate action		41 (30-49)	29 (21-36)	20 (13-27)	26 (12-46)	47 (35-63)	63 (52-77)	2020-2025 [100%] (2020-2025)	2020-2025 [100%] (2020-2025)	2070-2075 [88%] (2060-...)	...-... [24%] (2080-..)	880 (640-1180)	790 (480-1160)	-20 (-280-0)	1.7 (1.4-1.8)	1.6 (1.1-1.8)	22 (14-71)	78 (69-97)	100 (98-100)	2030-2035 [100%] (2030-2040)	...-... [0%] (...-...)	...-... [0%] (...-...)
C3b [97]	NDCs	GS	52 (47-55)	29 (20-36)	18 (10-25)	5 (0-14)	46 (34-63)	68 (56-82)	2020-2025 [100%] (2020-2030)	2020-2025 [100%] (2020-2030)	2065-2070 [96%] (2060-2100)	...-... [42%] (2075-...)	910 (720-1150)	800 (560-1050)	-70 (-300-0)	1.8 (1.4-1.8)	1.6 (1.1-1.7)	17 (12-61)	73 (67-96)	99 (98-99)	2030-2035 [100%] (2030-2035)	...-... [0%] (...-...)	...-... [0%] (...-...)
C4 [159]	Below 2°C		50 (41-56)	38 (28-43)	28 (19-35)	10 (0-27)	31 (20-50)	49 (35-65)	2020-2025 [100%] (2020-2030)	2020-2025 [100%] (2020-2030)	2075-2080 [86%] (2065-...)	...-... [31%] (2075-...)	1210 (970-1500)	1160 (700-1490)	-30 (-390-0)	1.9 (1.5-2.0)	1.8 (1.2-2.0)	11 (7-50)	59 (50-93)	98 (95-99)	2030-2035 [100%] (2030-2035)	...-... [0%] (...-...)	...-... [0%] (...-...)
C5 [212]	Below 2.5°C		52 (46-56)	45 (36-52)	39 (30-49)	6 (-1-18)	18 (4-33)	29 (11-48)	2020-2025 [100%] (2020-2035)	2020-2025 [100%] (2020-2035)	...-... [40%] (2075-...)	...-... [11%] (2090-...)	1780 (1400-2360)	1780 (1260-2360)	0 (-140-0)	2.2 (1.6-2.5)	2.1 (1.5-2.5)	4 (0-28)	37 (18-84)	91 (83-99)	2030-2035 [100%] (2030-2035)	2060-2065 [99%] (2055-2095)	...-... [0%] (...-...)
C6 [97]	Below 3°C	SSP2-4.5 Mod-Act	54 (50-62)	53 (48-61)	52 (45-57)	2 (-10-11)	3 (-14-14)	5 (-2-18)	2030-2035 [100%] (2020-2085)	2030-2035 [100%] (2020-2085)	...-... [0%] (...-...)	...-... [0%] (...-...)	2790 (2440-3520)	2790 (2440-3520)	0 (0-0)	2.7 (2.0-2.9)	2.7 (2.0-2.9)	0 (0-2)	8 (2-45)	71 (53-96)	2030-2035 [100%] (2030-2035)	2050-2055 [100%] (2045-2060)	...-... [0%] (...-...)
C7 [164]	Below 4°C	SSP3-7.0 Cur-Pol	62 (53-69)	67 (56-76)	70 (58-83)	-11 (-18-3)	-19 (-31-0)	-24 (-41--2)	2090-2095 [100%] (2035-2100)	2090-2095 [100%] (2035-2100)	...-... [0%] (...-...)	...-... [0%] (...-...)	4220 (3160-5000)	4220 (3160-5000)	0 (0-0)	3.5 (2.5-3.9)	3.5 (2.5-3.9)	0 (0-0)	0 (0-5)	22 (7-80)	2030-2035 [100%] (2030-2035)	2045-2050 [100%] (2045-2055)	2080-2085 [100%] (2070-2100)
C8 [29]	Above 4°C	SSP5-8.5	71 (68-80)	79 (77-96)	87 (82-112)	-20 (-34--17)	-35 (-66--29)	-46 (-92--36)	2080-2085 [100%] (2060-2100)	2080-2085 [100%] (2060-2100)	...-... [0%] (...-...)	...-... [0%] (...-...)	5600 (4910-7450)	5600 (4910-7450)	0 (0-0)	4.2 (3.3-5.0)	4.2 (3.3-5.0)	0 (0-0)	0 (0-0)	4 (0-27)	2030-2035 [100%] (2025-2035)	2040-2045 [100%] (2040-2050)	2065-2070 [100%] (2060-2075)

0 Values in the table refer to the 50th and (5th-95th) percentile values. For emissions-related columns this relates to the distribution of all the scenarios in that category. For Temperature Change and Likelihood columns, single upper row values are the 50th percentile value across scenarios in that Category for the MAGICC climate model emulator.
For the bracketed ranges for temperatures and likelihoods, the median warming for every scenario in that category is calculated for each of the three climate model emulators (MAGICC, FaIR and CICERO-SCM). Subsequently, the 5th and 95th percentile values across all scenarios is calculated. The coolest and warmest outcomes (i.e., the lowest p5 of three emulators, and the highest p95, respectively) are shown in the brackets. Thus, these ranges cover the extent of scenario and climate model emulator uncertainty.

1 Category definitions consider at peak warming and warming at the end-of-century (2100).
C1: Below 1.5°C in 2100 with a greater than 50% probability and a peak warming higher than 1.5°C with less than 67% probability.
C2: Below 1.5°C in 2100 with a greater than 50% probability but peak warming higher than 1.5°C with greater than or equal to 67% probability.
C3: Likely below 2 °C throughout the century with greater than 67% probability.
C4, C5, C6, C7: Below 2 °C, 2.5 °C, 3 °C and 4 °C throughout the century, respectively, with greater than 50% probability.
C8: Peak warming above 4 °C with greater than or equal to 50% probability.

2 All warming levels are relative to the pre-industrial temperatures from the 1850-1900 period.

3 The warming profile of ***Neg*** peaks around 2060 and declines to below 1.5°C (50% likelihood) shortly after 2100. Whilst technically classified as a C3, it strongly exhibits the characteristics of C2 high overshoot scenarios.

4 C3 scenarios are sub-categorized according to policy ambition and consistent with Figure SPM 6. Hence the subtotals of C3a & C3b do not match the total of C3 scenarios, as there areC3 scenarios with policy categorizations not covered by C3a and C3b.

5 Percentage GHG reduction ranges shown here compare 2019 estimates from historical emissions assessed in Chapter 2 (58 Gt CO2) to the harmonized and infilled projections from the models. Negative values (e.g., in C7, C8) represent an increase in emissions.

6 Gross, % reductions and emissions milestones are based on model data for CO_2 & GHG emissions, which has been harmonized to 2015 values. See also Footnote 6.

7 Percentiles reported across all pathways in that category including pathways that do not reach net zero before 2100 (fraction in square brackets). If the fraction of pathways that reach net zero before 2100 (one minus fraction in square brackets) is lower than the fraction of pathways covered by a percentile (e.g., 0.95 for the 95th percentile), the percentile is not defined and denoted with "…".

8 For cases where models do not report all GHGs, missing GHG species are infilled and calculated as Kyoto basket with AR6 GWP-100 CO2-equivalent factors. For each scenario, a minimum of native reporting of CO2, CH4, and N2O emissions to 2100 was required for the assessment of the climate response and assignment to a climate category. Emissions scenarios without climate assessment are not included in the ranges. See Annex III.

9 For better comparability with the WGI assessment of the remaining carbon budget, the cumulative CO2 emissions of the pathways are harmonized to the 2015 CO_2 emissions levels used in the WGI assessment and are calculated for the future starting on 1 January 2020.

10 Temperature change (Global Surface Air Temperature - GSAT) for category (at peak and in 2100), based on the median warming for each scenario assessed using the probabilistic climate model emulators.

11 Probability of staying below the temperature thresholds for the scenarios in each category, taking into consideration the range of uncertainty from the climate model emulators consistent with the WGI AR6 assessment. The probabilities refer to the probability at peak temperature. Note that in the case of temperature overshoot (E.g., category C2 and some scenarios in C1), the probabilities at the end of the century are higher than the probability at peak temperature.

3.3.2.4 Mitigation strategies

Detailed sectoral implications are discussed in Section 3.4 and Chapters 5-11 (see also Table 3.3). The stringency of climate policy has clear implications for mitigation action (Figure 3.15). There are a number of important commonalities of pathways likely limiting warming to 2C and below: for instance, they all rely on significant improvement of energy efficiency, rapid decarbonisation of supply and, many of them, CDR (in energy supply or AFOLU), either in terms of net negative emissions or to compensate residual emissions. Still, there are also important differences and the (IMPs) show how different choices can steer the system into alternative directions with different combinations of response options. For decarbonisation of energy supply many options exist, including CCS, nuclear power, and renewables (see Chapter 6). In the majority of the scenarios reaching low greenhouse targets, a considerable amount of CCS is applied (panel d). The share of renewables is around 30-70% in the scenarios reaching a global average temperature change of likely below 2ºC and clearly above 40% for scenarios reaching 1.5ºC (panel c). Scenarios have been published with 100% renewable energy systems even at a global scale, partly reflecting the rapid progress made for these technologies in the last decade (Breyer and Jefferson 2020; Creutzig et al. 2017; Jacobson et al. 2018). These scenarios do not show in the graph due to a lack of information from non-energy sources. There is a debate in the literature on whether it is possible to achieve a 100% renewable energy system by 2050 (Brook et al. 2018). This critically depends on assumptions made on future system integration, system flexibility, storage options, consequences for material demand and the ability to supply high-temperature functions and specific mobility functions with renewable energy. The range of studies published showing 100% renewable energy systems show that it is possible to design such systems in the context of energy system models (Lehtveer and Hedenus 2015a,b; Hong et al. 2014a,b; Zappa et al. 2019; Pfenninger and Keirstead 2015; Sepulveda et al. 2018; IEA 2021b) (see also Box 6.6 in Chapter 6 on 100% renewables in net zero CO_2 systems). Panel e and f, finally, show the contribution of CDR – both in terms of net negative emissions and gross CDR. The contribution of total CDR obviously exceeds the net negative emissions. It should be noted that while a majority of scenarios relies on net negative emissions to reach stringent mitigation goals – this is not the case for all of them.

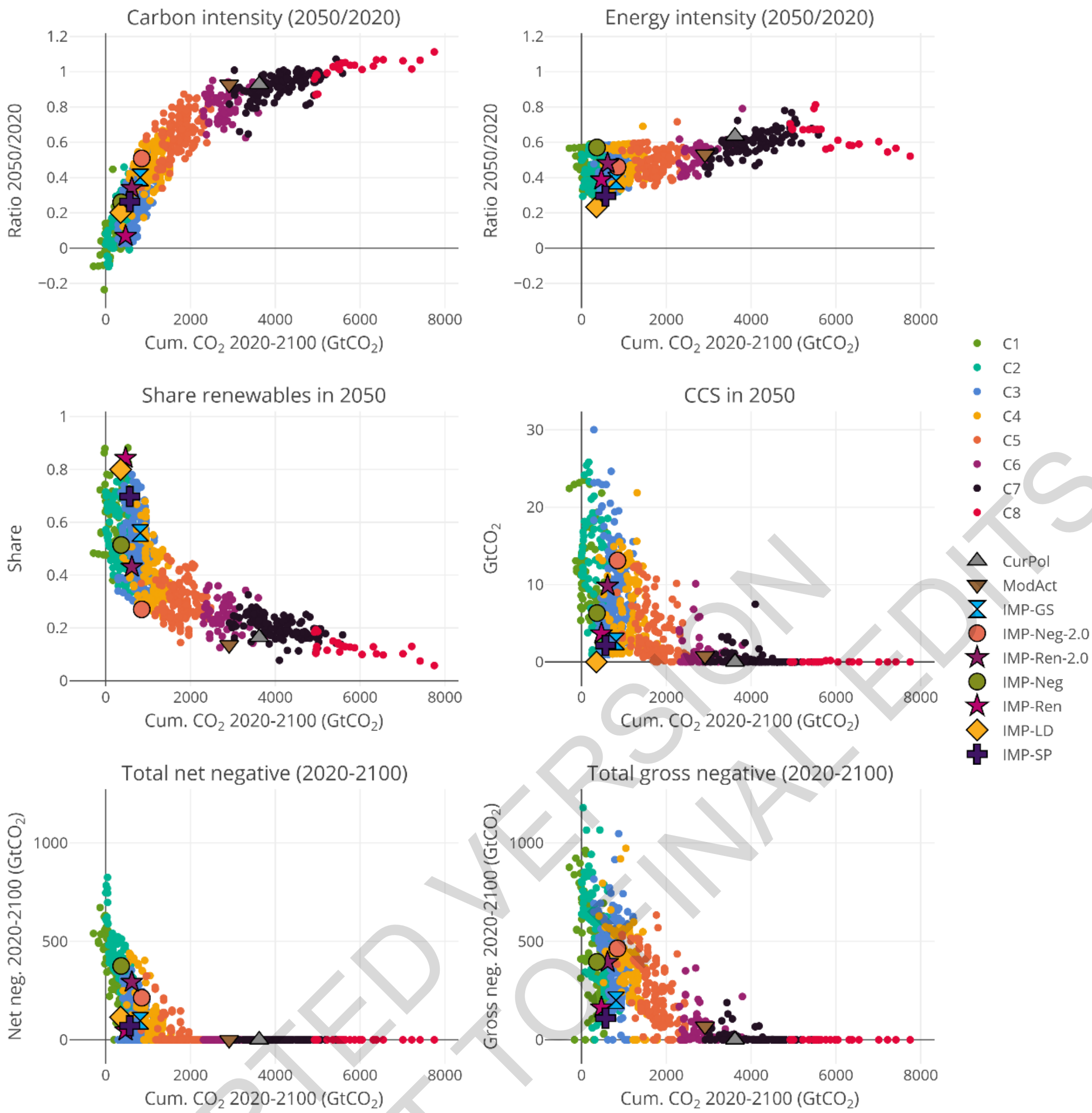

Figure 3.15: Characteristics of scenarios as a function of the remaining carbon budget (mean decarbonisation rate is shown as the average reduction in the period 2010-2050 divided by 2010 emissions). The categories C1-C7 are explained in Table 3.1

The spread shown in Figure 3.15 implies different mitigation strategies that could all lead to emissions levels consistent with the Paris Agreement (and reach zero emissions). The IMPs illustrate some options for different decarbonization pathways with heavy reliance on renewables (***Ren***), strong emphasis on energy demand reductions (***LD***), wide-spread deployment of CDR methods coupled with CCS (BECCS and DACCS) (***Neg***), mitigation in the context of sustainable development (***SP***) (Figure 3.16). For example, in some scenarios, a small part of the energy system is still based on fossil fuels in 2100 (***Neg***), while in others, fossil fuels are almost or completely phased out (***Ren***). Nevertheless, in all scenarios, fossil fuel use is greatly reduced and unabated coal use is completely phased out by 2050. Also, nuclear power can be part of a mitigation strategy (however, the literature only includes some scenarios with high-nuclear contributions, such as Berger et al. (2017)). This is explored further in Section 3.5. The different strategies are also clearly apparent in the way they scenarios reach net zero emissions. While ***GS*** and ***Neg*** rely significantly on BECCS and DACCS, their use is far more restricted in the other IMPs. Consistently, in these IMPs also residual emissions are also significantly lower.

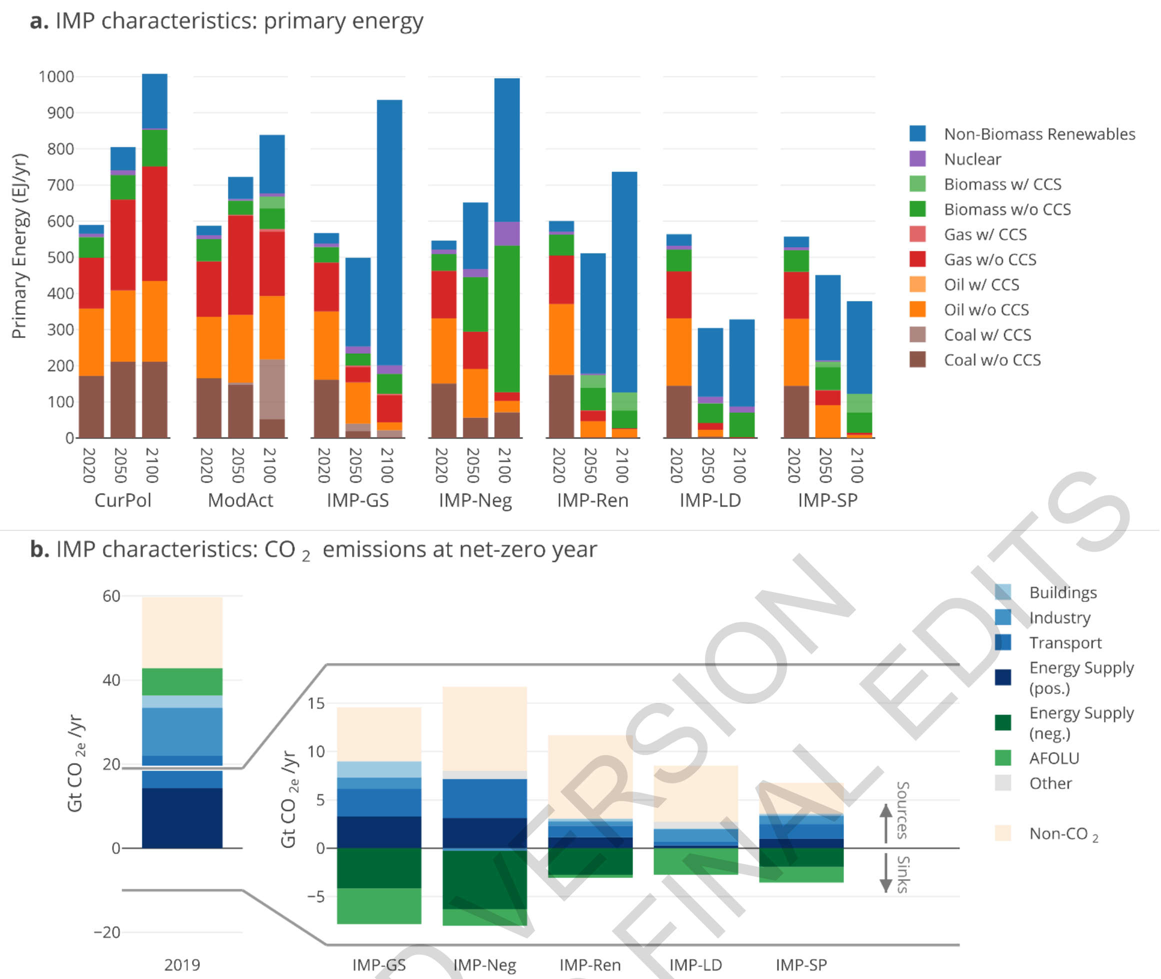

Figure 3.16: Primary energy use and net emissions at net zero year for the different IMPS

Mitigation pathways also have a regional dimension. In 2010, about 40% of emissions originated from the Developed Countries and Eastern Europe and west-central Asia regions. According to the projections shown in

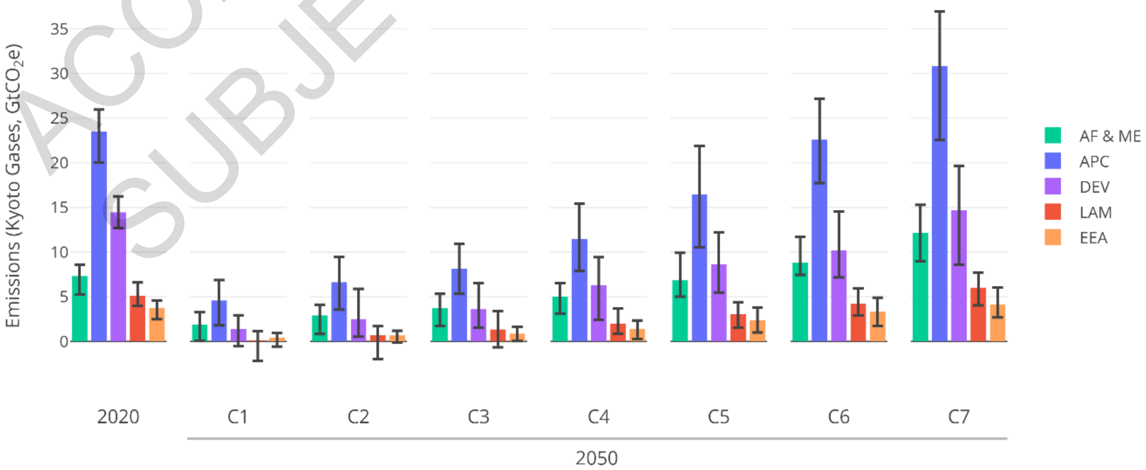

Figure 3.17, the share of the latter regions will further increase to about 70% by 2050. In the scenarios in the literature, emissions are typically almost equally reduced across the regions.

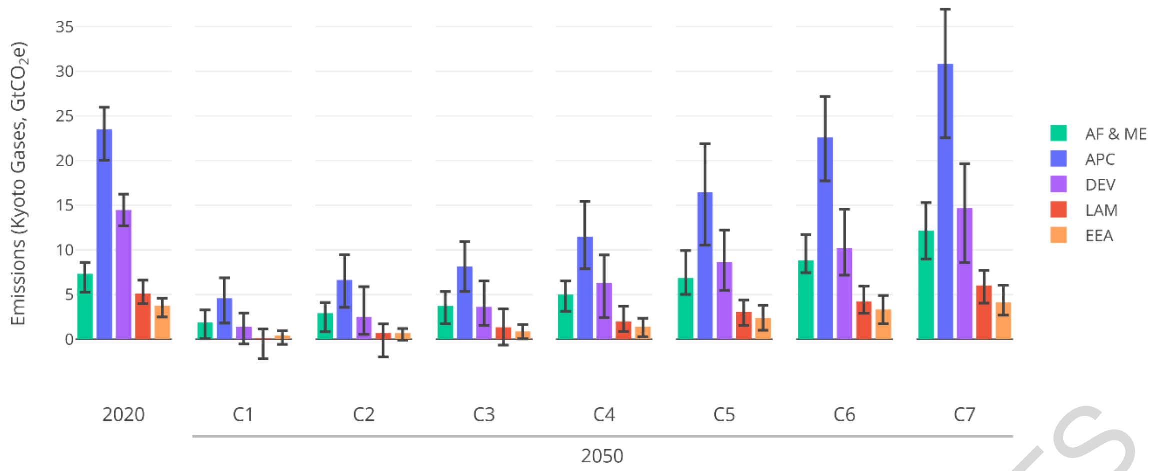

Figure 3.17[9]: Emissions by region (including 5-95[th] percentile range)

3.3.3 Climate impacts on mitigation potential

At the moment, climate change impact on mitigation potential is hardly considered in model-based scenarios. While a detailed overview of climate impacts is provided in IPCC WGII and Section 3.6 discusses the economic consequences, here we concentrate on the implications for mitigation potential. Climate change directly impacts the carbon budget via all kinds of feedbacks – which is included in the ranges provided for the carbon budget (e.g., 300-900 $GtCO_2$ for 17[th]-83[rd] percentile for not exceeding 1.5 °C; see Chapter 5 IPCC, 2021). Climate change, however, alters the production and consumption of energy (see also Chapter 6.5). An overview of the literature is provided by Yalew et al. (2020). In terms of supply, impacts could influence the cooling capacity of thermal plants, the potential and predictability of renewable energy, and energy infrastructure (Cronin et al. 2018a; van Vliet et al. 2016; Turner et al. 2017; Lucena et al. 2018; Gernaat et al. 2021; Yalew et al. 2020). Although the outcomes of these studies differ, they seem to suggest that although impacts might be relatively small at the global scale, they could be substantial at the regional scale (increasing or decreasing potential). Climate change can also impact energy demand, with rising temperatures resulting in decreases in heating demand and increases in cooling demand (Isaac and van Vuuren 2009; Zhou et al. 2014; Labriet et al. 2015; McFarland et al. 2015; Auffhammer et al. 2017; Clarke et al. 2018; van Ruijven et al. 2019; Yalew et al. 2020). As expected, the increase in cooling demand dominates the impact in warm regions and decreases in heating demand in cold regions (Clarke et al. 2018; Zhou et al. 2014; Isaac and van Vuuren 2009). Globally, most studies show a net increase in energy demand at the end of the century due to climate impacts (van Ruijven et al. 2019; Isaac and van Vuuren 2009; Clarke et al. 2018); however, one study shows a net decrease (Labriet et al. 2015). Only a few studies quantify the combined impacts of climate change on energy supply and energy demand (Emodi et al. 2019; Steinberg et al. 2020; McFarland et al. 2015; Mima and Criqui 2015). These studies show increases in electricity generation in the USA (McFarland et al. 2015; Steinberg et al. 2020) and increases in CO_2 emissions in Australia (Emodi et al. 2019) or the USA (McFarland et al. 2015).

Climate change can impact the potential for AFOLU mitigation action by altering terrestrial carbon uptake, crop yields and bioenergy potential (see also Chapter 7). Carbon sequestration in forests may be positively or adversely affected by climate change and CO_2 fertilization. On the one hand, elevated CO_2 levels and higher temperatures could enhance tree growth rates, carbon sequestration, and timber and biomass production (Beach et al. 2015; Kim et al. 2017; Anderegg et al. 2020). On the other hand,

FOOTNOTE[9] The countries and areas classification in this figure deviate from the standard classification scheme adopted by WGIII as set out in Annex II, section 1.

climate change could lead to greater frequency and intensity of disturbance events in forests, such as fires, prolonged droughts, storms, pests and diseases (Kim et al. 2017; Anderegg et al. 2020). The impact of climate change on crop yields could also indirectly impact the availability of land for mitigation and AFOLU emissions (Meijl et al. 2018; Calvin et al. 2013; Kyle et al. 2014; Bajželj and Richards 2014; Beach et al. 2015). The impact is, however, uncertain, as discussed in WGII Chapter 5. A few studies estimate the effect of climate impacts on AFOLU on mitigation, finding increases in carbon prices or mitigation costs by 1-6% in most scenarios (Calvin et al. 2013; Kyle et al. 2014).

In summary, a limited number of studies quantify the impact of climate on emissions pathways. The most important impact in energy systems might be through the impact on demand, although climate change could also impact renewable mitigation potential -certainly at the local and regional scale. Climate change might be more important for land-use related mitigation measures, including afforestation, bioenergy and nature-based solutions. The net effect of changes in climate and CO_2 fertilization are uncertain but could be substantial (see also Chapter 7).

3.4 Integrating sectoral analysis into systems transformations

This section describes the role of sectors in long-term emissions pathways (see Table 3.3). We discuss both sectoral aspects of IAM pathways and some insights from sectoral studies. Sectoral studies typically include more detail and additional mitigation options compared to IAMs. However, sectoral studies miss potential feedbacks and cross-sectoral linkages that are captured by IAMs. Additionally, since IAMs include all emissions sources, these models can be used to identify pathways to a particular climate goals. In such pathways, emissions are balanced across sectors typically based on relative marginal abatement costs; as a result, some sectors are sources and some are sinks at the time of net zero CO_2 emissions. For these reasons, the mitigation observed in each sector in an IAM may differ from the potential in sectoral studies. Given the strengths and limitations of each type of model, IAMs and sectoral models are complementary, providing different perspectives.

Table 3.3: Section 3.4 structure, definitions, and relevant chapters

Section	Sector	What is included	Relevant chapter(s)
3.4.1	Cross-sector	Supply and demand, bioenergy, timing of net zero CO_2, other interactions among sectors	Chapter 5, 12
3.4.2	Energy supply	Energy resources, transformation (e.g., electricity generation, refineries, etc.)	Chapter 6
3.4.3	Buildings[1]	Residential and commercial buildings, other non-specified[2]	Chapter 9
3.4.4	Transportation[1]	Road, rail, aviation, and shipping	Chapter 10
3.4.5	Industry[1]	Industrial energy use and industrial processes	Chapter 11
3.4.6	AFOLU	Agriculture, forestry, and other land use	Chapter 7
3.4.7	Other CDR	CDR options not included in individual sectors (e.g., direct air carbon capture and sequestration, enhanced weathering)	Chapter 12

[1] Direct energy use and direct emissions only; emissions do not include those associated with energy production

[2] Other non-specified fuel use, including military. Some models report this category in the buildings sector, while others report it in the "Other" sector

3.4.1 Cross-sector linkages

3.4.1.1 Demand and supply strategies

Most IAM pathways rely heavily on supply-side mitigation strategies, including fuel switching, decarbonization of fuels, and CDR (Creutzig et al. 2016; Bertram et al. 2018; Rogelj et al. 2018b; Mundaca et al. 2019). For demand-side mitigation, IAMs incorporate changes in energy efficiency, but many other demand-side options (e.g., behaviour and lifestyle changes) are often excluded from models (van Sluisveld et al. 2015; Creutzig et al. 2016; Wilson et al. 2019; van den Berg et al. 2019). In addition, this mitigation is typically price-driven and limited in magnitude (Yeh et al. 2017; Sharmina et al. 2020; Luderer et al. 2018; Wachsmuth and Duscha 2019). In contrast, bottom-up modelling studies show considerable potential for demand-side mitigation (Yeh et al. 2017; Wachsmuth and Duscha 2019; Creutzig et al. 2016; Mundaca et al. 2019) (see also Chapter 5), which can slow emissions growth and/or reduce emissions (Samadi et al. 2017; Creutzig et al. 2016).

A small number of mitigation pathways include stringent demand-side mitigation, including changes in thermostat set points (van Vuuren et al. 2018; van Sluisveld et al. 2016), more efficient or smarter appliances (Grubler et al. 2018; Napp et al. 2019; van Sluisveld et al. 2016), increased recycling or reduced industrial goods (van de Ven et al. 2018; Liu et al. 2018; van Sluisveld et al. 2016; Grubler et al. 2018; Napp et al. 2019), telework and travel avoidance (van de Ven et al. 2018; Grubler et al. 2018), shifts to public transit (van Vuuren et al. 2018; van Sluisveld et al. 2016; Grubler et al. 2018), reductions in food waste (van de Ven et al. 2018) and less meat intensive diets (van de Ven et al. 2018; van Vuuren et al. 2018; Liu et al. 2018). These pathways show reduced dependence on CDR and reduced pressure on land (van de Ven et al. 2018; van Vuuren et al. 2018; Grubler et al. 2018; Rogelj et al. 2018a) (Chapter 5.3.3). However, the representation of these demand-side mitigation options in IAMs is limited, with most models excluding the costs of such changes (van Sluisveld et al. 2016), using stylised assumptions to represent them (van den Berg et al. 2019), and excluding rebound effects (Brockway et al. 2021; Krey et al. 2019). Furthermore, there are questions about the achievability of such pathways, including whether the behavioural changes included are feasible (Azevedo et al. 2021) and the extent to which development and demand can be decoupled (Semieniuk et al. 2021; Steckel et al. 2013; Keyßer and Lenzen 2021; Brockway et al. 2021).

Figure 3.18: Indicators of demand and supply-side mitigation in the Illustrative Pathways (lines) and the 5-95% range of Reference, 1.5°C and 2°C scenarios (shaded areas). shows indicators of supply- and demand-side mitigation in the IMPs, as well as the range across the database. Two of these IMPs (***SP***, ***LD***) show strong reductions in energy demand, resulting in less reliance on bioenergy and limited CDR from energy supply. In contrast, ***Neg*** has higher energy demand, depending more on bioenergy and net negative CO_2 emissions from energy supply.

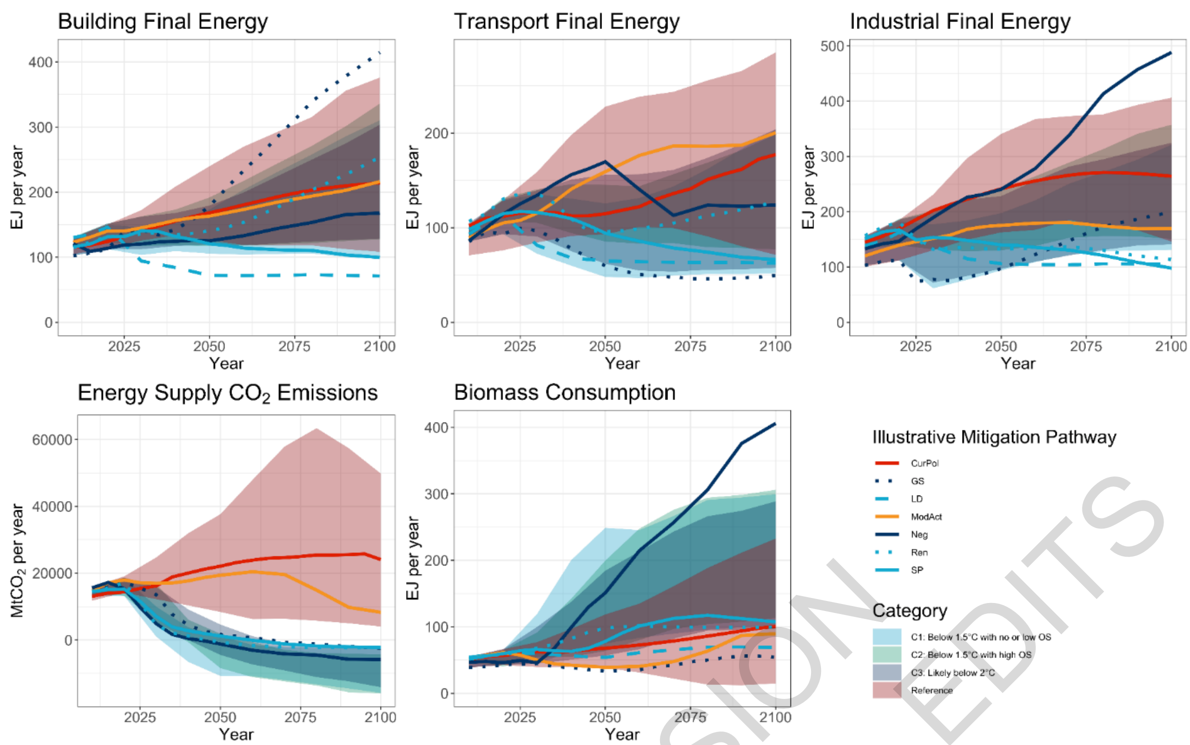

Figure 3.18: Indicators of demand and supply-side mitigation in the Illustrative Pathways (lines) and the 5-95% range of Reference, 1.5°C and 2°C scenarios (shaded areas).

3.4.1.2 Sectoral emissions strategies and the timing of net zero

Mitigation pathways show differences in the timing of decarbonization (Figure 3.20) and the timing of net zero (Figure 3.19) across sectors and regions (*high confidence*); the timing in a given sector depends on the cost of abatement in it, the availability of CDR options, the scenario design, near-term emissions levels, and the amount of non-CO_2 abatement (Yeh et al. 2017; Emmerling et al. 2019; Rogelj et al. 2019a,b; Johansson et al. 2020; van Soest et al. 2021b; Ou et al. 2021; Azevedo et al. 2021) (Cross-Chapter Box 3 in this chapter). However, delaying emissions reductions, or more limited emissions reductions in one sector or region, involves compensating reductions in other sectors or regions if warming is to be limited *(high confidence)* (Rochedo et al. 2018; Price and Keppo 2017; Grubler et al. 2018; van Soest et al. 2021b).

Table 3.4: Energy, emissions and CDR characteristics of the pathways by climate category for 2030, 2050, 2100. Source: AR6 scenarios database

p50 (p5-p95) [0]	Global Mean Surface Air Temperature change		Low-carbon share of Primary Energy [3,4] [%] 2020 = 16 (12-18)			CO_2 intensity of Primary Energy Index 2020 = 100			Final energy demand [EJ/yr] 2020 = 419 (367-458)			Final energy intensity of GDP Index 2020 = 100			Electricity share in final energy [%] 2020 = 20 (18-25)		
Category [1, 2] [# pathways]	Category description	WG1 SSP & IPs alignment	2030	2050	2100	2030	2050	2100	2030	2050	2100	2030	2050	2100	2030	2050	2100
C1 [97]	Below 1.5°C with no or limited overshoot	SP, LD Ren, SSP1-1.9	32 (17-48)	68 (25-86)	75 (19-98)	65 (49-75)	8 (-8-24)	-3 (-20-8)	399 (293-447)	410 (325-540)	612 (321-818)	71 (59-81)	46 (34-60)	26 (14-45)	27 (23-35)	52 (40-64)	66 (50-78)
C2 [133]	Below 1.5°C with high overshoot	Neg	24 (11-35)	57 (19-77)	86 (25-97)	79 (66-94)	18 (2-37)	-14 (-25-0)	458 (372-504)	442 (345-561)	675 (415-819)	76 (64-88)	44 (35-63)	23 (15-45)	25 (20-29)	45 (34-56)	61 (49-73)
C3 [311]	Likely below 2°C	SSP2-2.6 GS	24 (16-32)	51 (29-75)	73 (34-94)	84 (70-95)	31 (9-47)	-1 (-19-8)	446 (356-491)	448 (344-540)	625 (421-788)	77 (65-88)	50 (36-62)	26 (18-41)	24 (20-29)	42 (30-54)	60 (43-72)
C4 [159]	Below 2°C		21 (14-24)	39 (24-63)	71 (34-91)	92 (80-100)	45 (26-64)	-3 (-21-9)	459 (379-497)	489 (362-601)	641 (450-796)	76 (71-87)	45 (39-65)	22 (19-41)	23 (19-28)	35 (23-44)	56 (44-69)
C5 [212]	Below 2.5°C		21 (12-24)	31 (22-44)	67 (42-84)	92 (84-102)	66 (50-84)	9 (-13-32)	466 (389-499)	519 (435-585)	680 (383-812)	77 (74-88)	51 (45-66)	23 (18-40)	23 (19-28)	32 (19-41)	53 (40-65)
C6 [97]	Below 3°C	SSP2-4.5 Mod-Act	20 (11-23)	25 (14-36)	47 (28-65)	94 (87-101)	82 (67-92)	47 (21-78)	467 (410-508)	551 (471-632)	701 (432-910)	79 (75-89)	55 (50-70)	26 (20-42)	23 (19-28)	29 (19-38)	48 (30-56)
C7 [164]	Below 4°C	SSP3-7.0 Cur-Pol	17 (11-21)	19 (8-29)	29 (8-51)	98 (91-101)	94 (80-101)	73 (56-106)	492 (434-540)	599 (513-701)	804 (557-983)	85 (76-91)	64 (54-76)	33 (27-48)	24 (20-28)	29 (23-35)	41 (29-50)
C8 [29]	Above 4°C	SSP5-8.5	13 (11-17)	13 (9-20)	29 (14-45)	102 (99-103)	106 (104-109)	91 (87-95)	540 (413-574)	696 (504-856)	941 (692-1136)	89 (88-92)	73 (64-79)	47 (25-51)	26 (22-30)	31 (28-35)	43 (35-50)

Category [1, 2] [# pathways]	CO_2 intensity of electricity [Mt CO_2/ TWh] 2020 = 469 (419-538)			Non-energy GHG emissions [Gt CO_2-eq] 2020 = 18 (15-21)			Fossil CCS (2100) [Gt CO_2] 2020 = 0 (0-0)				CDR (2100) [Gt CO_2] 2020 = 0 (0-4)			
	2030	2050	2100	2030	2050	2100	2030	2050	2100	2020-2100	2030	2050	2100	2020-2100
C1 [97]	99 (4-215)	-5 (-66-11)	-4 (-104-1)	10 (5-13)	5 (1-9)	2 (-2-9)	1 (0-5)	2 (0-13)	3 (0-16)	196 (3-882)	1 (0-4)	6 (1-13)	13 (0-20)	659 (63-1012)
C2 [133]	218 (99-353)	0 (-75-16)	-1 (-118-3)	13 (10-19)	6 (2-9)	1 (-7-7)	0 (0-4)	3 (0-13)	1 (0-16)	280 (7-831)	1 (0-4)	6 (0-17)	17 (-1-26)	687 (0-1282)
C3 [311]	248 (93-375)	5 (-72-51)	-8 (-105-5)	12 (6-18)	7 (3-12)	5 (-1-8)	0 (0-3)	3 (0-12)	5 (0-15)	266 (7-773)	1 (0-4)	5 (0-11)	13 (0-20)	569 (0-923)
C4 [159]	322 (227-381)	24 (-48-112)	-14 (-117-7)	13 (8-19)	9 (3-12)	2 (-1-9)	0 (0-2)	2 (0-9)	6 (0-16)	279 (7-684)	1 (0-4)	4 (0-9)	15 (0-19)	553 (0-841)
C5 [212]	341 (257-418)	107 (14-208)	-3 (-73-34)	15 (10-19)	10 (5-15)	4 (-1-11)	0 (0-1)	1 (0-7)	5 (0-15)	200 (5-730)	1 (0-4)	2 (0-5)	11 (0-18)	392 (0-720)
C6 [97]	354 (257-469)	216 (69-317)	28 (-20-166)	17 (11-20)	13 (9-17)	8 (2-12)	0 (0-0)	0 (0-4)	4 (0-16)	47 (0-536)	1 (0-4)	2 (0-5)	6 (0-12)	222 (0-474)
C7 [164]	414 (311-538)	311 (130-499)	185 (12-461)	19 (13-24)	19 (14-25)	16 (9-26)	0 (0-0)	0 (0-2)	0 (0-8)	0 (0-221)	0 (0-3)	0 (0-3)	0 (0-5)	6 (0-318)
C8 [29]	463 (372-514)	425 (352-484)	189 (142-441)	20 (19-25)	21 (20-29)	20 (13-31)	0 (0-0)	0 (0-0)	0 (0-2)	0 (0-38)	0 (0-1)	0 (0-2)	0 (0-3)	0 (0-207)

Footnotes

0 Values in the table refer to the 50th and (5th-95th) percentile values.

1 Category definitions consider at peak warming and warming at the end-of-century (2100).
C1: Below 1.5°C in 2100 with a greater than 50% probability and a peak warming higher than 1.5°C with less than 67% probability.
C2: Below 1.5°C in 2100 with a greater than 50% probability but peak warming higher than 1.5°C with greater than or equal to 67% probability.
C3: Likely below 2 °C throughout the century with greater than 67% probability.
C4, C5, C6, C7: Below 2 °C, 2.5 °C, 3 °C and 4 °C throughout the century, respectively, with greater than 50% probability.
C8: Peak warming above 4 °C with greater than or equal to 50% probability.

2 The warming profile of ***Neg*** peaks around 2060 and declines thereafter to below 1.5°C (50% likelihood) shortly after 2100. Whilst technically classified as a C3, it strongly exhibits the characteristics of C2 high overshoot scenarios.

3 Primary Energy as calculated in 'Direct Equivalent' terms according to IPCC reporting conventions.

4 Low carbon energy here defined to include: renewables (including biomass, solar, wind, hydro, geothermal, ocean); fossil fuels when used with CCS; and, nuclear power.

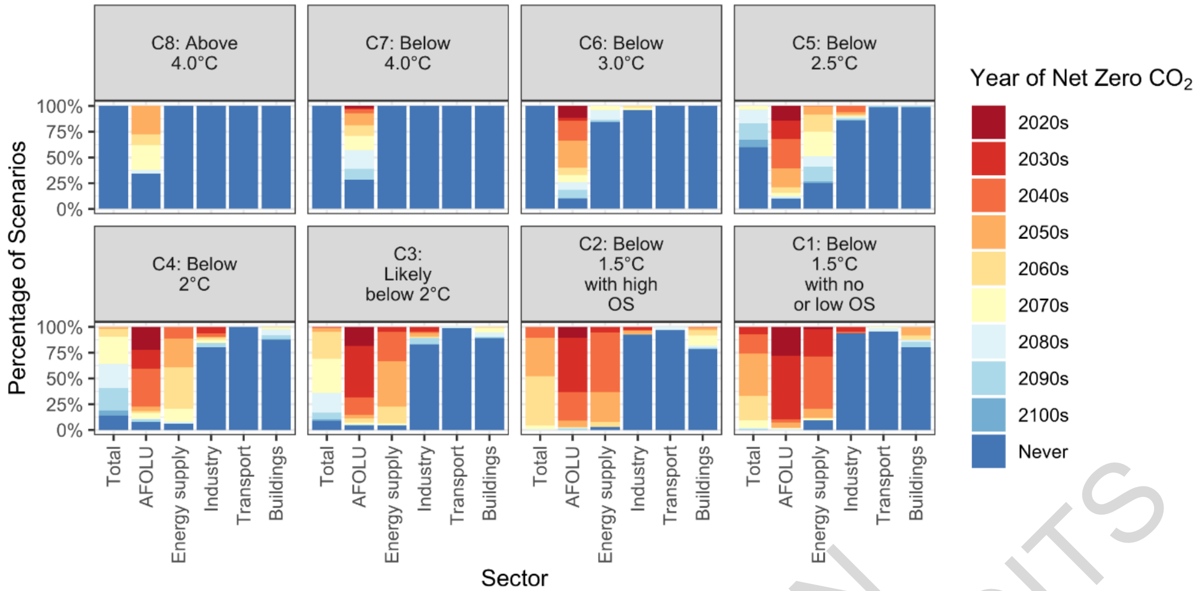

Figure 3.19: Decade in which sectoral CO_2 emissions first reach net negative values. Each panel is a different temperature level. The colours indicate the decade in which CO_2 emissions go negative; the y-axis indicates the share of scenarios achieving net zero in that decade. Only scenarios that pass the vetting criteria are included (see Section 3.2). Scenarios achieving net zero prior to 2020 are excluded.

At the time of net zero global CO_2 emissions, emissions in some sectors are positive and some negative. In cost-effective mitigation pathways, the energy supply sector typically reaches net zero CO_2 before the economy as a whole, while the demand sectors reach net zero CO_2 later, if at all (Pietzcker et al. 2014; Price and Keppo 2017; Luderer et al. 2018; Rogelj et al. 2018a,b; Méjean et al. 2019; Azevedo et al. 2021) (Chapter 6.7). CO_2 emissions from transport, industry, and buildings are positive, and non-CO_2 GHG emissions are also positive at the time of global net zero CO_2 emissions (Figure 3.20).

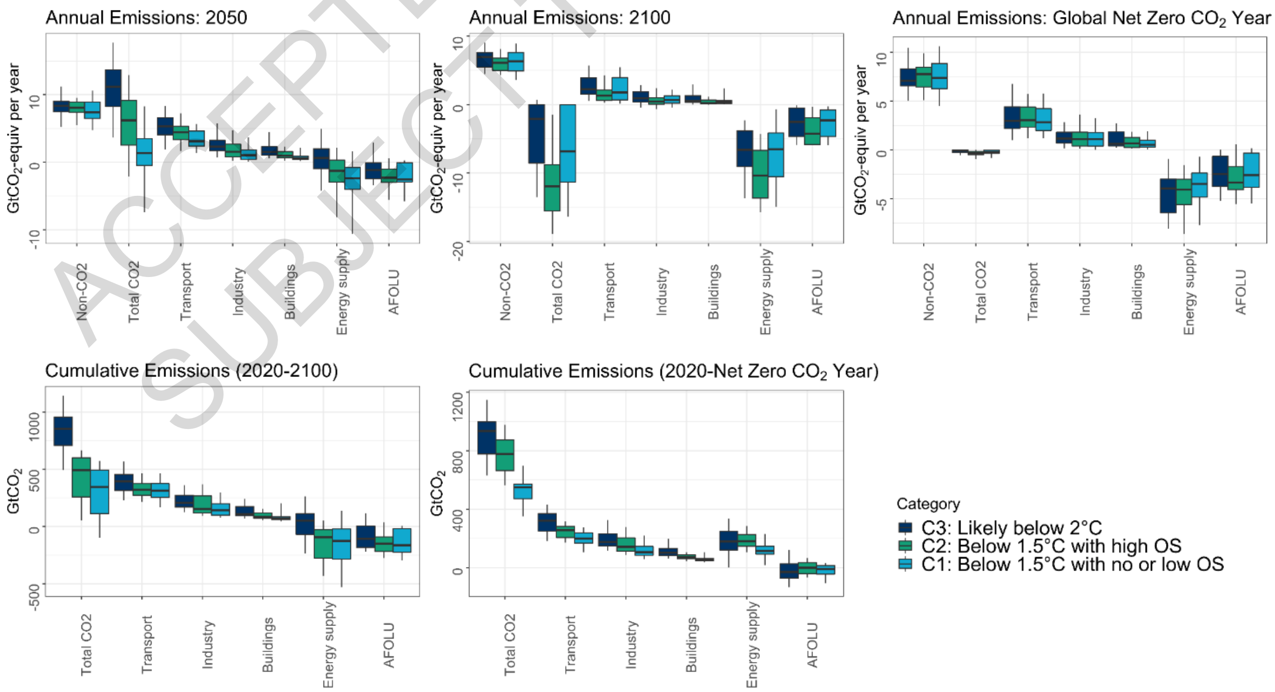

Figure 3.20: Greenhouse gas emissions, including CO_2 emissions by sector and total non-CO_2 GHGs in 2050 (top left), 2100 (top middle), year of global net zero CO_2 (top right), cumulative CO_2 emissions from

2020-2100 (bottom left), and cumulative CO_2 emissions from 2020 until the year of net zero CO_2 for scenarios that limit warming to below 2°C. Scenarios are grouped by their temperature category. "Industry" includes CO_2 emissions associated with industrial energy use only; sectors shown in this figure do not necessarily sum to total CO_2. In this, and other figures in Section 3.4, unless stated otherwise, only scenarios that pass the vetting criteria are included (see Section 3.2). Boxes indicate the interquartile range, the median is shown with a horizontal black line, while vertical lines show the 5 to 95% interval.

So, while pathways indicate some flexibility in emissions reductions across sectors, all pathways involve substantial CO_2 emissions reductions in all sectors and regions (*high confidence*) (Rogelj et al. 2018a,b; Luderer et al. 2018; Méjean et al. 2019; Azevedo et al. 2021). Projected CO_2 emissions reductions between 2019 and 2050 in 1.5°C pathways with no or limited overshoot are around 77% for energy demand, with a 5-95% range of 31 to 96%,[10] 115% for energy supply (90 to 167%), and 148% for AFOLU (94 to 387%). In likely 2°C pathways, projected CO_2 emissions are reduced between 2019 and 2050 by around 49% for energy demand, 97% for energy supply, and 136% for AFOLU (see also 3.4.2-3.4.6). Almost 75% of GHG reductions at the time of net zero GHG are from the energy system, 13% are from AFOLU CO_2, and 13% from non-CO_2 (Figure 3.21). These reductions are achieved through a variety of sectoral strategies, illustrated in Figure 3.21 (right panel), and described in Sections 3.4.2 to 3.4.7; the primary strategies include declines in fossil energy, increases in low carbon energy use, and CDR to address residual emissions.

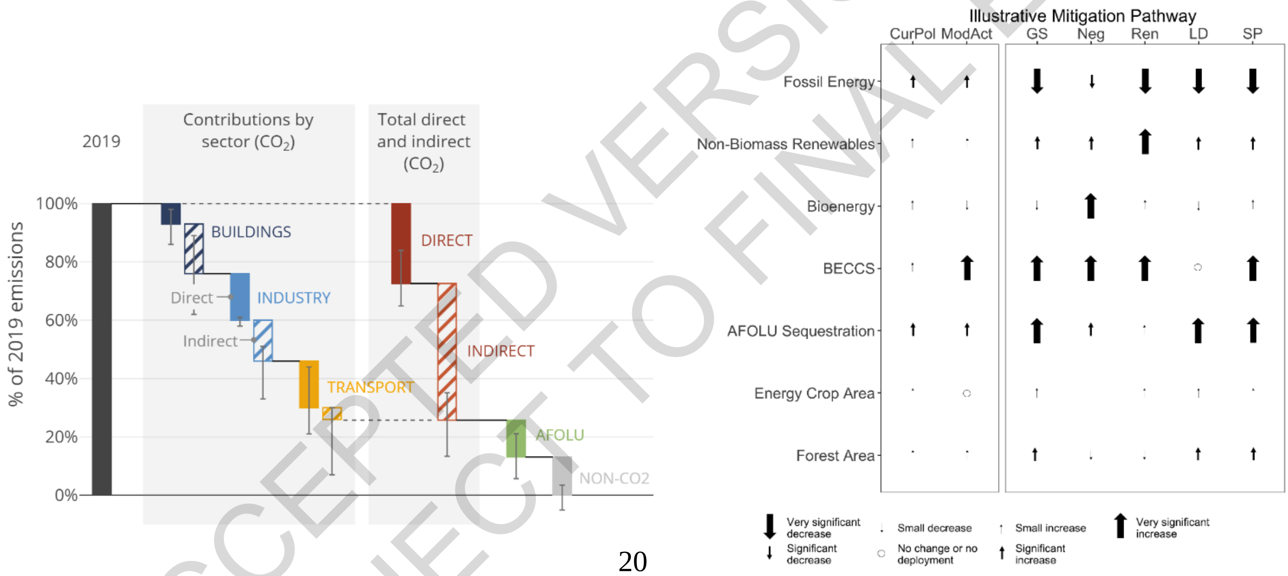

Figure 3.21: Left panel: Greenhouse gas emissions reductions from 2019 by sector at the year of net zero GHG for all scenarios that reach net zero GHG. Emissions reductions by sector for direct (demand) and indirect (upstream supply) are shown as the percent of total GHG reductions.
Right panel: key indicators in 2050 for the IMPs. Definitions of significant and very significant are defined relative to 2019 and vary between indicators, as follows: fossil energy (significant >10%, very significant >50%), renewables (>150 EJ yr^{-1}, >200 EJ yr^{-1}), bioenergy (>100%, >200%), BECCS (>2.0 $GtCO2\ yr^{-1}$, >3.5 $GtCO2\ yr^{-1}$), AFOLU (>100% decline, >130%), energy crops (>150 million ha, >400), forest (>5% increase, >15%).

In the context of mitigation pathways, only a few studies have examined solar radiation modification (SRM), typically focusing on Stratospheric Aerosol Injection (Emmerling and Tavoni 2018a,b; Arinoa et al. 2016; Belaia et al. 2021; Rickels et al. 2020; Heutel et al. 2018; Helwegen et al. 2019). These studies find that substantial mitigation is required to limit warming to a given level, even if

FOOTNOTE [10] Unless otherwise specified, the values in parentheses in Section 3.4 from this point forward indicate the 5-95% range.

SRM is available (Moreno-Cruz and Smulders 2017; Emmerling and Tavoni 2018b; Belaia et al. 2021). SRM may reduce some climate impacts, reduce peak temperatures, lower mitigation costs, and extend the time available to achieve mitigation; however, SRM does not address ocean acidification and may involve risks to crop yields, economies, human health, or ecosystems (WGII Chapter 16; WGI TS; WGI Ch 5; SR1.5 SPM; Cross-Working Group Box 4 in Chapter 14). There also are significant uncertainties surrounding SRM, including uncertainties on the costs and risks, which can substantially alter the amount of SRM used in modelled pathways (Tavoni et al. 2017; NASEM 2021; Heutel et al. 2018; Helwegen et al. 2019; IPCC 2018). Furthermore, the degree of international cooperation can influence the amount of SRM deployed in scenarios, with uncoordinated action resulting in larger SRM deployment and consequently larger risks/impacts from SRM (Emmerling and Tavoni 2018a). Bridging research and governance involves consideration of the full range of societal choices and ramifications (Sugiyama et al. 2018). More information on SRM, including the caveats, risks, uncertainties, and governance issues is found in WGI Chapter 4, WGIII Chapter 14, and Cross-Working Group Box 4 in Chapter 14).

3.4.1.3 Linkages among sectors

Mitigation in one sector can be dependent upon mitigation in another sector, or may involve trade-offs between sectors. Mitigation in energy demand often includes electrification (Luderer et al. 2018; Pietzcker et al. 2014; Sharmina et al. 2020; DeAngelo et al. 2021), however such pathways only result in reduced emissions *if* the electricity sector is decarbonized (Zhang and Fujimori 2020) (see also Chapter 12). Relatedly, the mitigation potential of some sectors (e.g., transportation) depends on the decarbonization of liquid fuels, e.g., through biofuels (Wise et al. 2017; Pietzcker et al. 2014; Sharmina et al. 2020); Chapter 12). In other cases, mitigation in one sector results in reduced emissions in another sector. For example, increased recycling can reduce primary resource extraction; planting trees or green roofs in urban areas can reduce the energy demand associated with space cooling (Chapter 12).

Mitigation in one sector can also result in additional emissions in another. One example is electrification of end use which can result in increased emissions from energy supply. However, one comparitively well-researched example of this linkage is bioenergy. An increase in demand for bioenergy within the energy system has the potential to influence emissions in the AFOLU sector through the intensification of land and forest management and/or via land use change (Smith et al. 2019; Daioglou et al. 2019; Smith et al. 2020a; IPCC 2019a). The effect of bioenergy and BECCS on mitigation depends on a variety of factors in modelled pathways. In the energy system, the emissions mitigation depends on the scale of deployment, the conversion technology, and the fuel displaced (Calvin et al. 2021). Limiting or excluding bioenergy and/or BECCS increases mitigation cost and may limit the ability of a model to reach a low warming level (Edmonds et al. 2013; Calvin et al. 2014b; Muratori et al. 2020; Luderer et al. 2018). In AFOLU, bioenergy can increase or decrease terrestrial carbon stocks and carbon sequestration, depending on the scale, biomass feedstock, land management practices, and prior land use (Calvin et al. 2014c; Wise et al. 2015; Smith et al. 2019, 2020a; IPCC 2019a; Calvin et al. 2021).

Pathways with very high biomass production for energy use typically include very high carbon prices in the energy system (Popp et al. 2017; Rogelj et al. 2018b), little or no land policy (Calvin et al. 2014b), a high discount rate (Emmerling et al. 2019), and limited non-BECCS CDR options (e.g., afforestation, DACCS) (Fuhrman et al. 2020; Realmonte et al. 2019; Chen and Tavoni 2013; Marcucci et al. 2017; Calvin et al. 2014b). Higher levels of bioenergy consumption are likely to involve trade-offs with mitigation in other sectors, notably in construction (i.e., wood for material and structural products) and AFOLU (carbon stocks and future carbon sequestration), as well as trade-offs with sustainability (Section 3.7) and feasibility concerns (Section 3.8). Not all of these trade-offs are fully represented in all IAMs. Based on sectoral studies, the technical potential for bioenergy, when constraints for food security and environmental considerations are included, are 5-50 and 50-250 EJ yr^{-1} in 2050 for residues and dedicated biomass production systems, respectively (Chapter 7). Bioenergy deployment in IAMs is within the range of these potentials, with between 75 and 248 EJ yr^{-1} in 2050 in pathways that limit warming to 1.5°C with no or limited overshoot. Finally, IAMs do not include all potential feedstock and management practices, and have limited representation of institutions, governance, and local context (Butnar et al. 2020; Brown et al. 2019; Calvin et al. 2021).

The inclusion of CDR options, like BECCS, can affect the timing of emissions mitigation in IAM scenarios, i.e., delays in mitigations actions are compensated by net negative emissions in the second half of the century. However, studies with limited net negative emissions in the long-term require very rapid declines in emissions in the near-term (van Vuuren et al. 2017). Especially in forest-based systems, increased harvesting of forests can perturb the carbon balance of forestry systems, increasing emissions for some period; the duration of this period of increased emissions, preceding net emissions reductions, can be very variable (Mitchell et al. 2012; Lamers and Junginger 2013; Röder et al. 2019; Hanssen et al. 2020; Cowie et al. 2021). However, the factors contributing to differences in recovery time are known (Zanchi et al. 2012; Laganière et al. 2017; Mitchell et al. 2012; Lamers and Junginger 2013; Röder et al. 2019). Some studies that consider market-mediated effects find that an increased demand for biomass from forests can provide incentives to maintain existing forests and potentially to expand forest areas, providing addition carbon sequestration as well as additional biomass (Kim et al. 2018; Dwivedi et al. 2014; Baker et al. 2019; Favero et al. 2020). However, these responses are uncertain and likely to vary geographically.

3.4.2 Energy supply

Without mitigation, energy consumption and supply emissions continue to rise (*high confidence*) (Riahi et al. 2017; Bauer et al. 2017; Kriegler et al. 2016; Mcjeon et al. 2021) (see also Chapter 6.7). While the share of renewable energy continues to grow in reference scenarios, fossil fuel accounts for the largest share of primary energy (Riahi et al. 2017; Bauer et al. 2017; Price and Keppo 2017).

In scenarios likely to limit warming to 2°C and below, transition of the energy supply sector to a low or no carbon system is rapid (Rogelj et al. 2016, 2018b; Luderer et al. 2018; Grubler et al. 2018; van Vuuren et al. 2018). CO_2 emissions from energy supply reach net zero around 2041 (2033 to 2057) in pathways limiting warming to below 1.5°C with no or limited overshoot and around 2053 (2040 to 2066) in pathways likely to limit warming to 2°C. Emissions reductions continue, with emissions reaching -7.1 $GtCO_2$ per year (-15 to -2.3 $GtCO_2$ per year) in 2100 in all pathways likely to limit warming to 2°C and below.

All pathways likely to limit warming to 2°C and below show substantial reductions in fossil fuel consumption and a near elimination of the use of coal without CCS (*high confidence*) (Welsby et al. 2021; Bauer et al. 2017; van Vuuren et al. 2018; Rogelj et al. 2018a,b; Grubler et al. 2018; Luderer et al. 2018; Azevedo et al. 2021; Mcjeon et al. 2021) (Figure 3.22). In these pathways, the use of coal, gas and oil is reduced by 90, 25, and 41%, respectively, between 2019 and 2050 and 91, 39, and 78% between 2019 and 2100; coal without CCS is further reduced to 99% below its 2019 levels in 2100. These pathways show an increase in low carbon energy, with 88% (69-97%) of primary energy from low carbon sources in 2100, with different combinations of low carbon fuels (e.g., non-biomass renewables, biomass, nuclear, and CCS) (Rogelj et al. 2018a,b; van Vuuren et al. 2018) (Chapter 6.7, Section 3.4.1). Across all pathways likely to limit warming to 2°C and below, non-biomass renewables account for 52% (24 to 77%) of primary energy in 2100 (Pietzcker et al. 2017; Creutzig et al. 2017; Rogelj et al. 2018b); Figure 3.22, Chapter 6). There are some studies analysing the potential for 100% renewable energy systems (Hansen et al. 2019); however, there are a range of issues around such systems (see Chapter 6.6, Box 6.6).

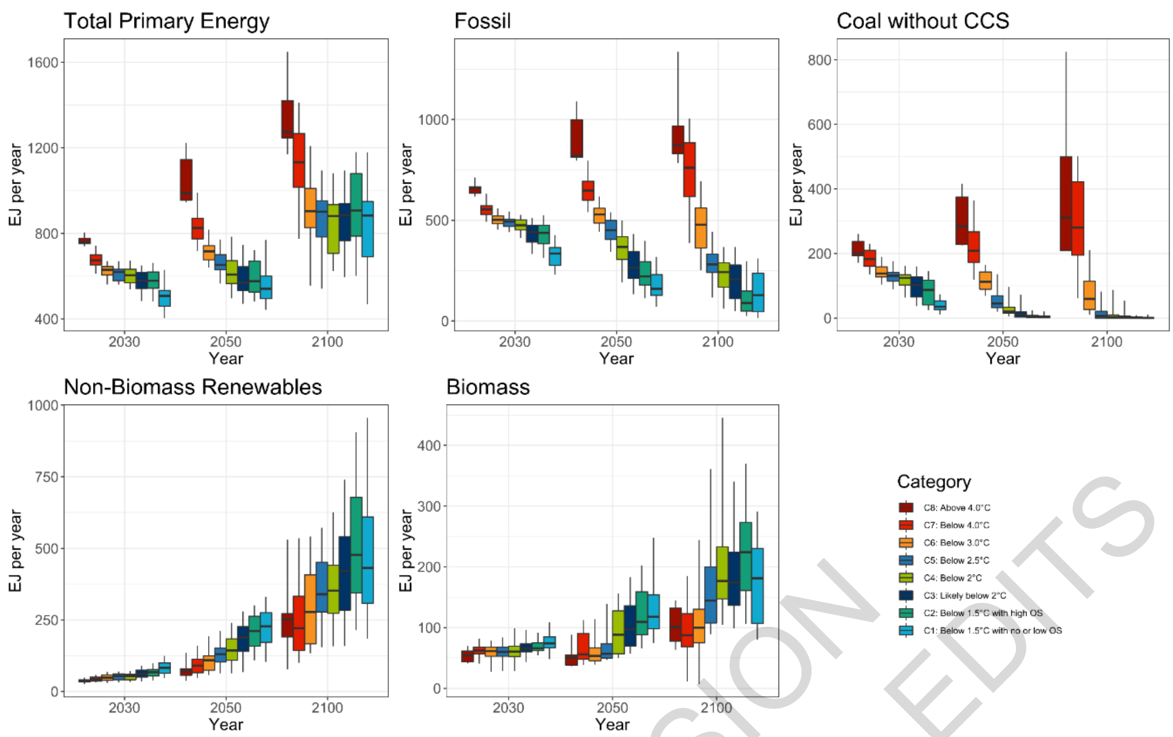

Figure 3.22 Primary energy consumption across scenarios: total primary energy (top left), fossil fuels (top middle), coal without CCS (top right), non-biomass renewables (bottom left), and biomass (bottom middle). Scenarios are grouped by their temperature category. Primary energy is reported in direct equivalent, where one unit of nuclear or non-biomass renewable energy output is reported as one unit of primary energy. Not all subcategories of primary energy are shown.

Stringent emissions reductions at the level required to limit warming to 2°C or 1.5°C are achieved through increased electrification of end-use, resulting in increased electricity generation in all pathways (*high confidence*) (Figure 3.23) (Rogelj et al. 2018a; Azevedo et al. 2021). Nearly all electricity in pathways likely to limit warming to 2℃ and below is from low or no carbon fuels (Rogelj et al. 2018a; Azevedo et al. 2021), with different shares of nuclear, biomass, non-biomass renewables, and fossil CCS across pathways. Low emissions scenarios also show increases in hydrogen use (Figure 3.23).

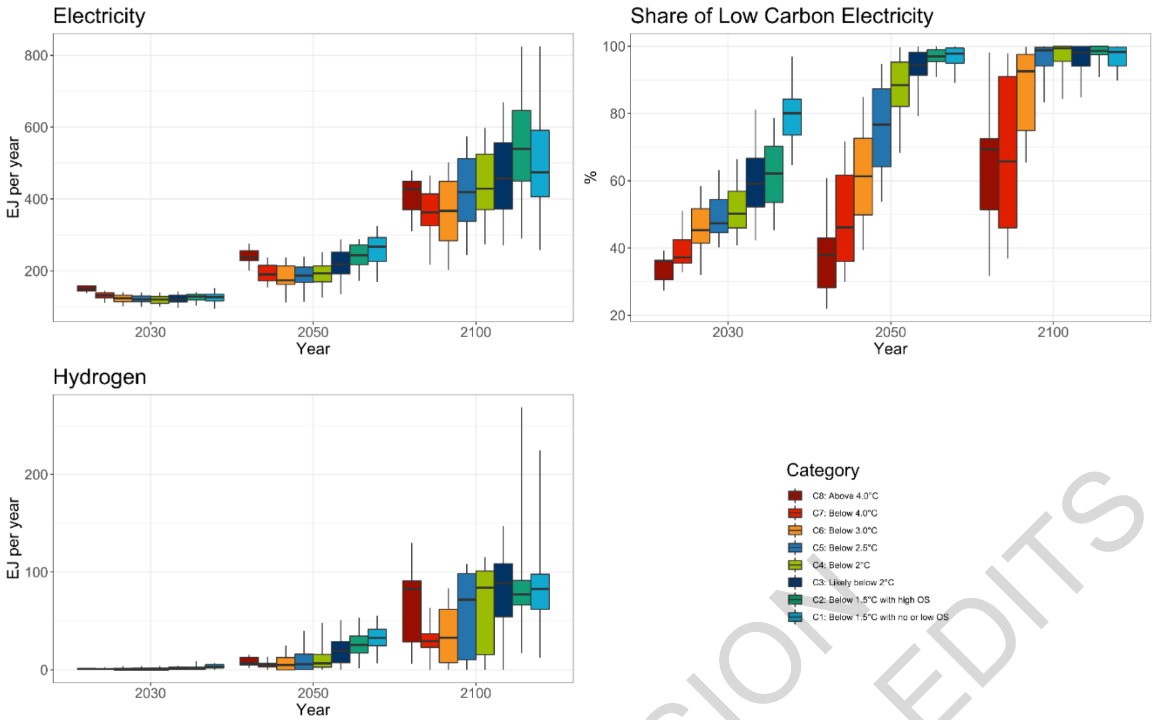

Figure 3.23: Electricity (top left), share of low carbon electricity (top right), and hydrogen (bottom left) production across all scenarios, grouped by the categories introduced in section 3.2. Low carbon includes non-biomass renewables, biomass, nuclear, and CCS.

3.4.3 Buildings

Global final energy use in the building sector increases in all pathways as a result of population growth and increasing affluence (Figure 3.24). There is very little difference in final energy intensity for the buildings sector across scenarios. Direct CO2 emissions from the buildings sector vary more widely across temperature stabilization levels than energy consumption. In 2100, scenarios above 3ºC [C7-C8] still show an increase of CO2 emissions from buildings around 29% above 2019, while all scenarios likely to limit warming to 2ºC and below have emission reductions of around 85% (8-100%). Carbon intensity declines in all scenarios, but much more sharply as the warming level is reduced.

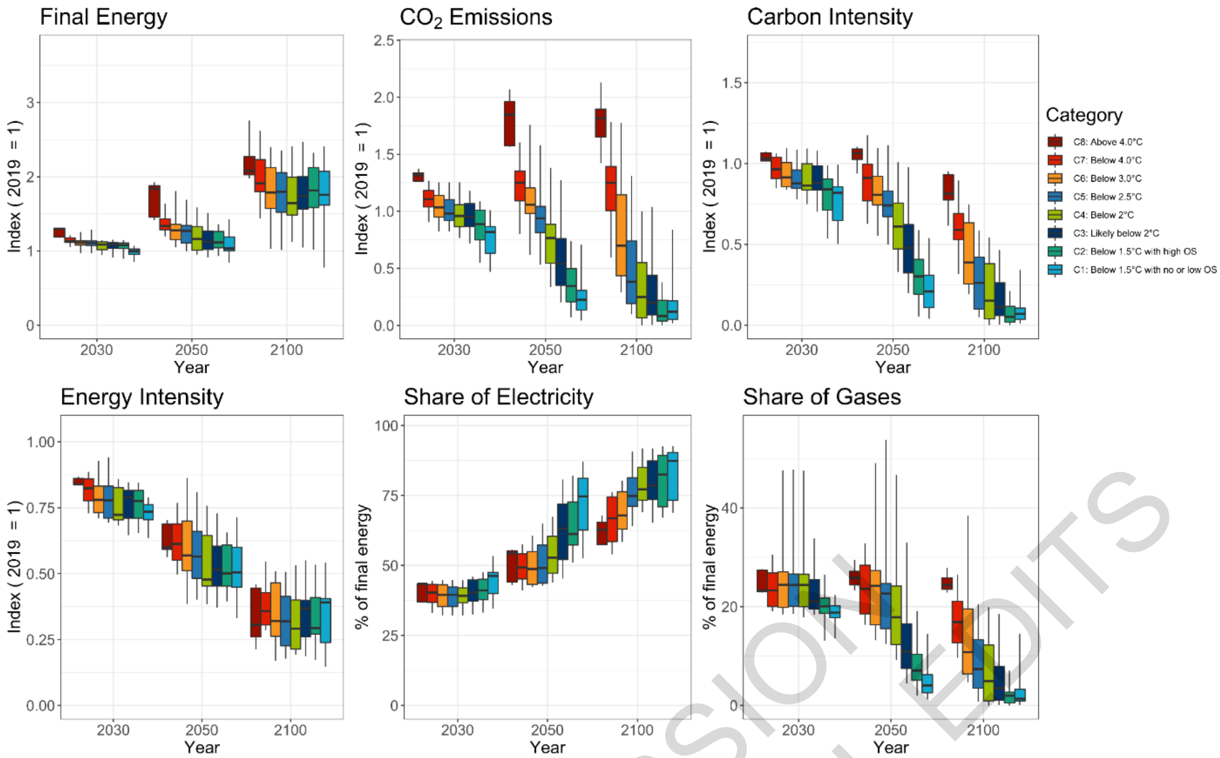

Figure 3.24: Buildings final energy (top left), CO_2 emissions (top middle), carbon intensity (top right), energy intensity (bottom left), share of final energy from electricity (bottom middle), and share of final energy from gases (bottom right). Energy intensity is final energy per unit of GDP. Carbon intensity is CO_2 emissions per EJ of final energy. The first four indicators are indexed to 2019[11], where values less than 1 indicate a reduction.

In all scenarios, the share of electricity in final energy use increases, a trend that is accelerated by 2050 for the scenarios likely to limit warming to 2ºC and below (Figure 3.23). By 2100, the low warming scenarios show large shares of electricity in final energy consumption for buildings. The opposite is observed for gases.

While several global IAM models have developed their buildings modules considerably over the past decade (Daioglou et al. 2012; Knobloch et al. 2017; Clarke et al. 2018; Edelenbosch et al. 2021; Mastrucci et al. 2021), the extremely limited availability of key sectoral variables in the AR6 scenarios database (such as floor space and energy use for individual services) prohibit a detailed analysis of sectoral dynamics. Individual studies in the literature often focus on single aspects of the buildings sector, though collectively providing a more comprehensive overview (Edelenbosch et al. 2020; Ürge-Vorsatz et al. 2020). For example, energy demand is driven by economic development that fulfills basic needs (Mastrucci et al. 2019; Rao et al. 2019a), but also drives up floorspace in general (Daioglou et al. 2012; Levesque et al. 2018; Mastrucci et al. 2021) and ownership of energy intensive appliances such as air conditioners (Isaac and van Vuuren 2009; Colelli and Cian 2020; Poblete-Cazenave et al. 2021). These dynamics are heterogeneous and lead to differences in energy demand and emission mitigation potential across urban/rural buildings and income levels (Krey et al. 2012; Poblete-Cazenave et al. 2021). Mitigation scenarios rely on fuel switching and technology (Dagnachew et al. 2020; Knobloch et al. 2017), efficiency improvement in building envelopes (Edelenbosch et al. 2021; Levesque et al. 2018) and behavioural changes (Niamir et al. 2018, 2020;

FOOTNOTE [11] 2019 values are from model results and interpolated from other years when not directly reported.

van Sluisveld et al. 2016). The in-depth dynamics of mitigation in the building sector are explored in Chapter 9.

3.4.4 Transport

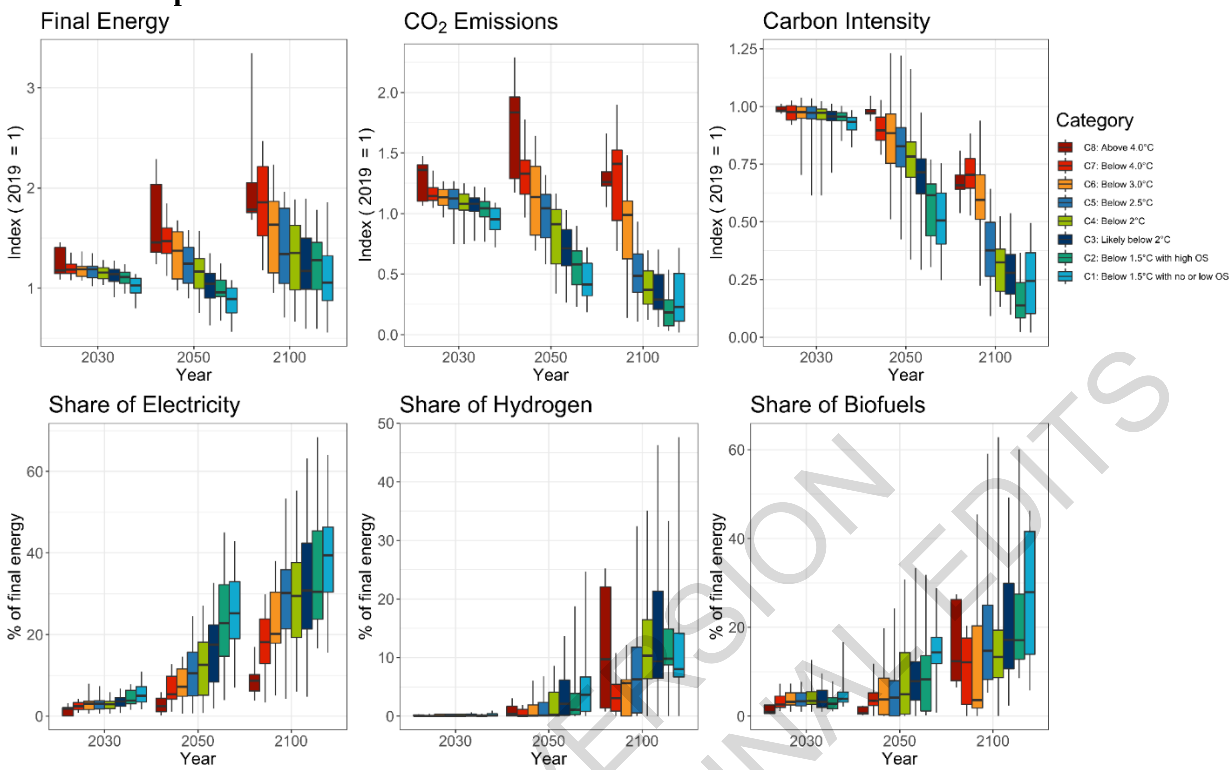

Figure 3.25: Transport final energy (top left), CO_2 emissions (top middle), carbon intensity (top right), and share of final energy from electricity (bottom left), hydrogen (bottom middle), and biofuels (bottom right). See Chapter 10 for a discussion of energy intensity. Carbon intensity is CO_2 emissions per EJ of final energy. The first three indicators are indexed to 2019[12], where values less than 1 indicate a reduction.

Reference scenarios show growth in transport demand, particularly in aviation and freight (Yeh et al. 2017; Sharmina et al. 2020; Müller-Casseres et al. 2021b). Energy consumption continues to be dominated by fossil fuels in reference scenarios, with some increases in electrification (Edelenbosch et al. 2020; Yeh et al. 2017). CO_2 emissions from transport increase for most models in reference scenarios (Yeh et al. 2017; Edelenbosch et al. 2020).

The relative contribution of demand-side reduction, energy efficiency improvements, fuel switching, and decarbonisation of fuels, varyies by model, level of mitigation, mitigation options available, and underlying socio-economic pathway (Longden 2014; Wise et al. 2017; Luderer et al. 2018; Yeh et al. 2017; Edelenbosch et al. 2020; Müller-Casseres et al. 2021a,b). IAMs typically rely on technology-focused measures like energy efficiency improvements and fuel switching to reduce carbon emissions (Pietzcker et al. 2014; Edelenbosch et al. 2017a; Yeh et al. 2017; Zhang et al. 2018a,b; Rogelj et al. 2018b; Sharmina et al. 2020). Many mitigation pathways show electrification of the transport system (Luderer et al. 2018; Pietzcker et al. 2014; Longden 2014; Zhang et al. 2018a); however, without decarbonization of the electricity system, transport electrification can increase total energy system emissions (Zhang and Fujimori 2020). A small number of pathways include demand-side mitigation measures in the transport sector; these studies show reduced carbon prices and reduced dependence on

FOOTNOTE [12] 2019 values are from model results and interpolated from other years when not directly reported.

CDR (Grubler et al. 2018; Méjean et al. 2019; van de Ven et al. 2018; Zhang et al. 2018c) (Section 3.4.1).

Across all IAM scenarios assessed, final energy demand for transport continues to grow, including in many stringent mitigation pathways (Figure 3.25). The carbon intensity of energy declines substantially by 2100 in likely 2°C and below scenarios, leading to substantial declines in transport sector CO2 emissions with increased electrification of the transport system (Figure 3.23).
The transport sector has more detail than other sectors in many IAMs (Edelenbosch et al. 2020); however, there is considerable variation across models. Some models (e.g., GCAM, IMAGE, MESSAGE-GLOBIOM) represent different transport modes with endogenous shifts across modes as a function of income, price, and modal speed (Edelenbosch et al. 2020).[13] However, IAMs, including those with detailed transport, exclude several supply-side (e.g., synthetic fuels) and demand-side (e.g., behaviour change, reduced shipping, telework and automation) mitigation options (Davis et al. 2018; Köhler et al. 2020; Mittal et al. 2017; Gota et al. 2019; Wilson et al. 2019; Creutzig et al. 2016; Sharmina et al. 2020; Pietzcker et al. 2014; Lefèvre et al. 2021; Müller-Casseres et al. 2021a,b).

As a result of these missing options and differences in how mitigation is implemented, IAMs tend to show less mitigation than the potential from national transport/energy models (Wachsmuth and Duscha 2019; Gota et al. 2019; Yeh et al. 2017; Edelenbosch et al. 2020). For the transport sector as a whole, studies suggest a mitigation potential of 4-5 GtCO_2 per year in 2030 (Edelenbosch et al. 2020) with complete decarbonization possible by 2050 (Gota et al. 2019; Wachsmuth and Duscha 2019). However, in the scenarios assessed in this chapter that limit warming to below 1.5°C with no or limited overshoot, transport sector CO_2 emissions are reduced by only 59% (28% to 81%) in 2050 compared to 2015. IAM pathways also show less electrification than the potential from other studies; pathways that limit warming to below 1.5°C with no or limited overshoot show a median of 25% (7 to 43%) of final energy from electricity in 2050, while the IEA NZE scenario includes 45% (IEA 2021a).

FOOTNOTE [13] Some of these models are treated as global transport energy sectoral models (GTEMs) in Chapter 10.

3.4.5 Industry

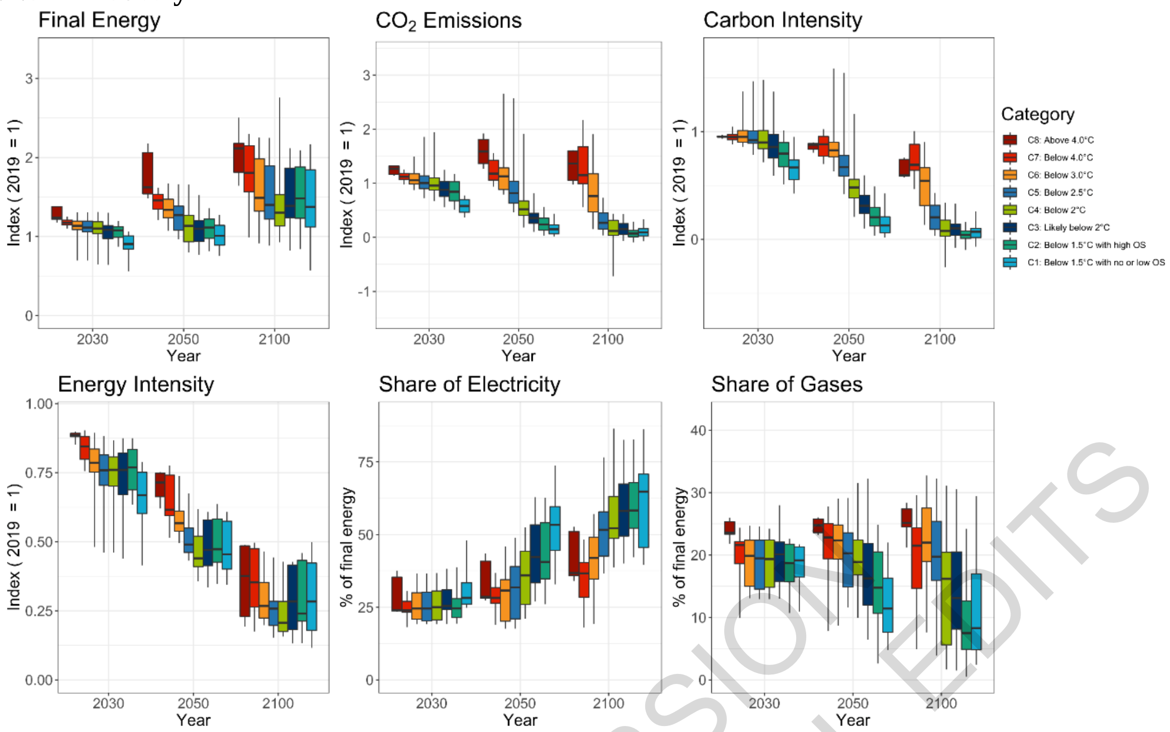

Figure 3.26: Industrial final energy, including feedstocks (top left), CO_2 emissions (top middle), carbon intensity (top right), energy intensity (bottom left), share of final energy from electricity (bottom middle), and share of final energy from gases (bottom right). Energy intensity is final energy per unit of GDP. Carbon intensity is CO_2 emissions per EJ of final energy. The first four indicators are indexed to 2019,[14] where values less than 1 indicate a reduction. Industrial sector CO_2 emissions include fuel combustion emissions only.

Reference scenarios show declines in energy intensity, but increases in final energy use in the industrial sector (Edelenbosch et al. 2017b). These scenarios show increases in CO_2 emissions both for the total industrial sector (Edelenbosch et al. 2020; Luderer et al. 2018; Edelenbosch et al. 2017b) and individual subsectors like cement and iron and steel (van Ruijven et al. 2016; van Sluisveld et al. 2021) or chemicals (Daioglou et al. 2014; van Sluisveld et al. 2021).

In mitigation pathways, CO_2 emissions reductions are achieved through a combination of energy savings (via energy efficiency improvements and energy conservation), structural change, fuel switching, and decarbonization of fuels (Grubler et al. 2018; Luderer et al. 2018; Edelenbosch et al. 2017b, 2020). Mitigation pathways show reductions in final energy for industry compared to the baseline (Edelenbosch et al. 2017b; Luderer et al. 2018; Edelenbosch et al. 2020) and reductions in the carbon intensity of the industrial sector through both fuel switching and the use of CCS (Paltsev et al. 2021; Luderer et al. 2018; Edelenbosch et al. 2017b, 2020; van Ruijven et al. 2016; van Sluisveld et al. 2021). The mitigation potential differs depending on the industrial subsector and the availability of CCS, with larger potential reductions in the steel sector (van Ruijven et al. 2016) and cement industry (Sanjuán et al. 2020) than in the chemicals sector (Daioglou et al. 2014). Many scenarios, including stringent mitigation scenarios, show continued growth in final energy; however, the carbon intensity of energy declines in all mitigation scenarios (Figure 3.26).

The representation of the industry sector is very aggregate in most IAMs, with only a small subset of models disaggregating key sectors such as cement, fertilizer, chemicals, and iron and steel (Pauliuk et

FOOTNOTE [14] 2019 values are from model results and interpolated from other years when not directly reported.

al. 2017; Edelenbosch et al. 2017b; Daioglou et al. 2014; van Sluisveld et al. 2021) (Napp et al. 2019). IAMs often account for both energy combustion and feedstocks (Edelenbosch et al. 2017b), but IAMs typically ignore material flows and miss linkages between sectors (Kermeli et al. 2019; Pauliuk et al. 2017). By excluding these processes, IAMs misrepresent the mitigation potential of the industry sector, e.g. by overlooking mitigation from material efficiency and circular economies (Sharmina et al. 2020), which can have substantial mitigation potential (Chapter 5.3.4, Chapter 11.3).

Sectoral studies indicate a large mitigation potential in the industrial sector by 2050, including the potential for net zero CO_2 emissions for steel, plastics, ammonia, and cement (Section 11.4.1). Detailed industry sector pathways show emissions reductions between 39 and 94% by mid-century compared to present day[15] (Section 11.4.2) and a substantial increase in direct electrification (IEA 2021a). IAMs show comparable mitigation potential to sectoral studies with median reductions in CO_2 emissions between 2019 and 2050 of 70% in scenarios likely to limit warming to 2°C and below and a maximum reduction of 96% (Figure 3.26). Some differences between IAMs and sectoral models can be attributed to differences in technology availability, with IAMs sometimes including more technologies (van Ruijven et al. 2016) and sometimes less (Sharmina et al. 2020). Figure 3.27: Reduction in AFOLU GHG emissions from 2019. The AFOLU CO_2 estimates in this figure are not necessarily comparable with country GHG inventories (see Chapter 7).

3.4.6 Agriculture, Forestry and Other Land Use (AFOLU)

Mitigation pathways show substantial reductions in CO_2 emissions, but more modest reductions in AFOLU CH_4 and N_2O emissions (*high confidence*) (Popp et al. 2017; Roe et al. 2019; Reisinger et al. 2021) (Figure 3.27). Pathways limiting warming to likely 2°C or below are projected to reach net zero CO_2 emissions in the AFOLU sector around 2033 (2024-2060); however AFOLU CH_4 and N_2O emissions remain positive in all pathways (Figure 3.27). While IAMs include many land-based mitigation options, these models exclude several options with large mitigation potential, such as biochar, agroforestry, restoration/avoided conversion of coastal wetlands, and restoration/avoided conversion of peatland (Smith et al. 2019; IPCC 2019a) (see also Chapter 7, Section 3.4). Sectoral studies show higher mitigation potential than IAM pathways, as these studies include more mitigation options than IAMs (*medium confidence*) (Chapter 7).

FOOTNOTE [15] Some studies calculate emissions reductions in 2050 compared to 2014, while others note emissions reductions in 2060 relative to 2018.

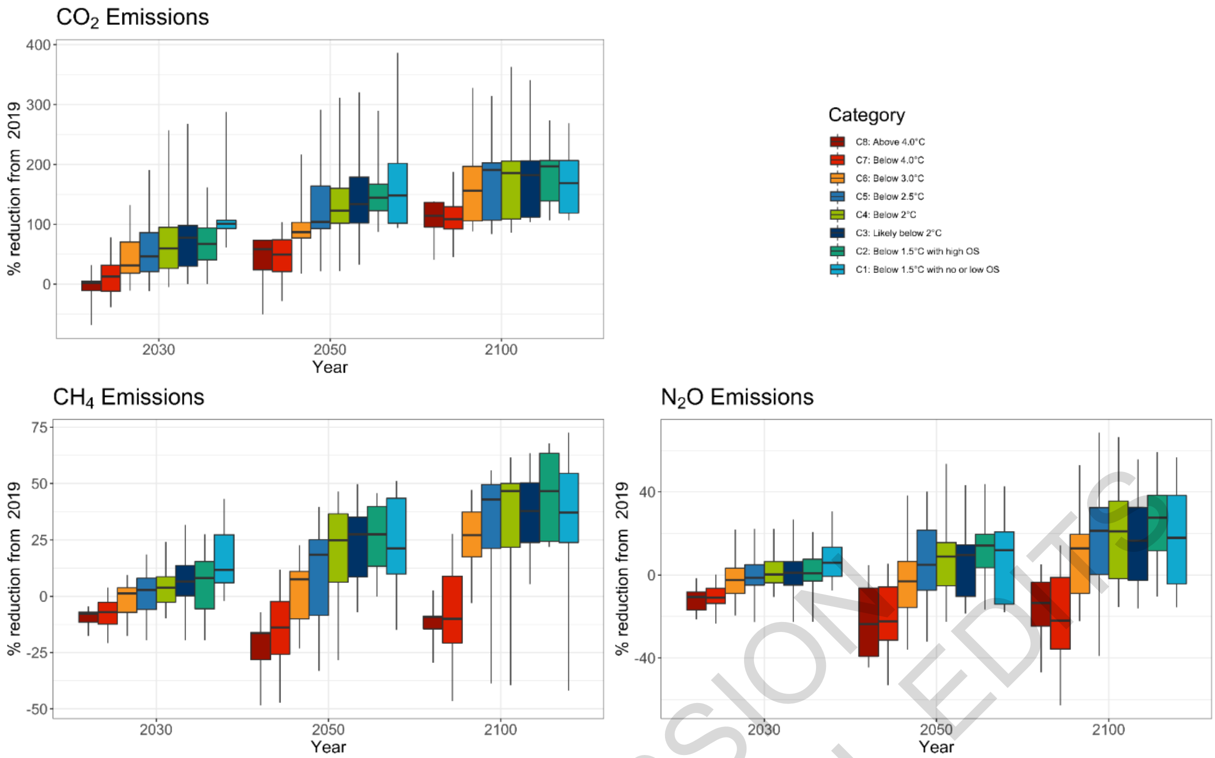

Figure 3.27: Reduction in AFOLU GHG emissions from 2019. The AFOLU CO_2 estimates in this figure are not necessarily comparable with country GHG inventories (see Chapter 7).

Limiting warming to likely 2°C or below can result in large scale transformation of the land surface (*high confidence*) (Popp et al. 2017; Rogelj et al. 2018a,b; Brown et al. 2019; Roe et al. 2019). The scale of land transformation depends, *inter alia*, on the temperature goal and the mitigation options included (Popp et al. 2017; Rogelj et al. 2018a; IPCC 2019a). Pathways with more demand-side mitigation options show less land transformation than those with more limited options (van Vuuren et al. 2018; Grubler et al. 2018; IPCC 2019a). Most of these pathways show increases in forest cover, with an increase of 322 million ha (-67 to 890 million ha) in 2050 in 1.5°C pathways with no or limited overshoot, whereas bottom up models portray an economic potential of 300-500 million ha of additional forest (Chapter 7). Many IAM pathways also include large amounts of energy cropland area, to supply biomass for bioenergy and BECCS, with 199 (56-482) million ha in 2050 in 1.5°C pathways with no or limited overshoot. Large land transformations, such as afforestation/reforestation and widespread planting of energy crops, can have implications for biodiversity and sustainable development (see Section 3.7, Chapter 7 - Subsection 7.7.4, Chapter 12 - Section 12.5).

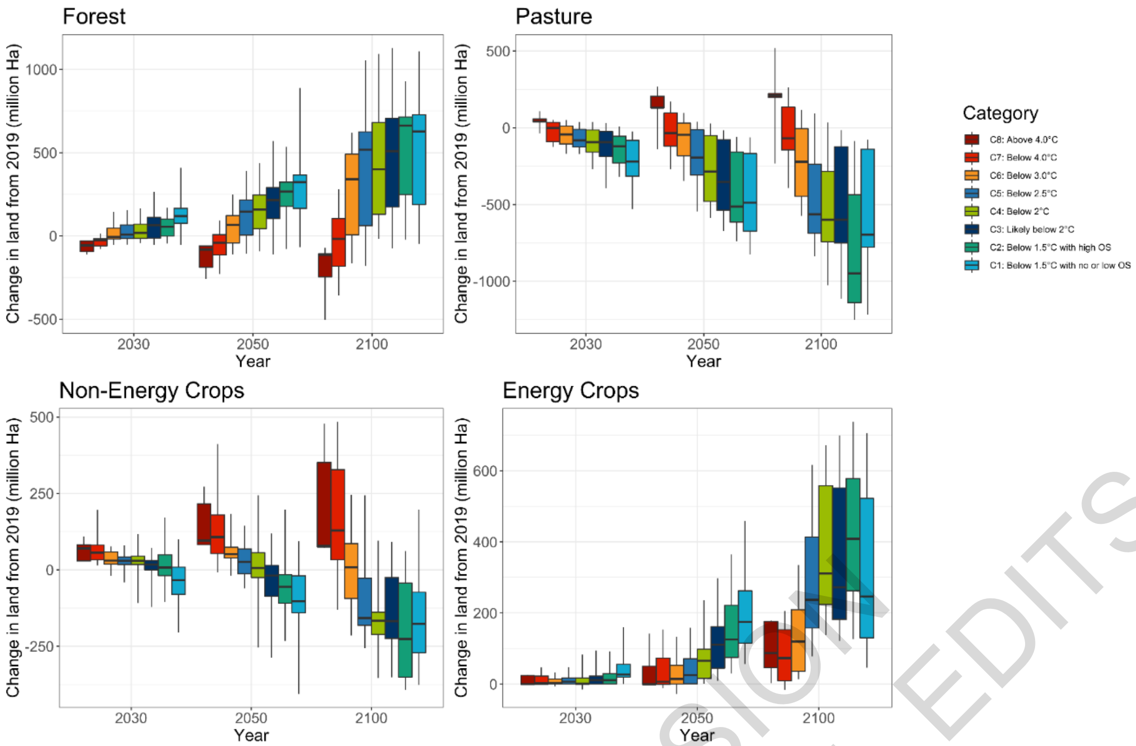

Figure 3.28: Change in Land Cover from 2019 in million hectares. Positive values indicate an increase in area.

Delayed mitigation has implications for land use transitions (Hasegawa et al. 2021a). Delaying mitigation action can result in a temporary overshoot of temperature and large-scale deployment of CDR in the second half of the century to reduce temperatures from their peak to a given level (Smith et al. 2019; Hasegawa et al. 2021a). IAM pathways rely on afforestation and BECCS as CDR measures, so delayed mitigation action results in substantial land use change in the second half of the century with implications for sustainable development (Hasegawa et al. 2021a) (see also Section 3.7). Shifting to earlier mitigation action reduces the amount of land required for this, though at the cost of larger land use transitions earlier in the century (Hasegawa et al. 2021a). Earlier action could also reduce climate impacts on agriculture and land-based mitigation options (Smith et al. 2019).

Some AFOLU mitigation options can enhance vegetation and soil carbon stocks such as reforestation, restoration of degraded ecosystems, protection of ecosystems with high carbon stocks and changes to agricultural land management to increase soil carbon (*high confidence*) (Fuss et al. 2018; Griscom et al. 2017; de Coninck et al. 2018; Smith et al. 2019) (WGIII Chapter 7). The timescales associated with these options indicate that carbon sinks in terrestrial vegetation and soil systems can be maintained or enhanced so as to contribute towards long-term mitigation (*high confidence*); however, many AFOLU mitigation options do not continue to sequester carbon indefinitely (IPCC 2019a; Fuss et al. 2018; de Coninck et al. 2018)(WGIII Chapter 7). In the very long term (latter part of the century and beyond), it will become more challenging to continue to enhance vegetation and soil carbon stocks, so that the associated carbon sinks could diminish or even become sources (*high confidence*) (IPCC 2019a; de Coninck et al. 2018) (WGI Chapter 5). Sustainable forest management, including harvest and forest regeneration, can help to remediate and slow any decline in the forest carbon sink, for example by restoring degraded forest areas, and so go some way towards addressing the issue of sink saturation (IPCC 2019) (WGI Chapter 5; WGIII Chapter 7). The accumulated carbon resulting from mitigation options that enhance carbon sequestration (e.g., reforestation, soil carbon sequestration) is also at risk of future loss due to disturbances (e.g., fire, pests) (Anderegg et al. 2020; Boysen et al. 2017; IPCC 2019a; Smith et al. 2019; Fuss et al. 2018; de Coninck et al. 2018)(WGI

Chapter 5). Maintaining the resultant high vegetation and soil carbon stocks could limit future land use options, as maintaining these carbon stocks would require retaining the land use and land cover configuration implemented to achieve the increased stocks.

Anthropogenic land CO_2 emissions and removals in IAM pathways cannot be directly compared with those reported in national GHG inventories (high confidence) (Grassi et al. 2018, 2021) (Chapter 7.2). Due to differences in definitions for the area of managed forests and what is emissions and removals are considered anthropogenic, the reported anthropogenic land CO_2 emissions and removals differ by ~5.5 $GtCO_2$ yr^{-1} between IAMs, which rely on bookkeeping approaches (e.g., (Houghton and Nassikas 2017), and national GHG inventories (Grassi et al. 2021). Such differences in definitions can alter the reported time at which anthropogenic net zero CO_2 emissions are reached for a given emission scenario. Using national inventories would lead to an earlier reported time of net zero (van Soest et al. 2021b) or to lower calculated cumulative emissions until the time of net zero (Grassi et al. 2021) as compared to IAM pathways. The numerical differences are purely due to differences in the conventions applied for reporting the anthropogenic emissions and do not have any implications for the underlying land-use changes or mitigation measures in the pathways. Grassi et al. (Grassi et al. 2021) offers a methodology for adjusting to reconcile these differences and enable a more accurate assessment of the collective progress achieved under the Paris Agreement (Chapter 7, Cross-Chapter Box 6 in Chapter 7).

3.4.7 Other Carbon Dioxide Removal Options

Table 3.5: Carbon dioxide removal in assessed pathways. Scenarios are grouped by temperature categories, as defined in section 3.2.4. Quantity indicates the median and 5-95% range of cumulative sequestration from 2020 to 2100 in $GtCO_2$. Count indicates the number of scenarios with positive values for that option.

CDR Option	Below 1.5°C with no or limited OS		Below 1.5°C with high OS		Likely below 2°C	
	Quantity	Count	Quantity	Count	Quantity	Count
Total CDR	584 (192 to 959)	95	645 (333 to 1221)	123	533 (193 to 895)	294
CO_2 removal on managed land including A/R	262 (17 to 397)	64	330 (28 to 439)	82	209 (20 to 415)	196
BECCS	334 (32 to 780)	91	464 (226 to 842)	122	291 (174 to 653)	294
Enhanced weathering	0 (0 to 47)	2	0 (0 to 0)	1	0 (0 to 0)	1
DACCS	30 (0 to 308)	31	109 (0 to 539)	24	19 (0 to 253)	91

This subsection includes other CDR options not discussed in the previous subsections, including direct air carbon capture and storage (DACCS), enhanced weathering, and ocean-based approaches, focusing on the role of these options in long-term mitigation pathways, using both IAMs (Rickels et al. 2018; Realmonte et al. 2019; Chen and Tavoni 2013; Marcucci et al. 2017; Strefler et al. 2021a; Fuhrman et al. 2019, 2020, 2021; Akimoto et al. 2021) and non-IAMs (Fuss et al. 2013; González and Ilyina 2016; Bednar et al. 2021; Shayegh et al. 2021). There are other options discussed in the literature, like methane capture (Jackson et al. 2019), however, the role of these options in long-term mitigation pathways has not been quantified and are thus excluded here. Chapter 12 includes a more detailed description of the individual technologies, including their costs, potentials, financing, risks, impacts, maturity and upscaling.

Very few studies and pathways include other CDR options (Table 3.5). Pathways with DACCS include potentially large removal from DACCS (up to 37 $GtCO_2$ yr^{-1} in 2100) in the second half of the century (Realmonte et al. 2019; Marcucci et al. 2017; Chen and Tavoni 2013; Fuhrman et al. 2020, 2021; Shayegh et al. 2021; Akimoto et al. 2021) and reduced cost of mitigation (Bistline and Blanford 2021; Strefler et al. 2021a). At large scales, the use of DACCS has substantial implications for energy use, emissions, land, and water; substituting DACCS for BECCS results in increased energy usage, but reduced land use change and water withdrawals (Fuhrman et al., 2020, 2021; Chapter 12.3.2; IPCC WGI Chapter 5). The level of deployment of DACCS is sensitive to the rate at which it can be scaled up, the climate goal or carbon budget, the underlying socioeconomic scenario, the availability of other decarbonization options, the cost of DACCS and other mitigation options, and the strength of carbon cycle feedbacks (Honegger and Reiner 2018; Fuss et al. 2013; Fuhrman et al. 2021; Bistline and Blanford 2021; Chen and Tavoni 2013; Strefler et al. 2021a; Fuhrman et al. 2020; Realmonte et al. 2019) (IPCC WGI Chapter 5). Since DACCS consumes energy, its effectiveness depends on the type of energy used; the use of fossil fuels would reduce its sequestration efficiency (Creutzig et al. 2019; Babacan et al. 2020; NASEM 2019). Studies with additional CDR options in addition to DACCS (e.g., enhanced weathering, BECCS, afforestation, biochar, and soil carbon sequestration) find that CO_2 removal is spread across available options (Holz et al. 2018; Strefler et al. 2021a). Similar to DACCS, the deployment of deep ocean storage depends on cost and the strength of carbon cycle feedbacks (Rickels et al. 2018).

3.5 Interaction between near-, medium- and long-term action in mitigation pathways

This section assesses the relationship between long-term climate goals and short- to medium-term emissions reduction strategies based on the mitigation pathway literature. After an overview of this relationship (3.5.1), it provides an assessment of what currently planned near-term action implies for limiting warming to 1.5-2°C (3.5.2), and to what extent pathways with accelerated action beyond current NDCs can improve the ability to keep long-term targets in reach (3.5.3).

The assessment in this section shows that if mitigation ambitions in current NDCs[16] are followed until 2030, leading to estimated emissions of 47-57 $GtCO_2$-eq in 2030[17] (Chapter 4.2.2), it is no longer possible to stay below 1.5°C warming with no or limited overshoot (*high confidence*). Instead, it would entail high overshoot (typically >0.1ºC) and reliance on net negative CO_2 emissions with uncertain potential to return warming to 1.5°C by the end of the century. It would also strongly increase mitigation challenges to likely limit warming to 2°C *(high confidence)*. GHG emissions

FOOTNOTE [16] The term "**current NDCs**" used in this section and throughout the report refers to the most recent nationally determined contributions submitted to the UNFCCC as well as those publicly announced with sufficient detail on targets, but not yet submitted, up to 11 October 2021, and reflected in studies published up to 11 October 2021. In contrast, "**original NDCs**" refers to nationally determined contributions that were initially submitted to the Paris Agreement by parties, largely reflecting the state of submissions until the year 2019. See Chapter 4.2.

FOOTNOTE [17] In this section, the emissions range associated with current (or original) NDCs refer to the combined emissions ranges from the two cases of implementing only the unconditional elements of current NDCs (50-57 $GtCO_2$-eq) and implementing both unconditional and conditional elements of current NDCs (47-53 $GtCO_2$-eq), if not specified otherwise.

reductions would need to abruptly increase after 2030 to an annual average rate of 1.3-2.1 GtCO2-eq during the period 2030-2050, around 70% higher than in mitigation pathways assuming immediate action[18] to likely limit warming to 2°C. The higher post-2030 reduction rates would have to be obtained in an environment of continued build-up of fossil fuel infrastructure and less development of low carbon alternatives until 2030. A lock-in into fossil-fuel intensive production systems (carbon lock-in) will increase the societal, economic and political strain of a rapid low-carbon transition after 2030 (*high confidence*).

The section builds on previous assessments in the IPCC's Fifth Assessment Report (Clarke et al. 2014) and Special Report on 1.5°C Warming (Rogelj et al. 2018a). The literature assessed in these two reports has focused on delayed action until 2030 in the context of limiting warming to 2°C (den Elzen et al. 2010; van Vuuren and Riahi 2011; Kriegler et al. 2015; Luderer et al. 2013, 2016; Riahi et al. 2015; Rogelj et al. 2013a) and 1.5°C (Strefler et al. 2018; Luderer et al. 2018; Rogelj et al. 2013b). Here we provide an update of these assessments drawing on the most recent literature on global mitigation pathways. New studies have focused, inter alia, on constraining near term developments by peak warming limits (Rogelj et al. 2019b; Strefler et al. 2021b; Riahi et al. 2021) and updating assumptions about near- and medium term emissions developments based on national plans and long-term strategies (Roelfsema et al. 2020) (Chapter 4.2). Several studies have explored new types of pathways with accelerated action bridging between current policy plans and the goal of limiting warming below 2°C (Kriegler et al. 2018a; van Soest et al. 2021a) and looked at hybrid international policy regimes to phase in global collective action (Bauer et al. 2020).

3.5.1 Relationship between long-term climate goals and near- to medium-term emissions reductions

The close link between cumulative CO_2 emissions and warming has strong implications for the relationship between near-, medium-, and long-term climate action to limit global warming. The AR6 WGI Assessment has estimated a remaining carbon budget of 500 (400) $GtCO_2$ from the beginning of 2020 onwards for staying below 1.5°C with 50% (67%) likelihood, subject to additional uncertainties about historic warming and the climate response and variations in warming from non-CO_2 climate forcers (Canadell and Monteiro 2019) (see also WGI Chapter 5, Section 5.5). For comparison, if current CO_2 emissions of more than 40 GtCO2 are keeping up until 2030, more than 400 $GtCO_2$ will be emitted during 2021–2030, already exhausting the remaining carbon budget for 1.5°C by 2030.

The relationship between warming limits and near term action is illustrated in Figure 3.29, using a set of 1.5-2°C scenarios with different levels of near term action, overshoot and non-CO_2 warming contribution from a recent study (Riahi et al. 2021). In general, the more CO_2 is emitted until 2030, the less CO_2 can be emitted thereafter to stay within a remaining carbon budget and below a warming limit. Scenarios with immediate action to observe the warming limit give the longest time to exhaust the associated remaining carbon budget and reach net zero CO_2 emissions (light blue line in Figure 3.29, Cross-Chapter Box 3 in this chapter). In comparison, following projected NDC emissions until 2030 would imply a more pronounced drop in emissions from 2030 levels to net zero to make up for the additional near-term emissions (orange lines in Figure 3.29). If such a drop does not occur, the remaining carbon budget is exceeded and net negative CO_2 emissions are required to return global mean temperature below the warming limit (black lines in Figure 3.29) (Fuss et al. 2014; Clarke et al. 2014; Rogelj et al. 2018a).

FOOTNOTE [18] In this section, near term emissions outcomes are often compared to near term emissions in mitigation **pathways with immediate action** towards a warming limit. These are defined as pathways that immediately after imposing the warming limit turn to global mitigation action tapping into all least cost abatement options available globally. These pathways are often called cost-effective or least-cost pathways in the literature. The onset of immediate action is defined by scenario design and is typically chosen to be the first time step after 2020 in immediate action scenarios assessed in this report.

The relationship between warming limits and near-term action is also affected by the warming contribution of non-CO_2 greenhouse gases and other short lived climate forcers (3.3, Working Group I 6.7). The estimated budget values for limiting warming to 1.5-2°C already assume stringent reductions in non-CO_2 greenhouse gases and non-CO_2 climate forcing as found in 1.5-2°C pathways (3.3, Cross-Working Group Box 1; Working Group I 5.5, Box 5.2). Further variations in non-CO_2 warming observed across 1.5-2°C pathways can vary the median estimate for the remaining carbon budget by 220 $GtCO_2$ (Working Group I 5.5). In 1.5-2°C pathways, the non-CO_2 warming contribution differs strongly between the near-, medium and long term. Changes to the atmospheric composition of short-lived climate forcers dominate the warming response in the near term (Working Group I 6.7). CO_2 reductions are combined with strong reductions in air pollutant emissions due to rapid reduction in fossil fuel combustion and in some cases the assumption of stringent air quality policies (Rao et al. 2017b; Smith et al. 2020c). As air pollutants exert a net cooling effect, their reduction drives up non-CO_2 warming in the near term, which can be attenuated by the simultaneous reduction of methane and black carbon (Smith et al. 2020b; Shindell and Smith 2019) (Working Group I 6.7). After 2030, the reduction in methane concentrations and associated reductions in tropospheric ozone levels tend to dominate so that a peak and decline in non-CO_2 forcing and non-CO_2 induced warming can occur before net zero CO_2 is reached (Figure 3.29) (Rogelj et al. 2018a) The more stringent the reductions in methane and other short-lived warming agents like black carbon, the lower this peak and the earlier the decline of non-CO_2 warming, leading to a reduction of warming rates and overall warming in the near to medium term (Smith et al. 2020b; Harmsen et al. 2020). This is important for keeping warming below a tight warming limit that is already reached around mid-century as is the case in 1.5°C pathways (Xu and Ramanathan 2017). Early and deep reductions of methane emissions, and other short-lived warming agents like black carbon, provide space for residual CO_2-induced warming until the point of net zero CO2 emissions is reached (purple lines in Figure 3.29). Such emissions reductions have also been advocated due to co-benefits for, e.g., reducing air pollution (Rao et al. 2016; Shindell et al. 2017a, 2018; Shindell and Smith 2019; Rauner et al. 2020a; Vandyck et al. 2020).

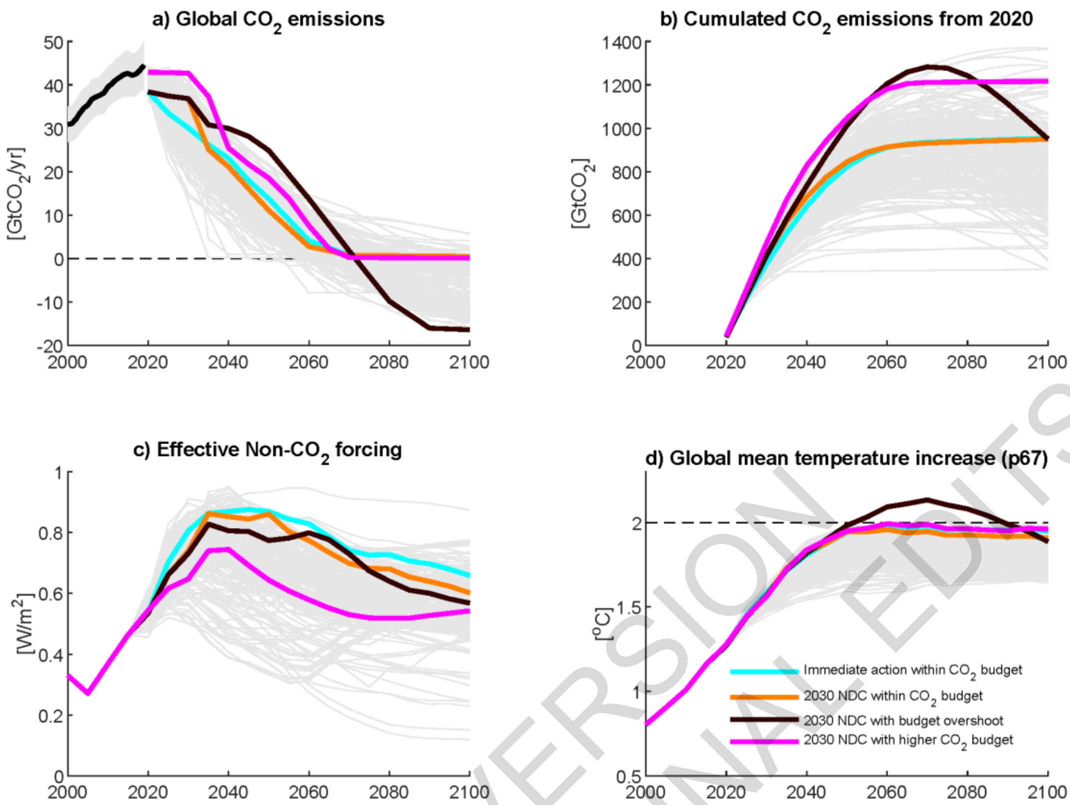

Figure 3.29: Illustration of emissions and climate response in four mitigation pathways with different assumptions about near term policy developments, global warming limit and non-CO_2 warming contribution drawn from Riahi et al. (2021). Shown are (a) CO_2 emissions trajectories, (b) cumulative CO_2 emissions, (c) effective non-CO_2 radiative forcing, and (d) the resulting estimate of the 67th percentile of global mean temperature response relative to 1850-1900. Light blue lines show a scenario that acts immediately on a remaining carbon budget of 900 $GtCO_2$ from 2020 without allowing net negative CO_2 emissions, i.e., temporary budget overshoot (COFFEE 1.1, Scenario EN_NPi2020_900). Orange and black lines show scenarios drawn from the same model that follow the NDCs until 2030 and thereafter introduce action to stay within the same budget – in one case excluding net negative CO_2 emissions like before (orange lines; COFFEE 1.1., Scenario EN-INDCi2030_900) and in the other allowing for a temporary overshoot of the carbon budget until 2100 (black lines; COFFEE 1.1., Scenario EN-INDCi2030_900f). Light blue lines describe a scenario following the NDCs until 2030, and then aiming for a higher budget of 2300 $GtCO_2$ without overshoot (AIM/CGE 2.2, Scenario EN-INDCi2030_1200). It is drawn from another model which projects a lower anthropogenic non-CO_2 forcing contribution and therefore achieves about the same temperature outcome as the other two non-overshoot scenarios despite the higher CO_2 budget. Grey funnels include the trajectories from all scenarios that likely limit warming to 2°C (Category C3). Historical CO_2 emissions until 2019 are from Chapter SM.2.1 EDGAR v6.0.

The relationship between long-term climate goals and near term action is further constrained by social, technological, economic and political factors (Aghion et al. 2019; Mercure et al. 2019; van Sluisveld et al. 2018b; Cherp et al. 2018; Jewell and Cherp 2020; Trutnevyte et al. 2019b). These factors influence path dependency and transition speed (Vogt-Schilb et al. 2018; Pahle et al. 2018). While detailed integrated assessment modelling of global mitigation pathways accounts for technology inertia (Bertram et al. 2015a; Mercure et al. 2018) and technology innovation and diffusion (Wilson et al. 2013; van Sluisveld et al. 2018a; Luderer et al. 2021), there are limitations in capturing socio-technical and political drivers of innovation, diffusion and transition processes (Keppo et al. 2021; Gambhir et al. 2019; Hirt et al. 2020; Köhler et al. 2019). Mitigation pathways show a wide range of transition speeds that have been interrogated in the context of socio-technical inertia (Gambhir et al. 2017; Kefford et al. 2018; Kriegler et al. 2018a; Brutschin et al. 2021) vs. accelerating technological change and self-enforcing socio-economic developments (Creutzig et al. 2017; Zenghelis 2019) (Section 3.8). Diagnostic analysis of detailed IAMs found a lag of 8-20 years between the convergence of emissions pricing and the convergence of emissions response after a period of differentiated emission prices (Harmsen et al. 2021). This provides a measure of the inertia to changing policy signals in the model response. It is about half the timescale of 20-40 years observed for major energy transitions (Grubb et al. 2021). Hence, the mitigation pathways assessed here capture socio-technical inertia in reducing emissions, but the limited modelling of socio-political factors may alter the extent and persistence of this inertia.

3.5.2 Implications of near-term emission levels for keeping long-term climate goals within reach

The implications of near-term climate action for long-term climate outcomes can be explored by comparing mitigation pathways with different near-term emissions developments aiming for the same climate target (Vrontisi et al. 2018; Riahi et al. 2015; Roelfsema et al. 2020). A particular example is the comparison of cost-effective pathways with immediate action to limit warming to 1.5-2°C with mitigation pathways pursuing more moderate mitigation action until 2030. After the adoption of the Paris Agreement, near term action was often modelled to reflect conditional and unconditional elements of originally submitted NDCs (2015-2019) (Fawcett et al. 2015; Fujimori et al. 2016a; Kriegler et al. 2018a; Vrontisi et al. 2018; Roelfsema et al. 2020). The most recent modelling studies also include submission of updated NDCs or announcements of planned updates in the first half of 2021 (Network for Greening the Financial System 2021; Riahi et al. 2021). Emissions levels under current NDCs (see footnote 15) are assessed to range between 47–57 $GtCO_2$-eq in 2030 (Chapter 4.2.2). This assessed range corresponds well to 2030 emissions levels in 2°C mitigation pathways in the literature that are designed to follow the original or current NDCs until 2030[19]. For the 139 scenarios of this kind that are collected in the AR6 scenario database and that still likely limit warming to 2°C, the 2030 emissions range is 52.5 (44.5-57) GtCO2-eq (based on native model reporting) and 52 (46.5-56) GtCO2-eq, respectively (based on harmonized emissions data for climate assessment (Annex III part II section 2.4); median and 5th to 95th percentile). This close match allows a robust assessment of the implications of implementing current NDCs for post-2030 mitigation efforts and warming outcomes based on the literature and the AR6 scenarios database.

The assessed emission ranges from implementing the unconditional (unconditional and conditional) elements of current NDCs implies an emissions gap to cost-effective mitigation pathways of 20-26 (16-24) $GtCO_2$-eq in 2030 for limiting warming to 1.5°C with no or limited overshoot and 10-17 (7-14) $GtCO_2$-eq in 2030 for likely limiting warming to 2°C (Chapter 4, Cross-Chapter Box 2 in chapter 2). The emissions gap gives rise to a number of mitigation challenges (Rogelj et al. 2013a; Kriegler et al. 2013a, 2018b,a; Riahi et al. 2015; Luderer et al. 2013, 2018; Fujimori et al. 2016b; Fawcett et al. 2015; Strefler et al. 2018; Winning et al. 2019; UNEP 2020; SEI et al. 2020): (i) larger transitional challenges post-2030 to still remain under the warming limit (, in particular higher CO_2 emissions reduction rates and technology transition rates required during 2030-2050; (ii) larger lock-in into carbon-intensive infrastructure and increased risk of stranded fossil fuel assets (3.5.2.2); and (iii) larger reliance on CDR to reach net zero CO_2 more rapidly and compensate excess emissions in the second half of the century (3.5.2.1). All these factors exacerbate socio-economic strain of

FOOTNOTE [19] The intended design of mitigation pathways in the literature can be deduced from underlying publications and study protocols. This information was collected as part of this assessment to establish a categorization of policy assumptions underpinning the mitigation pathways collected in the AR6 scenario database (3.2; Annex III Part II section 3.2).

implementing the transition, leading to an increased risk of overshooting the warming and a higher risk of climate change impacts (Drouet et al. 2021).

The challenges are illustrated in Table 3.6 and Figure 3.30, surveying global mitigation pathways in the literature that were collected in the AR6 scenarios database. There is a clear trend of increasing peak warming with increasing 2030 GHG emission levels (Figure 3.30a+b). In particular, there is no mitigation pathway designed to follow the NDCs until 2030 in 2030 that can limit warming to 1.5°C with no or limited overshoot. Our assessment confirms the finding of the IPCC Special Report on 1.5°C Warming for the case of current NDCs, including updates until 11 October 2021 that were assessed in the literature, that pathways following the NDCs until 2030 "*would not limit global warming to 1.5°C, even if supplemented by very challenging increases in the scale and ambition of emissions reductions after 2030*" (SR1.5 SPM). This assessment is now more robust than in SR1.5 as it is based on a larger set of 1.5-2°C pathways with better representation of current trends and plans covering a wider range of post-2030 emissions developments. In particular, a recent multi-model study limiting peak cumulative CO_2 emissions for a wide range of carbon budgets and immediate vs NDC-type action until 2030 established a feasibility frontier for the existence of such pathways across participating models (Riahi et al. 2021).

2030 emissions levels in the NDC range also tighten the remaining space to likely limit warming 2°C. As shown in Figure 3.30b, the 67th percentile of peak warming reaches values above 1.7°C warming in pathways with 2030 emissions levels in this range. To still have a likely chance to stay below 2°C, the global post-2030 GHG emission reduction rates would need to be abruptly raised in 2030 from 0-0.8 $GtCO_2$-eq yr^{-1} to an average of 1.3-2.1 $GtCO_2$-eq yr^{-1} during the period 2030-2050 (Figure 3.30c), around 70% of that in immediate mitigation pathways confirming findings in the literature (Winning et al. 2019). Their average reduction rate of 0.6-1.4 $GtCO_2$ yr^{-1} would already be unprecedented at the global scale and with a few exceptions national scale for an extended period of time (Riahi et al. 2015). For comparison, the impact of COVID-19 on the global economy is projected to lead to a decline of ca. 2.5-3 GtCO2 of global CO_2 emissions from fossil fuel and industry in 2020 (Friedlingstein et al. 2020) (Chapter 2.2).

The increased post-2030 transition challenge in mitigation pathways with moderate near term action is also reflected in the timing of reaching net zero CO_2 emissions (Figure 3.30d and Table 3.6) (Cross-Chapter Box 3 in this chapter). As 2030 emission levels and the cumulated CO_2 emissions until 2030 increase, the remaining time for dropping to net zero CO_2 and staying within the remaining carbon budget shortens (Figure 3.29). This gives rise to an inverted v-shape of the lower bound on the year of reaching net zero as a function of 2030 emissions levels. Reaching low in 2030 facilitates reaching net zero early (left leg of the inverted v), but staying high until 2030 also requires to reach net zero CO_2 faster to compensate for higher emissions early on (right leg of the inverted v). Overall, there is a considerable spread of the timing of net zero CO_2 for any 2030 emissions level due to variation in the timing of spending the remaining carbon budget and the non-CO_2 warming contribution (Cross-Chapter Box 3 in this chapter).

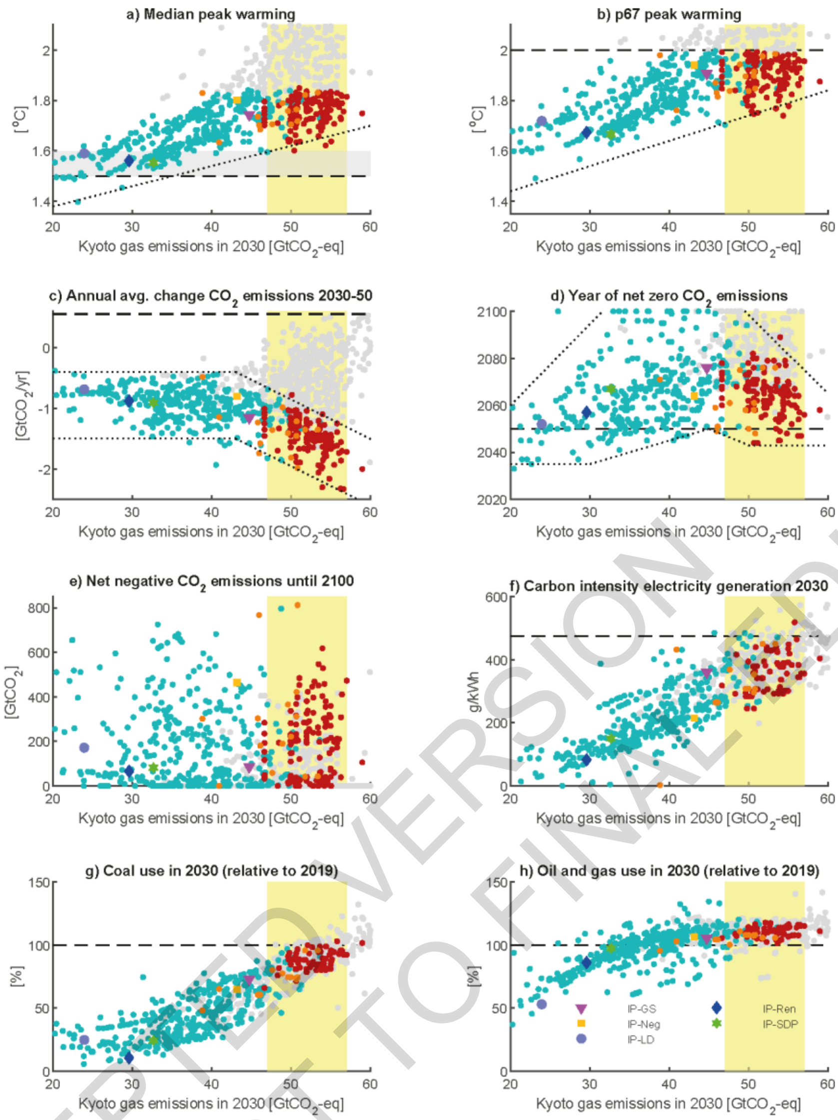

Figure 3.30: Relationship between level of global GHG emissions in 2030 and selected indicators as listed in the panel titles for scenarios collected in the AR6 scenario database. Emissions data based on harmonized emissions used for the climate assessment. All scenarios likely to limit warming to 2°C or below are coloured blue or red (see p67 peak warming in panel b). The large majority of blue coloured scenarios act immediately on the temperature target, while red coloured scenarios depict all those that were designed to follow the NDCs or lesser action until 2030 and orange coloured scenarios comprise a small set of pathways with additional regulatory action beyond NDCs (3.5.3). Grey coloured scenarios exceed the 2°C (p67), either by temporary overshoot or towards the end of the century. Large markers denote the 5 illustrative mitigation pathways (legend in Panel h; Section 3.2). Shaded yellow areas depict the estimated range of 2030 emissions from current NDCs (Chapter 4.2.2). Dotted lines are inserted in some panels to highlight trends in the dependency of selected output variables on 2030 GHG emissions levels (see text)

There is also a profound impact on the underlying transition of energy and land use (Table 3.6 and Figure 3.30f-h). Scenarios following NDCs until 2030 show a much smaller reduction in fossil fuel use, only half of the growth in renewable energy use, and a smaller reduction in CO_2 and CH_4 land use emissions in 2030 compared to immediate action scenarios. This is then followed by a much faster reduction of land use emissions and fossil fuels, and a larger increase of nuclear energy, bioenergy and non-biomass renewable energy during the medium term in order to get close to the levels of the immediate action pathways in 2050. This is combined with a larger amount of net negative CO2 emissions that are used to compensate the additional emissions before 2030. The faster transition during 2030-2050 is taking place from a greater investment in fossil fuel infrastructure and lower deployment of low carbon alternatives in 2030, adding to the socio-economic challenges to realize the higher transition rates (Section 3.5.2.2). Therefore, these pathways also show higher mitigation costs, particularly during the period 2030-2050, than immediate action scenarios (3.6.1, Figure 3.34d) (Liu et al. 2016; Vrontisi et al. 2018; Kriegler et al. 2018a).. Given these circumstances and the fact the modelling of socio-political and institutional constraints is limited in integrated assessment models (Keppo et al. 2021; Gambhir et al. 2019; Hirt et al. 2020; Köhler et al. 2019), the feasibility of realizing these scenarios is assessed to be lower (Gambhir et al. 2017; Napp et al. 2017; Brutschin et al. 2021) (cf. Section 3.8), increasing the risk of an overshoot of climate goals.

Table 3.6: Comparison of key scenario characteristics for four scenario classes (see Table 3.2): (i) immediate action to limit warming to 1.5°C with no or limited overshoot, (ii) near team action following the NDCs until 2030 and returning warming to below 1.5°C (50% chance) by 2100 with high overshoot, (iii) immediate action to likely limit warming to 2°C, and (iv) near term action following the NDCs until 2030 followed by post-2030 action to likely limit warming to 2°C. The classes (ii) and (iv) comprise the large majority of scenarios indicated by red dots, and the classes (i) and (iii) the scenarios depicted by blue dots in Figure 3.30. Shown are median and interquartile ranges (in brackets) for selected global indicators. Emissions ranges are based on harmonized emissions data for the climate assessment with the exception of land use CO2 emissions for which uncertainty in historic estimates is large. Numbers are rounded to the nearest 5.

Global indicators	**1.5°C**	**1.5°C by 2100**	**Likely < 2°C**	
	Immediate action, with no or limited overshoot (C1, 97 scenarios)	NDCs until 2030, with overshoot before 2100 (subset of 42 scenarios in C2)	Immediate action (C3a, 204 scenarios)	NDCs until 2030 (C3b; 97 scenarios)
Kyoto GHG emissions in 2030 (% rel to 2019)	-45 (-50,-40)	-5 (-5,0)	-25 (-35,-20)	-5 (-10,0)
in 2050 (% rel to 2019)	-85 (-90,-80)	-75 (-85,-70)	-65 (-70,-60)	-70 (-70,-60)
CO_2 emissions change in 2030 (% rel to 2019)	-50 (-60,-40)	-5 (-5,0)	-25 (-35,-20)	-5 (-5,0)
in 2050 (% rel to 2019)	-100 (-105,-95)	-85 (-95,-80)	-70 (-80,-65)	-75 (-80,-65)
Net land use CO_2 emissions in 2030 (% rel to 2019)	-100 (-105,-95)	-30 (-60,-20)	-90 (-105,-75)	-20 (-80,-20)
in 2050 (% rel to 2019)	-150 (-200,-100)	-135 (-165,-120)	-135 (-185,-100)	-130 (-145,-115)
CH_4 emissions in 2030 (% rel to 2019)	-35 (-40,-30)	-5 (-5,0)	-25 (-35,-20)	-10 (-15,-5)
in 2050 (% rel to 2019)	-50 (-60,-45)	-50 (-60,-45)	-45 (-50,-40)	-50 (-65,-45)
Cumulative CCS until 2100 ($GtCO_2$)	665 (520,900)	670 (535,865)	605 (490,895)	535 (440,725)
of which BECCS ($GtCO_2$)	330 (250,560)	365 (280,590)	350 (240,455)	270 (240,400)
Cumulative net negative CO2 emissions until 2100 ($GtCO_2$)	190 (0,385)	320 (250,440)	10 (0,120)	70 (0,200)
Primary energy from coal in 2030 (% rel to 2019)	-75 (-80,-65)	-10 (-20,-5)	-50 (-65,-35)	-15 (-20,-10)
in 2050 (% rel to 2019)	-95 (-100,-80)	-90 (-100,-85)	-85 (-100,-65)	-80 (-90,-70)
Primary energy from oil in 2030 (% rel to 2019)	-10 (-25,0)	5 (5,10)	0 (-10,10)	10 (5,10)
in 2050 (% rel to 2019)	-60 (-75,-40)	-50 (-65,-30)	-30 (-45,-15)	-40 (-55,-20)

Primary energy from gas in 2030 (% rel to 2019)	-10 (-30,0)	15 (10,25)	10 (0,15)	15 (10,15)
in 2050 (% rel to 2019)	-45 (-60,-20)	-45 (-55,-25)	-10 (-35,15)	-30 (-45,-5)
Primary energy from nuclear in 2030 (% rel to 2019)	40 (5,70)	10 (0,25)	35 (5,50)	10 (0,30)
in 2050 (% rel to 2019)	90 (10,305)	100 (40,135)	85 (30,200)	75 (30,120)
Primary energy from biomass in 2030 (% rel to 2019)	75 (55,130)	45 (20,75)	60 (35,105)	45 (10,80)
in 2050 (% rel to 2019)	290 (215,430)	230 (170,440)	240 (130,355)	260 (95,435)
Primary energy from non-biomass renewables in 2030 (% rel to 2019)	225 (150,270)	100 (85,145)	150 (115,190)	115 (85,130)
in 2050 (% rel to 2019)	725 (540,955)	665 (515,925)	565 (415,765)	625 (545,705)
Carbon intensity of electricity in 2030 (% rel to 2019)	-75 (-85,-70)	-30 (-40,-30)	-60 (-70,-50)	-35 (-40,-30)
in 2050 (% rel to 2019)	-100 (-100,-100)	-100 (-100,-100)	-95 (-100,-95)	-100 (-100,-95)
Carbon intensity of non-electric final energy consumption in 2030 (% rel to 2019)	-40 (-50,-35)	0 (0,5)	-20 (-30,-15)	0 (0,0)
in 2050 (% rel to 2019)	-80 (-85,-75)	-70 (-75,-70)	-60 (-65,-55)	-65 (-70,-55)

3.5.2.1 Overshoot and net negative CO_2 emissions

If near to medium term emissions developments deplete the remaining carbon budget, the associated warming limit will be overshot. Some pathways that return median warming to below 1.5°C by the end of the century show mid-century overshoots of up to 1.8°C median warming. The overshoot tends to be the higher, the higher 2030 emissions. Mitigation pathways with 2030 emissions levels in the NDC range consistently overshoot 1.5°C by 0.15-0.3°C. This leads to higher risks from climate change impacts during the time of overshoot compared to pathways that limit warming to 1.5°C with no or limited overshoot (Tachiiri et al. 2019; Hofmann et al. 2019; Schleussner et al. 2016a; Mengel et al. 2018; Drouet et al. 2021; Lenton et al. 2019). Furthermore, even if warming is reversed by net negative emissions, other climate changes such as sea level rise would continue in their current direction for decades to millennia (WGI Chapter 4.6 and Chapter 5.6).

Returning warming to lower levels requires net negative CO_2 emissions in the second half of the century (Fuss et al. 2014; Clarke et al. 2014; Rogelj et al. 2018a). The amount of net negative CO_2 emissions in pathways limiting warming to 1.5-2°C climate goals varies widely, with some pathways not deploying net negative CO_2 emissions at all and others deploying up to -600 to -800 $GtCO_2$. The amount of net negative CO_2 emissions tends to increase with 2030 emissions levels (Figure 3.30e and Table 3.6). Studies confirmed the ability of net negative CO_2 emissions to reduce warming, but pointed to path dependencies in the storage of carbon and heat in the Earth system and the need for further research particularly for cases of high overshoot (Keller et al. 2018a,b; Tokarska et al. 2019; Zickfeld et al. 2016, 2021). WGI assessed the reduction in global surface temperature to be approximately linearly related to cumulative CO2 removal and, with lower confidence, that the amount of cooling per unit CO2 removed is approximately independent of the rate and amount of removal (WGI TS.3.3.2). Still there remains large uncertainty about a potential asymmetry between the warming response to CO_2 emissions and the cooling response to net negative CO_2 emissions (Zickfeld et al. 2021). It was also shown that warming can adversely affect the efficacy of carbon dioxide removal measures and hence the ability to achieve net negative CO_2 emissions (Boysen et al. 2016).

Obtaining net negative CO_2 emissions requires massive deployment of carbon dioxide removal (CDR) in the second half of the century, on the order of 220 (160-370) GtCO2 for each 0.1°C degree of cooling (based on the assessment of the likely range of the transient response to cumulative CO_2 emissions in WGI Chap. 5.5, not taking into account potential asymmetries in the temperature response to CO_2 emissions and removals). CDR is assessed in detail in Chapter 12.3 of this report (see also Cross-Chapter Box 8 in Chapter 12). Here we only point to the finding that CDR ramp-up rates and absolute deployment levels are tightly limited by techno-economic, social, political, institutional and sustainability constraints (Smith et al. 2016; Boysen et al. 2017; Nemet et al. 2018; Fuss et al. 2018, 2020; Hilaire et al. 2019; Jia et al. 2019) (Chapter 12.3). CDR therefore cannot be deployed arbitrarily to compensate any degree of overshoot. A fraction of models was not able to compute pathways that would follow the mitigation ambition in unconditional and conditional NDCs until 2030 and return warming to below 1.5°C by 2100 (Luderer et al. 2018; Roelfsema et al. 2020; Riahi et al. 2021).There exists a three-way trade-off between near-term emissions developments until 2030, transitional challenges during 2030-50, and long-term CDR deployment post 2050 (Sanderson et al. 2016; Holz et al. 2018; Strefler et al. 2018). For example, Strefler et al. (2018) find that if CO_2 emission levels stay around 40 $GtCO_2$ until 2030, within the range of what is projected for current unconditional and conditional NDCs, rather than being halved to 20 $GtCO_2$ until 2030, CDR deployment in the second half of the century would have to increase by 50%-100%, depending on whether the 2030-2050 CO_2 emissions reduction rate is doubled from 6% to 12% or kept at 6% per year. This three-way trade-off has also been identified at the national level (Pan et al. 2020).

In addition to enabling a temporary budget overshoot by net negative CO_2 emissions in the second half of the century, CDR can also be used to compensate – on an annual basis - residual CO_2 emissions from sources that are difficult to eliminate and to reach net zero CO_2 emissions more rapidly if deployed before this point (Kriegler et al. 2013b; Rogelj et al. 2018a). This explains its continued deployment in pathways that exclude overshoot and net negative CO_2 emissions (Riahi et al. 2021). However, given the timescales that would likely be needed to ramp-up CDR to Gigaton scale (Nemet et al. 2018), it can be expected to only make a limited contribution to reaching net zero CO_2 as fast as possible. In the vast majority (95%) of 1.5-2°C mitigation pathways assessed in this report, cumulative CDR deployment did not exceed 100 $GtCO_2$ until mid-century. This adds to the risk of excessively relying on CDR to compensate for weak mitigation action until 2030 by either facilitating massive net CO_2 emissions reduction rates during 2030-2050 or allowing a high temporary overshoot of 1.5°C until the end of the century. If international burden sharing considerations are taken into account, the CDR penalty for weak action could increase further, in particular for developed countries (Fyson et al. 2020). Further assessment of CDR deployment in 1.5-2°C mitigation pathways is found in Section 3.4.7.

3.5.2.2 Carbon lock-in and stranded assets

There already exists a substantial and growing carbon lock-in today, as measured by committed emissions associated with existing long-lived infrastructure {Chapter 2.7, Figure 2.31}. If existing fossil-fuel infrastructure would continue to be operated as historically, they would entail CO_2 emissions exceeding the carbon budget for 1.5°C {Chapter 2.7.2, Figure 2.32}. However, owner-operators and societies may choose to retire existing infrastructure earlier than in the past, and committed emissions are thus contingent on the competitiveness of non-emitting alternative technologies and climate policy ambition. Therefore, in mitigation pathways, some infrastructure may become stranded assets. Stranded assets have been defined as "assets that have suffered from unanticipated or premature write-downs, devaluations or conversion to liabilities" (Caldecott 2017).

A systematic map of the literature on carbon lock-in has synthesized quantification of stranded-assets in the mitigation pathways literature, and showed that (i) coal power plants are the most exposed to risk of becoming stranded, (ii) delayed mitigation action increases stranded assets and (iii) sectoral distribution and amount of stranded assets differ between countries (Fisch-Romito et al. 2020). There is high agreement that existing fossil fuel infrastructure would need to be retired earlier than historically, used less, or retrofitted with CCS, to stay within the remaining carbon budgets of limiting warming to 1.5°C or 2°C (Johnson et al. 2016; Kefford et al. 2018; Pfeiffer et al. 2018; Cui et al. 2019; Fofrich et al. 2020; Rogelj et al. 2018a). Studies estimate that cumulative early retired power plant capacities by 2060 can be up to 600 GW for gas and 1700 GW for coal (Iyer et al. 2015a; Kefford et al. 2018), that only 42% of the total capital stock of both operating and planned coal-fired powers plants can be utilized to be compatible with the 2°C target (Pfeiffer et al. 2018), and that coal-fired power plants in scenarios consistent with keeping global warming below 2°C or 1.5°C retire one to three decades earlier than historically has been the case (Cui et al. 2019; Fofrich et al. 2020). After coal, electricity production based on gas is also projected to be phased out, with some capacity remaining as back-up (van Soest et al. 2017a). Kefford et al. (2018) find USD541 billion worth of stranded fossil fuel power plants could be created by 2060, with China and India the most exposed.

Some publications have suggested that stranded long-lived assets may be even more important outside of the power sector. While stranded power sector assets by 2050 could reach up to USD1.8 trillion in scenarios consistent with a 2°C target, Saygin et al. (2019) found a range of USD5-11 trillion in the buildings sectors. Muldoon-Smith and Greenhalgh (2019) have even estimated a potential value at risk for global real estate assets up to USD21 trillion. More broadly, the set of economic activities that are potentially affected by a low carbon transition is wide and includes also energy-intensive industries, transport and housing, as reflected in the concept of climate policy relevant sectors introduced in Battiston et al. (2017). The sectoral distribution and amount of stranded assets differ across countries (Fisch-Romito et al. 2020). Capital for fossil fuel production and distribution represents a larger share of potentially stranded assets in fossil fuel producing countries such as the United States and Russia. Electricity generation would be a larger share of total stranded assets in emerging countries because this capital is relatively new compared to its operational lifetime. Conversely, buildings could represent a larger part of stranded capital in more developed countries such as the United States, EU or even Russia because of high market value and low turnover rate.

Many quantitative estimates of stranded assets along mitigation pathways have focused on fossil fuel power plants in pathways characterized by mitigation ambition until 2030 corresponding to the current NDCs followed by strengthened action afterwards to limit warming to 2°C or lower (Bertram et al. 2015a; Iyer et al. 2015b; Lane et al. 2016; Farfan and Breyer 2017; van Soest et al. 2017a; Luderer et al. 2018; Kriegler et al. 2018a; Cui et al. 2019; Saygin et al. 2019; SEI et al. 2020). Pathways following current NDCs until 2030 do not show a significant reduction of coal, oil and gas use (Figure 3.30f-h, Table 3.6) compared to immediate action pathways. Stranded coal power assets are evaluated to be higher by a factor of 2-3 if action is strengthened after 2030 rather than now (Iyer et al. 2015b; Cui et al. 2019). There is high agreement that the later climate policies are implemented, the higher the expected stranded assets and the societal, economic and political strain of strengthening action. Associated price increases for carbon-intensive goods and transitional macro-economic costs have been found to scale with the emissions gap in 2030 (Kriegler et al. 2013a). At the aggregate level of the whole global economy, Rozenberg et al. (2015) showed that each year of delaying the start of mitigation decreases the required CO_2 intensity of new production by 20-50 gCO_2/USD. Carbon lock-in can have a long-lasting effect on future emissions trajectories after 2030. Luderer et al. (2018) compared cost-effective pathways with immediate action to limit warming to 1.5-2°C with pathways following the NDCs until 2030 and adopting the pricing policy of the cost-effective pathways thereafter and found that the majority of additional CO_2 emissions from carbon lock-in occurs after 2030, reaching a cumulative amount of 290 (160–330) $GtCO_2$ by 2100 (2.7.2). Early action and avoidance of investments in new carbon-intensive assets can minimize these risks.

The risk of stranded assets has implications for workers depending from those assets, asset owners, assets portfolio managers, financial institutions and the stability of the financial system. Chapter 6 assesses the risks and implications of stranded assets for energy systems (6.7.3, Box 6.11) and fossil fuels (6.7.4). The implications of stranded assets for inequality and just transition are assessed in Chapter 17 (17.3.2.3). Chapter 15 assesses the literature on those implications for the financial system as well as on coping options (15.5.2, 15.6.1).
On the other hand, mitigation, by limiting climate change, reduces the risk of destroyed or stranded assets from the physical impacts of climate change on natural and human systems, from more frequent, intense or extended extreme events and from sea level rise (O'Neill et al. 2020a). The literature on mitigation pathways rarely includes an evaluation of stranded assets from climate change impacts. Unruh (Unruh 2019) suggest that these are the real stranded assets of carbon lock-in and could prove much more costly.

3.5.2.3 Global accelerated action towards long-term climate goals

A growing literature explores long-term mitigation pathways with accelerated near-term action going beyond the NDCs (Jiang et al. 2017; Roelfsema et al. 2018; Graichen et al. 2017; Kriegler et al. 2018a; van Soest et al. 2021a; Fekete et al. 2021). Global accelerated action pathways are designed to transition more gradually from current policies and planned implementation of NDCs onto a 1.5-2°C pathway and at the same time alleviate the abrupt transition in 2030 that would be caused by following the NDCs until 2030 and strengthening towards limiting warming to 2°C thereafter (Section 3.5.2). Therefore they have sometimes been called bridging scenarios / pathways in the literature (IEA 2011; Spencer et al. 2015; van Soest et al. 2021a). They rely on regionally differentiated regulatory and pricing policies to gradually strengthening regional and sectoral action beyond the mitigation ambition in the NDCs. There are limitations to this approach. The tighter the warming limit, the more is disruptive action becoming inevitable to achieve the speed of transition that would be required (Kriegler et al. 2018a). Cost effective pathways already have abrupt shifts in deployments, investments and prices at the time a stringent warming limit is imposed reflecting the fact that the overall response to climate change has so far been misaligned with long-term climate goals (Geiges et al. 2019; Rogelj et al. 2016; Fawcett et al. 2015; Schleussner et al. 2016b). Disruptive action can help to break lock-ins and enable transformative change (Vogt-Schilb et al. 2018).

The large literature on accelerating climate action was assessed in the IPCC Special Report on 1.5°C Warming (de Coninck et al. 2018) and is taken up in this report primarily in Chapters 4, 13, and 14. Accelerating climate action and facilitating transformational change requires a perspective on socio-technical transitions (Geels et al. 2016b; Geels 2018; Geels et al. 2016a), a portfolio of policy instruments to manage technological and environmental change (Goulder and Parry 2008; Fischer and Newell 2008; Acemoglu et al. 2012, 2016), a notion of path dependency and policy sequencing (Meckling et al. 2017; Pahle et al. 2018; Pierson 2000) and the evolvement of poly-centric governance layers of institutions and norms in support of the transformation (Messner 2015; Leach et al. 2007; Dietz et al. 2003). This subsection is focused on an assessment of the emerging quantitative literature on global accelerated action pathways towards 1.5-2°C, which to a large extent abstracts from the underlying processes and uses a number of stylized approaches to generate these pathways. A representative of accelerated action pathways has been identified as one of the illustrative mitigation pathways in this assessment (***GS***, Figure 3.31).

One approach relies on augmenting initially moderate emissions pricing policies with robust anticipation of ratcheting up climate action in the future (Spencer et al. 2015). If announcements of strong future climate policies are perceived to be credible, they can help to prevent carbon lock-in as investors anticipating high future costs of GHG emissions would reduce investment into fossil fuel infrastructure, such as coal power plants (Bauer et al. 2018b). However, the effectiveness of such announcements strongly hinges on their credibility. If investors believe that policy makers could drop them if anticipatory action did not occur, they may not undertake such action.

Another approach relies on international cooperation to strengthen near term climate action. These studies build on international climate policy architectures that could incentivize a coalition of like-minded countries to raise their mitigation ambition beyond what is stated in their current NDC (Graichen et al. 2017). Examples are the idea of climate clubs characterized by harmonized carbon and technology markets (Pihl 2020; Nordhaus 2015; Keohane et al. 2017; Paroussos et al. 2019) and the Powering Past Coal Alliance (Jewell et al. 2019). Paroussos et al. (2019) find economic benefits of joining a climate club despite the associated higher mitigation effort, in particular due to access to technology and climate finance. Graichen et al. (2017) find an additional reduction of 5-11 $GtCO_2eq$ compared to the mitigation ambition in the NDCs from the successful implementation of international climate initiatives. Other studies assess benefits from international transfers of mitigation outcomes (Stua 2017; Edmonds et al. 2021). Edmonds et al. (2021) find economic gains from sharing NDC emissions reduction commitments compared to purely domestic implementation of NDCs. If reinvested in mitigation efforts, the study projects an additional reduction of 9 billion tonnes of CO_2 in 2030.

The most common approach relies on strengthening regulatory policies beyond current policy trends, also motivated by the finding that such policies have so far been employed more often than comprehensive carbon pricing (Roelfsema et al. 2018; Kriegler et al. 2018a; van Soest et al. 2021a; Fekete et al. 2021; IEA 2021a). Some studies have focused on generic regulatory policies such as low carbon support policies, fossil fuel sunset policies, and resource efficiency policies (Bertram et al. 2015b; Hatfield-Dodds et al. 2017). Bertram et al. (2015b) found that a moderate carbon price combined with a coal moratorium and ambitious low carbon support policies can limit efficiency losses until 2030 if emissions pricing is raised thereafter to limit warming to 2°C. They also showed that all three components are needed to achieve this outcome. Hatfield-Dodds et al. (2017) found that resource efficiency can lower 2050 emissions by an additional 15-20% while boosting near-term economic growth. The International Energy Agency (IEA 2021a) developed a detailed net zero scenario for the global energy sector characterized by a rapid phase out of fossil fuels, a massive clean energy and electrification push, and the stabilization of energy demand, leading to 10 $GtCO_2$ lower emissions from energy use in 2030 than in a scenario following the announced pledges.

The Paris Agreement has spurred the formulation of NDCs for 2030 and mid-century strategies around the world (cf. Chapter 4). This is giving researchers a rich empirical basis to formulate accelerated policy packages taking national decarbonisation pathways as a starting point (van Soest et al. 2017b; Waisman et al. 2019; Graichen et al. 2017; Jiang et al. 2017). The concept is to identify good practice policies that had demonstrable impact on pushing low carbon options or reducing emissions in a country or region and then consider a wider roll-out of these policies taking into account regional specificities (den Elzen et al. 2015; Kuramochi et al. 2018; Roelfsema et al. 2018; Kriegler et al. 2018a; Fekete et al. 2015, 2021). A challenge for this approach is to account for the fact that policy effectiveness varies with different political environments in different geographies. As a result, a global roll-out of good practice policies to close the emissions gap will still be an idealized benchmark, but it is useful to understand how much could be gained from it.

Accelerated action pathways derived with this approach show considerable scope for narrowing the emissions gap between pathways reflecting the ambition level of the NDCs and cost-effective mitigation pathways in 2030. Kriegler et al. (2018a) find around 10 $GtCO_2eq$ lower emissions compared to original NDCs from a global roll-out of good practice plus net zero policies and a moderate increase in regionally differentiated carbon pricing. Fekete et al. (2021) show that global replication of sector progress in five major economies would reduce GHG emissions in 2030 by about 20% compared to a current policy scenario. These findings were found in good agreement with a recent model comparison study based on results from 9 integrated assessment models (van Soest et al. 2021a). Based on these three studies, implementing accelerated action in terms of a global roll out of regulatory and moderate pricing policies is assessed to lead to global GHG emissions of 47 (38-51) $GtCO_2$-eq in 2030 (median and 5th to 95th percentile based on 10 distinct modelled pathways). This closes the implementation gap for the NDCs, and in addition falls below the emissions range implied by implementing unconditional and conditional elements of NDCs by 3-9 GtCO2-eq. However, it does not close the emissions gap to immediate action pathways likely limiting warming to 2°C, and, based on our assessment in Section 3.5.2, emission levels above 40 $GtCO_2$-eq in 2030 still have a very low prospect for keeping limiting warming to 1.5°C with no or limited overshoot in reach.

Figure 3.31 shows the intermediate position of accelerated action pathways derived by van Soest et al. (2021a) between pathways that follow the NDCs until 2030 and immediate action pathways likely limiting warming to 2°C. Accelerated action is able to reduce the abrupt shifts in emissions, fossil fuel use and low carbon power generation in 2030 and also limits peak warming more effectively than NDC pathways. But primarily due to the moderate carbon price assumptions (Fig. 3.31b), the reductions in emissions and particular fossil fuel use are markedly smaller than what would be obtained in the case of immediate action. The assessment shows that accelerated action until 2030 can have significant benefits in terms of reducing the mitigation challenges from following the NDCs until 2030. But putting a significant value on GHG emissions reductions globally remains a key element of moving onto 1.5-2°C pathways. The vast majority of pathways that limit warming to 2°C or below, independently of their differences in near term emission developments, converge to a global mitigation regime putting such a significant value on GHG emission reductions in all regions and sectors.

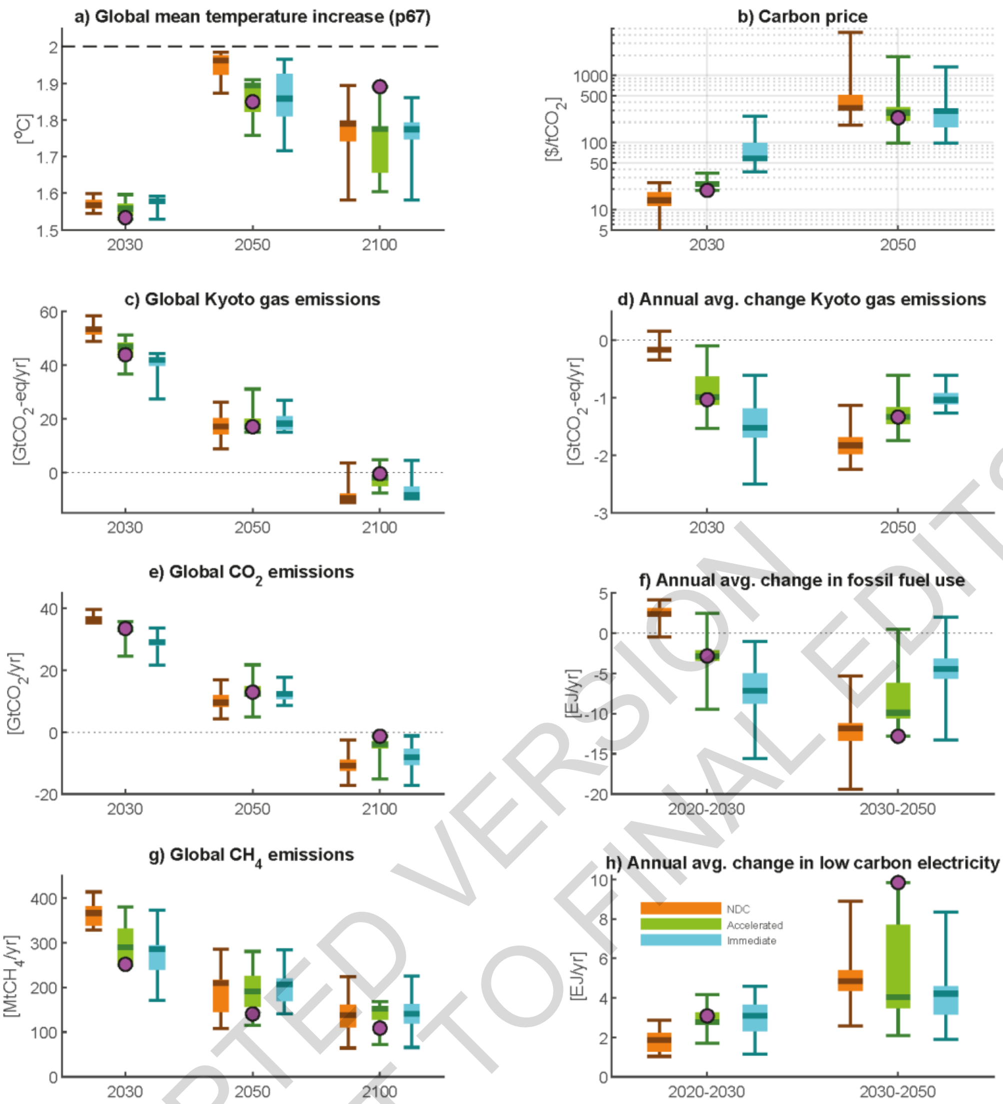

Figure 3.31: Comparison of (i) pathways with immediate action likely limiting warming to 2°C (Immediate, light blue), (ii) pathways following the NDCs until 2030 and aiming to likely stay below 2°C thereafter (NDC; orange) and (iii) pathways accelerating near term action until 2030 beyond NDC ambition levels and aiming to likely stay below 2°C thereafter (Accelerated) for selected indicators as listed in the panel titles, based on pathways from van Soest et al. (2021a)**. Low carbon electricity comprises renewable and nuclear power. Indicator ranges are shown as boxplots (full range, interquartile range, and median) for the years 2030, 2050 and 2100 (absolute values) and for the periods 2020-2030, 2030-2050 (change indicators). Ranges are based on nine models participating in** (van Soest et al. 2021a) **with only 7 models reporting emissions and climate results and 8 models reporting carbon prices. The purple dot denotes the illustrative mitigation pathway *GS* that was part of the study by van Soest et al.**

3.6 Economics of long-term mitigation and development pathways, including mitigation costs and benefits

A complete appraisal of economic effects and welfare effects at different temperature levels would include the macroeconomic impacts of investments in low-carbon solutions and structural change away from emitting activities, co-benefits and adverse side effects of mitigation, (avoided) climate damages, as well as (reduced) adaptation costs, with high temporal, spatial and social heterogeneity using a harmonized framework. If no such complete appraisal in a harmonized framework exists, key elements are emerging from the literature, and assessed in the following subsections: on aggregated economy-wide global mitigation costs (section 3.6.1), on the economic benefits of avoiding climate impacts (section 3.6.2), on economic benefits and costs associated with mitigation co-benefits and co-harms (section 3.6.3) and on the distribution of economic implications between economic sectors and actors (section 3.6.4).

3.6.1 Economy-wide implications of mitigation

3.6.1.1 Global economic effects of mitigation and carbon values in mitigation pathways

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Box 3.5 Concepts and modelling frameworks used for quantifying macro-economic effects of mitigation

Most studies that have developed mitigation pathways have used a Cost-effectiveness analysis (CEA) framework, which aim at comparing the costs of different mitigation strategies designed to meet a given climate change mitigation goal (e.g., an emission-reduction target or a temperature stabilization target) but does not represent economic impacts from climate change itself, nor the associated economic benefits of avoided impacts. Other studies use modelling frameworks that represent the feedback of damages from climate change on the economy in a Cost-benefit analysis (CBA) approach, which balances mitigation costs and benefits. This second type of studies is represented in section 3.6.2.

The marginal abatement cost of carbon, also called carbon price, is determined by the mitigation target under consideration: it describes the cost of reducing the last unit of emissions to reach the target at a given point in time. Total macro-economic mitigation costs (or gains) aggregate the economy-wide impacts of investments in low-carbon solutions and structural changes away from emitting activities. The total macro-economic effects of mitigation pathways are reported in terms of variations in economic output or consumption levels, measured against a Reference Scenario, also called Baseline, at various points in time or discounted over a given time period. Depending on the study, the Reference Scenario reflects specific assumptions about patterns of socio-economic development and assumes either no climate policies or the climate policies in place or planned at the time the study was carried out. When available in the AR6 scenarios database, this second type of Reference Scenario, with current policies, has been chosen for computation of mitigation costs. In the vast majority of studies that have produced the body of work on the cost of mitigation assessed here, and in particular in all studies that have submitted global scenarios to the AR6 scenarios database except (Schultes et al. 2021), the feedbacks of climate change impacts on the economic development pathways are not accounted for. This omission of climate impacts leads to overly optimistic economic projections in the reference scenarios, in particular in reference scenarios with no or limited mitigation action where the extent of global warming is the greatest. Mitigation cost estimates computed against no or limited policy reference scenarios therefore omit economic benefits brought by avoided climate change impact along mitigation pathways, and should be interpreted with care (Grant et al. 2020). When aggregate economic benefits from avoided climate change impacts are accounted for, mitigation is a welfare-enhancing strategy (see section 3.6.2).
If GDP or consumption in mitigation pathways are below the reference scenario levels, they are reported as losses or macro-economic costs. Such cost estimates give an indication on how economic activity slows relative to the reference scenario; they do not necessarily describe, in absolute terms, a reduction of economic output or consumption levels relative to previous years along the pathway. Aggregate mitigation costs depend strongly on the modelling framework used and the assumptions

about the reference scenario against which mitigation costs are measured, in particular whether the reference scenario is, or not, on the efficiency frontier of the economy. If the economy is assumed to be at the efficiency frontier in the reference scenario, mitigation inevitably leads to actual costs, at least in the short run until the production frontier evolves with technical and structural change. Starting from a reference scenario that is not on the efficiency frontier opens the possibility to simultaneously reduce emissions and obtain macroeconomic gains, depending on the design and implementation of mitigation policies. A number of factors can result in reference scenarios below the efficiency frontier, for instance distorting labour taxes and/or fossil fuel subsidies, misallocation or under-utilization of production factors such as involuntary unemployment, imperfect information or non-rational behaviours. Although these factors are pervasive, the modelling frameworks used to construct mitigation pathways are often limited in their ability to represent them (Köberle et al. 2021).

The absolute level of economic activity and welfare also strongly depends on the socioeconomic pathway assumptions regarding inter alia evolutions in demography, productivity, education levels, inequality and technical change and innovation. The GDP or consumption indicators reported in the database of scenarios, and synthesized below, represent the absolute level of aggregate economic activity or consumption but do not reflect welfare and well-being (Roberts et al. 2020), that notably depend on human needs satisfaction, distribution within society and inequality (see section 3.6.4).

Chapter 1 and Annex III give further elements on the economic concepts and on the modelling frameworks, including their limitations, used in this report, respectively.

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Estimates for the marginal abatement cost of carbon in mitigation pathways vary widely, depending on the modelling framework used and socioeconomic, technological and policy assumptions. However, it is robust across modelling frameworks that the marginal abatement cost of carbon increases for lower temperature categories, with a higher increase in the short-term than in the longer-term (Figure 3.32, left panel) (*high confidence*). The marginal abatement cost of carbon increases non-linearly with the decrease of CO_2 emissions level, but the uncertainty in the range of estimates also increases (Figure 3.33). Mitigation pathways with low-energy consumption patterns exhibit lower carbon values (Méjean et al. 2019; Meyer et al. 2021). In the context of the COVID-19 pandemic recovery, Kikstra et al. (2021a) also show that a low energy demand recovery scenario reduces carbon prices for a 1.5°C consistent pathway by 19% compared to a scenario with energy demand trends restored to pre-pandemic levels.

For optimization modelling frameworks, the time profile of marginal abatement costs of carbon depends on the discount rate, with lower discount rates implying higher carbon values in the short term but lower values in the long term (Emmerling et al. 2019) (see also Discounting in glossary and Annex III part I section 2). In that case, the discount rate also influences the shape of the emissions trajectory, with low discount rates implying more emission reduction in the short-term and, for low temperature categories, limiting CDR and temperature overshoot.

Pathways that correspond to NDCs in 2030 and strengthen action after 2030 imply higher marginal abatement costs of carbon in the longer run than pathways with stronger immediate global mitigation action (Figure 3.32, right panel) (*high confidence*).

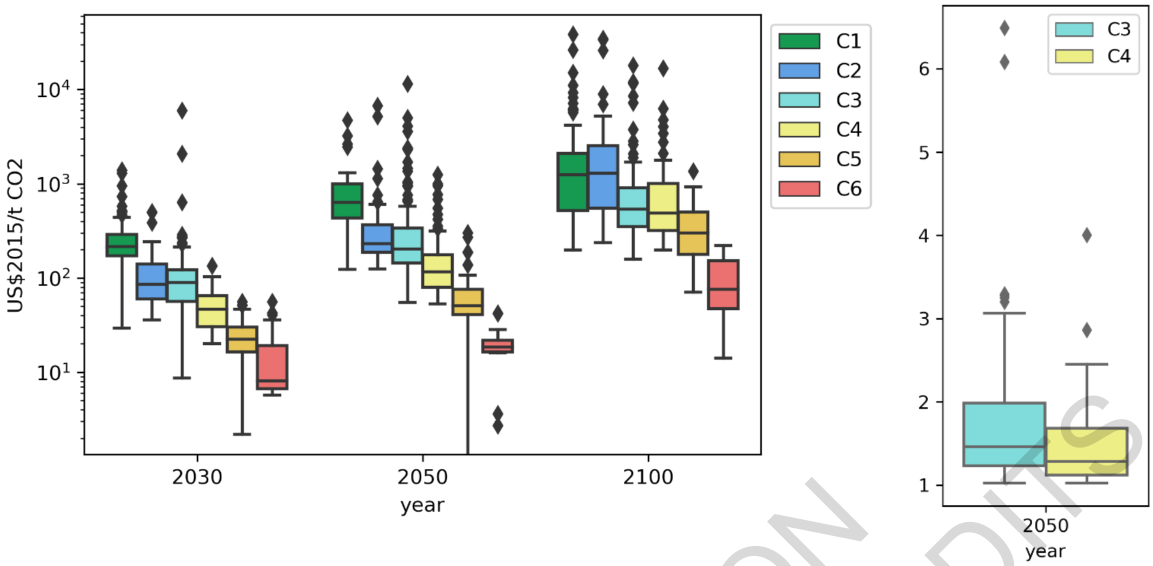

Figure 3.32: Marginal abatement cost of carbon in 2030, 2050 and 2100 for mitigation pathways with immediate global mitigation action (left panel), and ratio in 2050 between pathways that correspond to NDC in 2030 and strengthen action after 2030 and pathways with immediate global mitigation action, for C3 and C4 temperature categories (right panel).

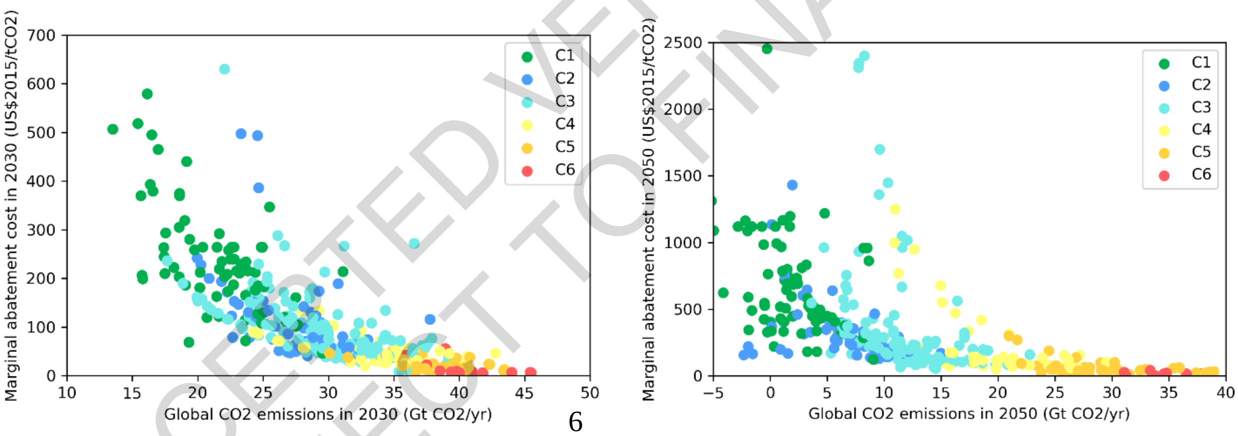

Figure 3.33: Marginal abatement cost of carbon with respect to CO_2 emissions for mitigation pathways with immediate global mitigation action, in 2030 (left panel) and 2050 (right panel).

Aggregate economic activity and consumption levels in mitigation pathways are primarily determined by socioeconomic development pathways but are also influenced by the stringency of the mitigation goal and the policy choices to reach the goal (*high confidence*). Mitigation pathways in temperature categories C1 and C2 entail losses in global consumption with respect to their baselines – not including benefits of avoided climate change impacts nor co-benefits or co-harms of mitigation action – that correspond to an annualized reduction of consumption growth by 0.04 (median value) (interquartile range [0.02-0.06]) percentage points over the century. For pathways in temperature categories C3 and C4 this reduction in global consumption growth is 0.03 (median value) (interquartile range [0.01-0.05]) percentage points over the century. In the majority of studies that focus on the economic effects of mitigation without accounting for climate damages, global economic growth and consumption growth is reduced compared to baseline scenarios (that omit damages from climate change), but mitigation pathways do not represent an absolute decrease of economic activity level (Figure 3.34, panels b and c).

However, the possibility for increased economic activity following mitigation action, and conversely the risk of large negative economic effects, are not excluded. Some studies find that mitigation increases the speed of economic growth compared to baseline scenarios (Pollitt and Mercure 2018; Mercure et al. 2019). These studies are based on a macroeconomic modelling framework that represent baselines below the efficiency frontier, based on non-equilibrium economic theory, and assume that mitigation is undertaken in such a way that green investments do not crowd-out investment in other parts of the economy – and therefore offers an economic stimulus. In the context of the recovery from the COVID-19 crisis, it is estimated that a green investment push, would initially boost the economy while also reducing GHG emissions (IMF 2020; Pollitt et al. 2021). Conversely, several studies find that only a GDP non-growth/degrowth or post-growth approach allow to reach climate stabilization below 2°C (Hardt and O'Neill 2017; D'Alessandro et al. 2020; Hickel and Kallis 2020; Nieto et al. 2020), or to minimize the risks of reliance on high energy-GDP decoupling, large-scale CDR and large-scale renewable energy deployment (Keyßer and Lenzen 2021). Similarly, feedbacks of financial system risk to amplify shocks induced by mitigation policy and lead to higher impact on economic activity (Stolbova et al. 2018).

Mitigation cost increases with the stringency of mitigation (Figure 3.34, panels b and c) (Hof et al. 2017; Vrontisi et al. 2018), but are reduced when energy demand is moderated through energy efficiency and lifestyle changes (Fujimori et al. 2014; Bibas et al. 2015; Liu et al. 2018; Méjean et al. 2019), when sustainable transport policies are implemented (Zhang et al. 2018c), and when international technology cooperation is fostered (Schultes et al. 2018; Paroussos et al. 2019). Mitigation costs also depend on assumptions on availability and costs of technologies (Clarke et al. 2014; Bosetti et al. 2015; Dessens et al. 2016; Creutzig et al. 2018; Napp et al. 2019; Giannousakis et al. 2021), on the representation of innovation dynamics in modelling frameworks (Hoekstra et al. 2017; Rengs et al. 2020) (see also chapter 16), as well as the representation of investment dynamics and financing mechanisms (Iyer et al. 2015c; Mercure et al. 2019; Battiston et al. 2021). In particular, endogenous and induced innovation reduce technology cost over time, create path-dependencies and reduce the macroeconomic cost of reaching a mitigation target (see also 1.7.1.2). Mitigation costs also depend on the socioeconomic assumptions (van Vuuren et al. 2020; Hof et al. 2017).

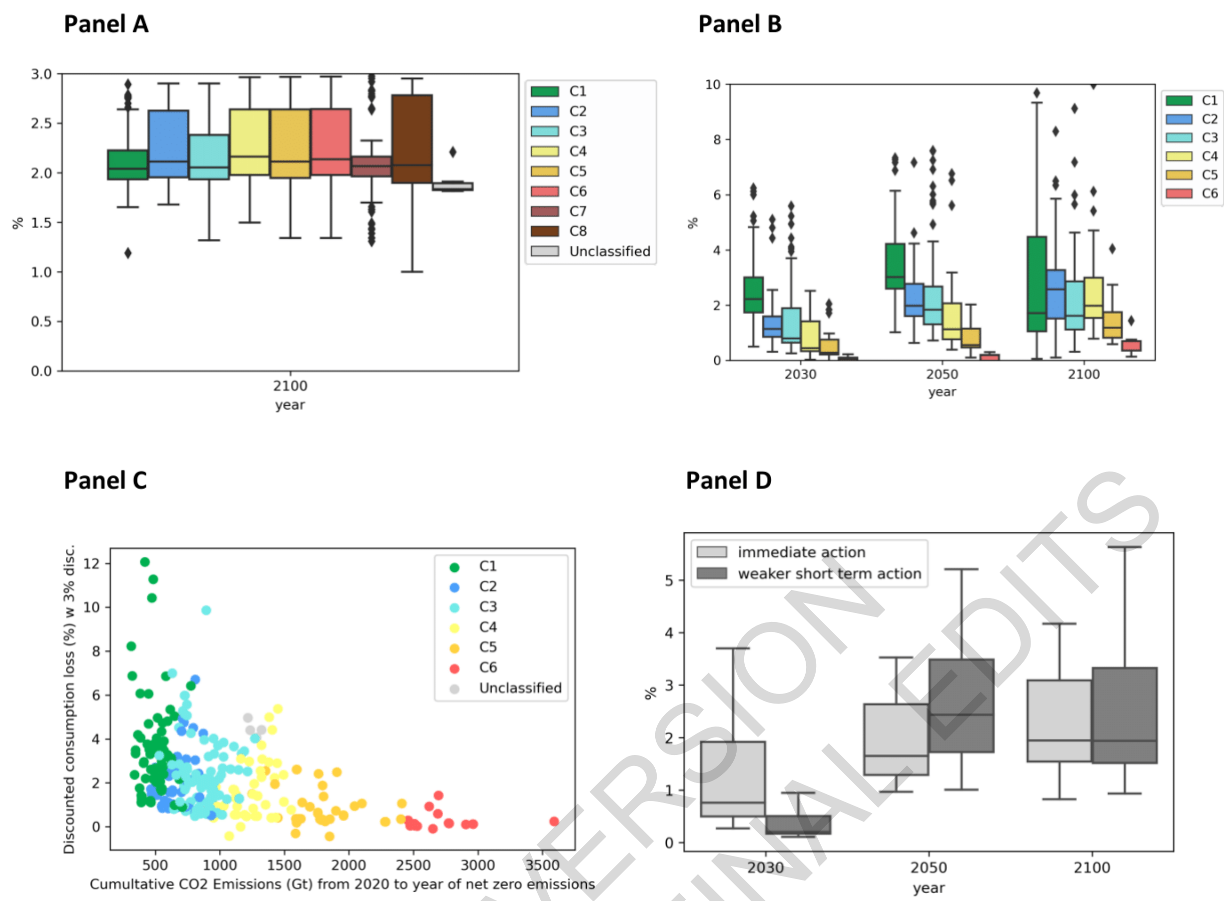

Figure 3.34: Panel (a): Mean annual global consumption growth rate over 2020-2100 for the mitigation pathways in the AR6 scenarios database. Panel (b): Global GDP loss compared to baselines (not accounting for climate change damages) in 2030, 2050 and 2100 for mitigation pathways with immediate global action. Panel (c): Total discounted consumption loss (with a 3% discount rate) in mitigation scenarios with respect to their corresponding baseline (not accounting for climate change damages) as a function of cumulative CO_2 emissions until date of net zero CO_2. Panel (d): Comparison of GDP losses compared to baselines (not accounting for climate change damages) in 2030, 2050 and 2100 for pairs of scenarios depicting immediate action pathways and delayed action pathways.

Mitigation pathways with early emissions reductions represent higher mitigation costs in the short run but bring long-term gains for the economy compared to delayed transition pathways (*high confidence*). Pathways with earlier mitigation action bring higher long-term GDP than pathways reaching the same end-of-century temperature with weaker early action (Figure 3.34, panel d). Comparing counterfactual history scenarios, Sanderson and O'Neill (2020) also find that delayed mitigation action leads to higher peak costs. Rogelj et al. (2019b) and Riahi et al. (2021) also show that pathways with earlier timing of net zero CO_2 lead to higher transition costs but lower long term mitigation costs, due to dynamic effects arising from lock-in avoidance and learning effects. For example, Riahi et al (2021) find that for a 2˚C target, the GDP losses (compared to a reference scenario without impacts from climate change) in 2100 are 5-70% lower in pathways that avoid net negative CO_2 emissions and temperature overshoot than in pathways with overshoot. Accounting also for climate change damage, van der Wijst et al. (2021a) show that avoiding net negative emissions leads to a small increase in total discounted mitigation costs over 2020-2100, between 5% and 14% in their medium assumptions, but does not increase mitigation costs when damages are high and when using a low discount rate, and becomes economically attractive if damages are not fully reversible. The modelled cost-optimal balance of mitigation action over time strongly depends on the discount rate used to compute or evaluate mitigation pathways: lower discount rates favour earlier mitigation, reducing both temperature overshoot and reliance on net negative carbon emissions (Emmerling et al. 2019; Riahi et al. 2021). Mitigation pathways with weak early action corresponding to NDCs in 2030 and strengthening action after 2030 to reach end-of-century temperature targets imply limited mitigation costs in 2030, compared to immediate global action pathways, but faster increase in costs post-2030, with implications for intergenerational equity (Aldy et al. 2016; Liu et al. 2016; Vrontisi et al. 2018). Emissions trading policies reduce global aggregate mitigation costs, in particular in the context of achieving NDCs (Fujimori et al. 2015, 2016a; Edmonds et al. 2021; Böhringer et al. 2021), and change the distribution of mitigation costs between regions and countries (see section 3.6.1.2).

3.6.1.2 Regional mitigation costs and effort-sharing regimes

The economic repercussions of mitigation policies vary across countries (Hof et al. 2017; Aldy et al. 2016): regional variations exist in institutions, economic and technological development, and mitigation opportunities. For a globally uniform carbon price, carbon intensive and energy exporting countries bear the highest economic costs because of a deeper transformation of their economies and of trade losses in the fossil markets (Stern et al. 2012; Tavoni et al. 2015; Böhringer et al. 2021). This finding is confirmed in Figure 3.35. Since carbon intensive countries are often poorer, uniform global carbon prices raises equity concerns (Tavoni et al. 2015). On the other hand, the climate economic benefits of mitigating climate change will be larger in poorer countries (Cross-Working Group Box 1). This reduces policy regressivity but does not eliminate it (Taconet et al. 2020; Gazzotti et al. 2021). Together with co-benefits, such as health benefits of improved air quality, the economic benefits of mitigating climate change are likely to outweigh mitigation costs in many regions (Li et al. 2018, 2019; Scovronick et al. 2021).

Regional policy costs depend on the evaluation framework (Budolfson et al. 2021), policy design, including revenue recycling, and on international coordination, especially among trade partners. By fostering technological change and finance, climate cooperation can generate economic benefits, both in large developing economies such as China and India (Paroussos et al. 2019) and industrialized countries such as Europe (Vrontisi et al. 2020). International coordination is a major driver of regional policy costs. Delayed participation in global mitigation efforts raises participation costs, especially in carbon intensive economies (Figure 3.35, right panel). Trading systems and transfers can deliver cost savings and improve equity (Rose et al. 2017a). On the other hand, measures that reduce imports of energy intensive goods such as carbon border tax adjustment may imply costs outside of the policy jurisdiction and have international equity repercussions, depending on how they are designed (Böhringer et al. 2012, 2017; Cosbey et al. 2019) (see also 13.6.6).

An equitable global emission trading scheme would require very large international financial transfers, in the order of several hundred billion USD per year (Tavoni et al. 2015; van den Berg et al. 2020; Bauer et al. 2020). The magnitude of transfers depends on the stringency of the climate goals and on the burden sharing principle. Equitable burden sharing compliant with the Paris Agreement leads to negative carbon allowances for developed countries as well as China by mid-century (van den Berg et al. 2020), more stringent than cost-optimal pathways. International transfers also depend on the underlying socio-economic development (Leimbach and Giannousakis 2019), as these drive the mitigation costs of meeting the Paris Agreement (Rogelj et al. 2018b). By contrast, achieving equity without international markets would result in a large discrepancy in regional carbon prices, up to a factor (Bauer et al. 2020). The efficiency-sovereignty trade-off can be partly resolved by allowing for limited differentiation of regional carbon prices: moderate financial transfers substantially reduce inefficiencies by narrowing the carbon price spread (Bauer et al. 2020).

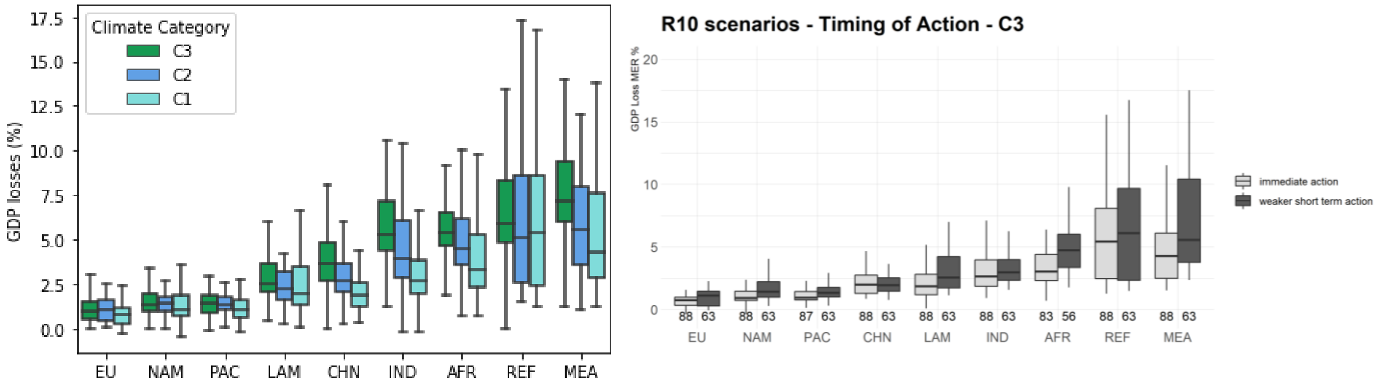

Figure 3.35: Left panel: Regional mitigation costs in the year 2050 (expressed as GDP losses between mitigation scenarios and corresponding baselines, not accounting for climate change damages), under the assumption of immediate global action with uniform global carbon pricing and no international transfers, by climate categories for the 2°C and 1.5°C (with and without overshoot) categories. Right panel: Policy costs in 2050 (as in panel a) for 1.5-2°C climate categories for scenario pairs that represent either immediate global action ('immediate') or delayed global action ('delayed') with weaker action in the short-term, strengthening to reach the same end-of-century temperature target.

3.6.1.3 Investments in mitigation pathways

Figure 3.36 and Figure 3.37 show increased investment needs in the energy sector in lower temperature categories, and a major shift away from fossil generation and extraction towards electricity, including for system enhancements for electricity transmission, distribution and storage, and low-carbon technologies. Investment needs in the electricity sector are USD2.3 trillion 2015 yr^{-1} over 2023-2050 on average for C1 pathways, USD2.0 trillion for C2 pathways, USD1.7 trillion for C3, USD1.2 trillion for C4 and USD0.9-1.1 billion for C5/C6/C7 (mean values for pathways in each temperature categories). The regional pattern of power sector investments broadly mirrors the global picture. However, the bulk of investment requirements are in medium- and low-income regions. These results from the AR6 scenarios database corroborate the findings from McCollum et al. (2018a), Zhou et al. (2019) and Bertram et al. (2021).

In the context of the COVID-19 pandemic recovery, (Kikstra et al. 2021a) show that a low energy demand recovery scenario reduces energy investments required until 2030 for a 1.5°C consistent pathway by 9% (corresponding to reducing total required energy investment by USD1.8 trillion) compared to a scenario with energy demand trends restored to pre-pandemic levels.

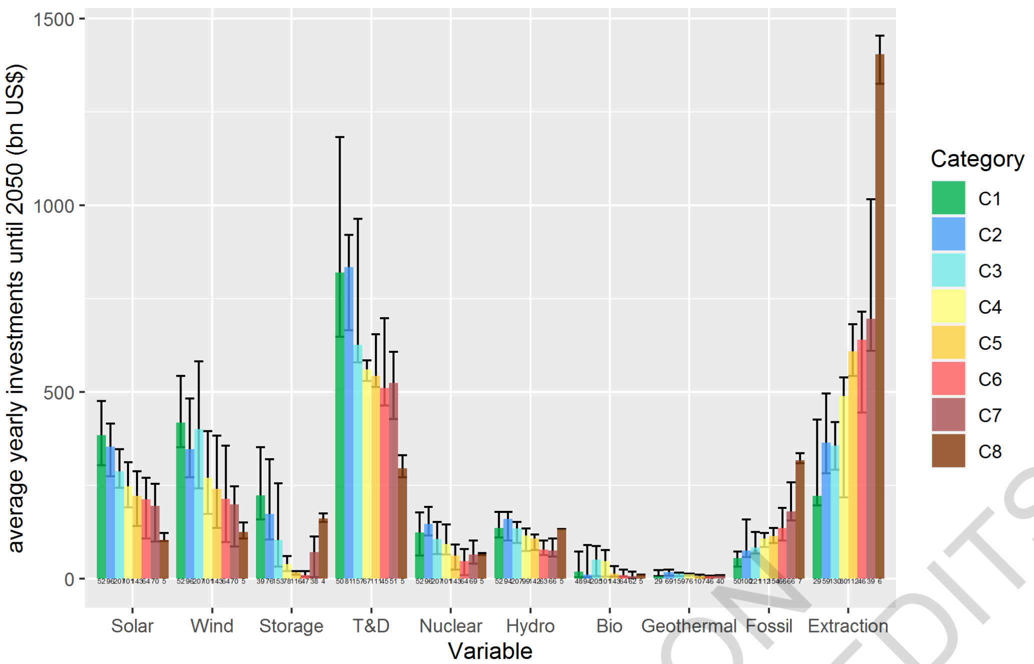

Figure 3.36: Global average yearly investments from 2023-2052 for 9 electricity supply subcomponents and for extraction of fossil fuels (in billion USD2015), in pathways by temperature categories. T&D: transmission and distribution of electricity. Bars show the median values (number of pathways at the bottom), and whiskers the interquartile ranges.

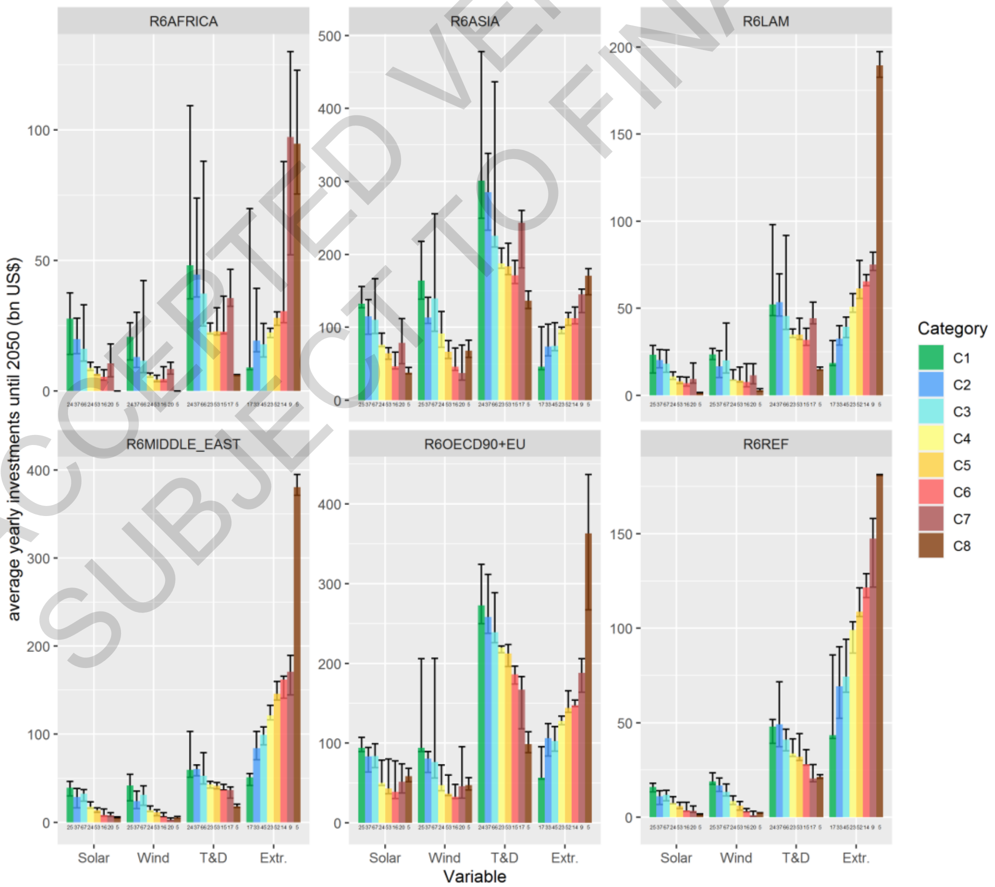

Figure 3.37: Average yearly investments from 2023-2052 for the four subcomponents of the energy system representing the larger amounts (in billion USD2015), by aggregate regions, in pathways by temperature categories. T&D: transmissions and distribution of electricity. Extr.: extraction of fossil

fuels. Bars show the median values (number of pathways at the bottom), and whiskers the interquartile ranges.

Few studies extend the scope of the investment needs quantification beyond the energy sector. Fisch-Romito and Guivarch (2019) and Ó Broin and Guivarch (2017) assess investment needs for transportation infrastructures and find lower investment needs in low-carbon pathways, due to a reduction in transport activity and a shift towards less road construction, compared to high-carbon pathways. Rozenberg and Fay (2019) estimate the funding needs to close the service gaps in water and sanitation, transportation, electricity, irrigation, and flood protection in thousands of scenarios, showing that infrastructure investment paths compatible with full decarbonization in the second half of the century need not cost more than more-polluting alternatives. Investment needs are estimated between 2 percent and 8 percent of GDP, depending on the quality and quantity of services targeted, the timing of investments, construction costs, and complementary policies.

Chapter 15 also reports investment requirements in global mitigation pathways in the near-term, compares them to recent investment trends, and assesses financing issues.

3.6.2 Economic benefits of avoiding climate changes impacts

START BOX HERE

Cross-Working Group Box 1: Economic benefits from avoided climate impacts along long-term mitigation pathways

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Mitigation reduces the extent of climate change and its impacts on ecosystems, infrastructure, and livelihoods. This box summarizes elements from the WGII report on aggregate climate change impacts and risks, putting them into the context of mitigation pathways. AR6 Working Group II provides an assessment of current lines of evidence regarding potential climate risks with future climate change, and therefore, the avoided risks from mitigating climate change. Regional and sectoral climate risks to physical and social systems are assessed (WGII Chapters 2-15). Over 100 of these are identified as Key Risks (KRs) and further synthesized by WGII Chapter 16 into eight overarching Representative Key Risks (RKRs) relating to low-lying coastal systems; terrestrial and ocean ecosystems; critical physical infrastructure, networks and services; living standards; human health; food security; water security; and peace and mobility (WGII 16.5.2). The RKR assessment finds that risks increase with global warming level, and also depend on socioeconomic development conditions, which shape exposure and vulnerability, and adaptation opportunities and responses. "Reasons For Concern", another WGII aggregate climate impacts risk framing, are also assessed to increase with climate change, with increasing risk for unique and threatened systems, extreme weather events, distribution of impacts, global aggregate impacts, and large-scale singular events (WGII Chapter 16). For human systems, in general, the poor and disadvantaged are found to have greater exposure level and vulnerability for a given hazard. With some increase in global average warming from today expected regardless of mitigation efforts, human and natural systems will be exposed to new conditions and additional adaptation will be needed (WGII Chapter 18). The range of dates for when a specific warming level could be reached depends on future global emissions, with significant overlap of ranges across emissions scenarios due to climate system response uncertainties (WGI Tables 4.2 and 4.5). The speed at which the climate changes is relevant to adaptation timing, possibilities, and net impacts.

WGII also assesses the growing literature estimating the global aggregate economic impacts of climate change and the social cost of carbon dioxide and other greenhouse gases (Cross-Working Box Economic: Estimating Global Economic Impacts from Climate Change and the Social Cost of Carbon", in WGII Chapter 16). The former represents aggregate estimates that inform assessment of the economic benefits of mitigation. This literature is characterized by significant variation in the estimates, including for today's level of global warming, due primarily to fundamental differences in methods, but also differences in impacts included, representation of socioeconomic exposure, consideration of adaptation, aggregation approach, and assumed persistence of damages. WGII's assessment identifies different approaches to quantification of aggregated economic impacts of climate change, including: physical modelling of impact processes, such as projected mortality rates from climate risks such as heat, vector- or waterborne diseases that are then monetized; structural economic modelling of impacts on production, consumption, and markets for economic sectors and regional economies; and statistical estimation of impacts based on observed historical responses to weather and climate. WGII finds that variation in estimated global economic impacts increases with warming in all methodologies, indicating higher risk in terms of economic impacts at higher temperatures (*high confidence*). Many estimates are nonlinear with marginal economic impacts increasing with temperature, although some show declining marginal economic impacts with temperature, and functional forms cannot be determined for all studies. WGII's assessment finds that the lack of comparability between methodologies does not allow for identification of robust ranges of global economic impact estimates (*high confidence*). Further, WGII identifies evaluating and reconciling differences in methodologies as a research priority for facilitating use of the different lines of evidence (*high confidence*). However, there are estimates that are higher than AR5, indicating that global aggregate economic impacts could be higher than previously estimated (*low confidence* due to the lack of comparability across methodologies and lack of robustness of estimates) (Cross-Working Box Economic).

Conceptually, the difference in aggregate economic impacts from climate change between two given temperature levels represents the aggregate economic benefits arising from avoided climate change impacts due to mitigation action. A subset of the studies whose estimates were evaluated by WGII (5 of 15) are used to derive illustrative estimates of aggregate economic benefits in 2100 arising from avoided climate change (Howard and Sterner 2017; Burke et al. 2018; Pretis et al. 2018; Kahn et al. 2019; Takakura et al. 2019). Burke et al. (2018), Pretis et al. (2018) and Kahn et al. (2019) are examples of statistical estimation of historical relationships between temperature and economic growth, whereas Takakura et al. (2019) is an example of structural modelling, which evaluates selected impact channels (impacts on agriculture productivity, undernourishment, heat-related mortality, labour productivity, cooling/heating demand, hydroelectric and thermal power generation capacity and fluvial flooding) with a general equilibrium model. Howard and Sterner (2017) and Rose et al. (2017b) estimate damage functions that can be used to compute the economic benefits of mitigation from avoiding a given temperature level for a lower one. Howard and Sterner (2017) estimate a damage function from a meta-analysis of aggregate economic impact studies, while Rose et al. (2017b) derive global functions by temperature and socioeconomic drivers from stylized aggregate Cost-Benefit-Analysis integrated assessment models using diagnostic experiments. Cross-Working Group Box 1 Figure 1 summarizes the global aggregate economic benefits in 2100 of avoided climate change impacts from individual studies corresponding to shifting from a higher temperature category (above 3°C, below 3°C or below 2.5°C) to below 2°C, as well as from below 2°C to below 1.5°C. Benefits are positive and increase with the temperature gap for any given study, and this result is robust across socioeconomic scenarios. The Figure provides evidence of a wide range of quantifications, and illustrates the important differences associated with methods. Panel a puts the studies used to calculate aggregate economic benefits arising from avoided impacts into the context of the broader set of studies assessed in WGII (WGII Cross-Working Group Box Economic, 16.6.2). However, economic benefits in 2100 arising from avoided impacts cannot be directly computed from damage estimates across this broader set of studies, due to inconsistencies - different socioeconomic assumptions, scenario designs, and counterfactual reference scenarios across studies. Furthermore, these types of estimates cannot be readily compared to mitigation cost estimates. The comparison would require a framework that ensures consistency in assumptions and dynamics and allows for consideration of benefits and costs along the entire pathway.

Cross-Working Group Box 1 Figure 1: Global aggregate economic benefits of mitigation from avoided climate change impacts in 2100 corresponding to shifting from a higher temperature category (4°C (3.75°C-4.25°C), 3°C(2.75°C-3.25°C) or above 2°C (2°C-2.5°C)) to below 2°C (1.5°C-2°C), as well as from below 2°C to below 1.5°C (1°C-1.5°C), from the five studies discussed in the text. Panel a is adapted from WGII CWGB ECONOMIC Figure 1, showing global aggregate economic impact estimates (% global GDP loss relative to GDP without additional climate change) by temperature change level. All estimates are shown in grey. Estimates used for the computation of estimated benefits in 2100 in Panel b are coloured for the selected studies, which provide results for different temperature change levels. See the WGII Chapter 16 box for discussion and assessment of the estimates in Panel a and the differences in methodologies. For B18 and T19, median estimates in the cluster are considered. Shape distinguishes the baseline scenarios. Temperature ranges are highlighted. HS17 estimates are based on their preferred model - 50th percentile of non-catastrophic damage. Panel b shows the implied aggregate economic benefits in 2100 of a lower temperature increase. Economic benefits for point estimates are computed as a difference, while economic benefits from the curve HS17 are computed as ranges from the segment differences.

Aggregate benefits from avoided impacts expressed in GDP terms, as in Figure 1, do not encompass all avoided climate risks, adaptation possibilities, and does not represent their influence on well-being and welfare (WGII Cross-Working Group Box Economic). Methodological challenges for economic impact estimates include representing uncertainty and variability, capturing interactions and spill overs, considering distributional effects, representing micro and macro adaptation processes, specifying non-gradual damages and non-linearities, and improving understanding of potential long-run growth effects. In addition, the economic benefits aggregated at the global scale provide limited insights into regional heterogeneity. Global economic impact studies with regional estimates find large differences across regions in absolute and percentage terms, with developing and transitional economies typically more vulnerable. Furthermore, (avoided) impacts for poorer households and poorer countries can represent a smaller share in aggregate quantifications expressed in GDP terms or monetary terms, compared to their influence on well-being and welfare (Hallegatte et al. 2020; Markhvida et al. 2020). Finally, as noted by WGII, other lines of evidence regarding climate risks, beyond monetary estimates, should be considered in decision-making, including key risks and Reasons for Concern.

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Cost-benefit analyses (CBA) aim to balance all costs and benefits in a unified framework (Nordhaus, 2008). Estimates of economic benefits from avoided climate change impacts depend on the types of damages accounted for, the assumed exposure and vulnerability to these damages as well as the adaptation capacity, which in turn are based on the development pathway assumed (Cross-Working

Group Box 1). CBA integrated assessment models raised critics, in particular for omitting elements of dynamic realism, such as inertia, induced innovation and path dependence, in their representation of mitigation (Grubb et al. 2021), and for underestimating damages from climate change, missing non-monetary damages, the uncertain and heterogeneous nature of damages and the risk of catastrophic damages (Stern 2013, 2016; Stern and Stiglitz 2021; Diaz and Moore 2017; Pindyck 2017; NASEM 2017; Stoerk et al. 2018). Emerging literature has started to address those gaps, and integrated into cost-benefit frameworks the account of heterogeneity of climate damage and inequality (Dennig et al. 2015; Budolfson et al. 2017; Fleurbaey et al. 2019; Kornek et al. 2021), damages with higher persistence, including damages on capital and growth (Dietz and Stern 2015; Moore and Diaz 2015; Moyer et al. 2014; Guivarch and Pottier 2018; Piontek et al. 2019; Ricke et al. 2018), risks of tipping points (Cai et al. 2015, 2016; Lontzek et al. 2015; Lemoine and Traeger 2016; van der Ploeg and de Zeeuw 2018; Cai and Lontzek 2019; Nordhaus 2019; Yumashev et al. 2019; Taconet et al. 2021) and damages to natural capital and non-market goods (Tol 1994; Sterner and Persson 2008; Bastien-Olvera and Moore 2020; Drupp and Hänsel 2021).

Each of these factors, when accounted for in a CBA framework, tends to increase the welfare benefit of mitigation, thus leading to stabilization at lower temperature in optimal mitigation pathways. The limitations in CBA modelling frameworks remain significant, their ability to represent all damages incomplete, and the uncertainty in estimates remains large. However, emerging evidence suggests that, even without accounting for co-benefits of mitigation on other sustainable development dimensions (see section 3.6.3 for elements on co-benefits), global benefits of pathways *likely* to limit warming to 2°C outweigh global mitigation costs over the 21st century: depending on the study, the reason for this result lies in assumptions of economic damages from climate change in the higher end of available estimates (Moore and Diaz 2015; Ueckerdt et al. 2019; Brown and Saunders 2020; Glanemann et al. 2020), in the introduction of risks of tipping-points (Cai and Lontzek 2019), in the consideration of damages to natural capital and non-market goods (Bastien-Olvera and Moore 2020) or in the combination of updated representations of carbon cycle and climate modules, updated damage estimates and/or updated representations of economic and mitigation dynamics (Dietz and Stern 2015; Hänsel et al. 2020; Wei et al. 2020; van der Wijst et al. 2021b). In the above studies that perform a sensitivity analysis, this result is found to be robust to a wide range of assumptions on social preferences (in particular on inequality aversion and pure rate of time preference) and holds except if assumptions of economic damages from climate change are in the lower end of available estimates and the pure rate of time preference is in the higher range of values usually considered (typically above 1.5%). However, although such pathways bring net benefits over time (in terms of aggregate discounted present value), they involve distributional consequences and transition costs (Brown and Saunders 2020; Brown et al. 2020) (see also sections 3.6.1.2 and 3.6.4).

The standard discounted utilitarian framework dominates CBA, thus often limiting the analysis to the question of discounting. CBA can be expanded to accommodate a wider variety of ethical values to assess mitigation pathways (Fleurbaey et al. 2019). The role of ethical values with regard to inequality and the situation of the worse-off (Adler et al. 2017), risk (van den Bergh and Botzen 2014; Drouet et al. 2015), and population size (Scovronick et al. 2017; Méjean et al. 2020) has been explored. In most of these studies, the optimal climate policy is found to be more stringent than the one obtained using a standard discounted utilitarian criterion.

Comparing economic costs and benefits of mitigation raises a number of methodological and fundamental difficulties. Monetizing the full range of climate change impacts is extremely hard, if not impossible (WGII chapter 16), as is aggregating costs and benefits over time and across individuals when values are heterogeneous (AR5, WGIII chapter 3; this assessment, Chapter 1). Other approaches should thus be considered in supplement for decision making (Chapter 1, section 1.7), in particular cost-effectiveness approaches that analyse how to achieve a defined mitigation objective at least cost or while also reaching other societal goals (Koomey 2013; Kaufman et al. 2020; Köberle et al. 2021; Stern and Stiglitz 2021). In cost effectiveness studies too, incorporating benefits from avoided climate damages influences the results and leads to more stringent mitigation in the short-term (Drouet et al. 2021; Schultes et al. 2021).

3.6.3 Aggregate economic implication of mitigation co-benefits and trade-offs

Mitigation actions have co-benefits and trade-offs with other sustainable development dimensions (section 3.7), beyond climate change, which imply welfare effects and economic effects, as well as other implications beyond the economic dimension. The majority of quantifications of mitigation costs and benefits synthesized in sections 3.6.1 and 3.6.2 do not account for these economic benefits and costs associated with co-benefits and trade-offs along mitigation pathways.

Systematic reviews of the literature on co-benefits and trade-offs from mitigation actions have shown that only a small portion of articles provide economic quantifications (Deng et al. 2017; Karlsson et al. 2020). Most economic quantifications use monetary valuation approaches. Improved air quality, and associated health effects, are the co-benefit category dominating the literature (Markandya et al. 2018; Vandyck et al. 2018; Scovronick et al. 2019; Howard et al. 2020; Karlsson et al. 2020b; Rauner et al. 2020a,b), but some studies cover other categories, including health effects from diet change (Springmann et al. 2016b) and biodiversity impacts (Rauner et al. 2020a). Regarding health effects from air quality improvement and from diet change, co-benefits are shown to be of the same order of magnitude as mitigation costs (Thompson et al. 2014; Springmann et al. 2016a,b; Markandya et al. 2018; Scovronick et al. 2019b; Howard et al. 2020; Rauner et al. 2020a,b; Liu et al. 2021; Yang et al. 2021). Co-benefits from improved air quality are concentrated sooner in time than economic benefits from avoided climate change impacts (Karlsson et al. 2020), such that when accounting both for positive health impacts from reduced air pollution and for negative climate effect of reduced cooling aerosols, optimal greenhouse gas mitigation pathways exhibit immediate and continual net economic benefits (Scovronick et al. 2019a). However, WGI chapter 6 (section 6.7.3) shows a delay in air pollution reduction benefits when they come from climate change mitigation policies compared with air pollution reduction policies.

Achieving co-benefits is not automatic but results from coordinated policies and implementation strategies (Clarke et al. 2014; McCollum et al. 2018a). Similarly, avoiding trade-offs requires targeted policies (van Vuuren et al. 2015; Bertram et al. 2018). There is limited evidence of such pathways, but the evidence shows that pathways mitigation pathways designed to reach multiple sustainable development goals instead of focusing exclusively on emissions reductions, result in limited additional costs compared to the increased benefits (Cameron et al. 2016; McCollum et al. 2018b; Fujimori et al. 2020a; Sognnaes et al. 2021).

3.6.4 Structural change, employment and distributional issues along mitigation pathways

Beyond aggregate effects at the economy wide level, mitigation pathways have heterogeneous economic implications for different sectors and different actors. Climate-related factors are only one driver of the future structure of the economy, of the future of employment, and of future inequality trends, as overarching trends in demographics, technological change (innovation, automation, etc.), education and institutions will be prominent drivers. For instance, Rao et al. (2019b) and Benveniste et al. (2021) have shown that income inequality projections for the 21st century vary significantly, depending on socioeconomic assumptions related to demography, education levels, social public spending and migrations. However, the sections below focus on climate-related factors, both climate mitigation actions themselves and the climate change impacts avoided along mitigation pathways, effects on structural change, including employment, and distributional effects.

3.6.4.1 Economic structural change and employment in long-term mitigation pathways

Mitigation pathways entail transformation of the energy sector, with structural change away from fossil energy and towards low-carbon energy (section 3.3), as well as broader economic structural change, including industrial restructuring and reductions in carbon-intensive activities in parallel to extensions in low-carbon activities.

Mitigation affects work through multiple channels, which impacts geographies, sectors and skill categories differently (Fankhaeser et al. 2008; Bowen et al. 2018; Malerba and Wiebe 2021). Aggregate employment impacts of mitigation pathways mainly depend on the aggregate macroeconomic effect of mitigation (see 3.6.1, 3.6.2) and of mitigation policy design and implementation (Freire-González 2018) (section 4.2.6.3). Most studies that quantify overall employment implications of mitigation policies are conducted at the national or regional scales (section 4.2.6.3), or sectoral scales (e.g., see chapter 6 for energy sector jobs). The evidence is limited at the multi-national or global scale, but studies generally find small differences in aggregate employment in mitigation pathways compared to baselines: the sign of the difference depends on the assumptions and modelling frameworks used and the policy design tested, with some studies or policy design cases leading to small increases in employment (Chateau and Saint-Martin 2013; Pollitt et al. 2015; Barker et al. 2016; Garcia-Casals et al. 2019; Fujimori et al. 2020a; Vrontisi et al. 2020; Malerba and Wiebe 2021) and other studies or policy design cases leading to small decreases (Chateau and Saint-Martin 2013; Vandyck et al. 2016). The small variations in aggregate employment hide substantial reallocation of jobs across sectors, with jobs creation in some sectors and jobs destruction in others. Mitigation action through thermal renovation of buildings, installation and maintenance of low-carbon generation, the build-out of public transit lead to jobs creation, while jobs are lost in fossil fuel extraction, energy supply and energy intensive sectors in mitigation pathways (von Stechow et al. 2015, 2016; Barker et al. 2016; Fuso Nerini et al. 2018; Perrier and Quirion 2018; Pollitt and Mercure 2018; Dominish et al. 2019; Garcia-Casals et al. 2019). In the energy sector, jobs losses in the fossil fuel sector are found to be compensated by gains in wind and solar jobs, leading to a net increase in energy sector jobs in 2050 in a mitigation pathway compatible with stabilization of the temperature increase below 2°C (Pai et al. 2021). Employment effects also differ by geographies, with energy-importing regions benefiting from net job creations but energy-exporting regions experiencing very small gains or suffering from net job destruction (Barker et al. 2016; Pollitt and Mercure 2018; Garcia-Casals et al. 2019; Malerba and Wiebe 2021). Coal phase-out raises acute issues of just transition for the coal-dependent countries (Spencer et al. 2018; Jakob et al. 2020) (section 4.5 and Box 6.2).

Mitigation action also affects employment through avoided climate change impacts. Mitigation reduces the risks to human health and associated impacts on labour and helps protect workers from the occupational health and safety hazards imposed by climate change (Kjellstrom et al. 2016, 2018, 2019 ; Levi et al. 2018; Day et al. 2019) (see WGII chapter 16).

3.6.4.2 Distributional implications of long-term mitigation pathways

Mitigation policies can have important distributive effects between and within countries, either reducing or increasing economic inequality and poverty, depending on policy instruments design and implementation (see section 3.6.1.2 for an assessment of the distribution of mitigation costs across regions in mitigation pathways, section 3.7, Box 3.6 and chapter 4 section 4.2.2.6 for an assessment of the fairness and ambition of NDCs, and section 4.5 for an assessment of national mitigation pathways along the criteria of equity, including just transition, as well as chapter 17, section 17.4.5 for equity in a just transition). For instance, emissions taxation has important distributive effects, both between and within income groups (Klenert et al. 2018; Cronin et al. 2018b; Pizer and Sexton 2019; Douenne 2020; Steckel et al. 2021). These effects are more significant in some sectors, such as transport, and depend on country-specific consumption structures (Dorband et al. 2019; Fullerton and Muehlegger 2019; Ohlendorf et al. 2021). However, revenues from emissions taxation can be used to lessen their regressive distributional impacts or even turn the policy into a progressive policy reducing inequality and/or leading to gains for lower income households (Cameron et al. 2016; Jakob and Steckel 2016; Fremstad and Paul 2019; Fujimori et al. 2020b; Böhringer et al. 2021; Steckel et al. 2021; Soergel et al. 2021b; Budolfson et al. 2021). Mitigation policies may affect the poorest through effects on energy and food prices (Hasegawa et al. 2015; Fujimori et al. 2019). Markkanen and Anger-Kraavi (2019) and Lamb et al. (2020) synthesize evidence from the existing literature on social co-impacts of climate change mitigation policy and their implications for inequality. They show that most policies can compound or lessen inequalities depending on contextual factors, policy design and policy implementation, but that negative inequality impacts of climate policies can be mitigated (and possibly even prevented), when distributive and procedural justice are taken into consideration in all stages of policy making, including policy planning, development and implementation, and when focusing on the carbon intensity of lifestyles, sufficiency and equity, wellbeing and decent living standards for all (see also 13.6).

Mitigation pathways also affect economic inequalities between and within countries, and poverty, through the reduction of climate change impacts that fall more heavily on low-income countries, communities and households and exacerbate poverty (WGII chapters 8 and 16). Higher levels of warming are projected to generate higher inequality between countries as well as within them (WGII chapter 16). Through avoiding impacts, mitigation thus reduces economic inequalities and poverty (*high confidence*).

A few studies consider both mitigation policies distributional impacts and avoided climate change impacts on inequalities along mitigation pathways. Rezai et al. (2018) find that unmitigated climate change impacts increase inequality, whereas mitigation has the potential to reverse this effect. Considering uncertainty in socioeconomic assumptions, emission pathways, mitigation costs, temperature response, and climate damage, Taconet et al. (2020) show that the uncertainties associated with socioeconomic assumptions and damage estimates are the main drivers of future inequalities between countries and that in most cases mitigation policies reduce future inequalities between countries. Gazzotti et al. (2021) show that inequality persists in 2°C consistent pathways due to regressivity of residual climate damages. However, the evidence on mitigation pathways implications for global inequality and poverty remains limited, and the modelling frameworks used have limited ability to fully represent the different dimensions of inequality and poverty and all the mechanisms by which mitigation affects inequality and poverty (Rao et al. 2017a; Emmerling and Tavoni 2021; Jafino et al. 2021).

3.7 Sustainable development, mitigation and avoided impacts

3.7.1 Synthesis findings on mitigation and sustainable development

Rapid and effective climate mitigation is a necessary part of sustainable development *(high confidence)* (see Cross-Chapter Box 5 in Chapter 4), but the latter can only be realized if climate mitigation becomes integrated with sustainable development policies *(high confidence)*. Targeted policy areas must include healthy nutrition, sustainable consumption and production, inequality and poverty alleviation, air quality and international collaboration *(high confidence)*. Lower energy demand enables synergies between mitigation and sustainability, with lower reliance on CDR *(high confidence)*.

This section covers the long-term interconnection of SD and mitigation, taking forward the holistic vision of SD described in the SDGs (Brandi 2015; Leal Filho et al. 2018). Recent studies have explored the aggregated impact of mitigation for multiple sustainable development dimensions (Hasegawa et al. 2014; Bertram et al. 2018; Grubler et al. 2018; McCollum et al. 2018b; Fuso Nerini et al. 2018; van Vuuren et al. 2019; Soergel et al. 2021a). For instance, Figure 3.38 shows selected mitigation co-benefits and trade-offs based on a subset of models and scenarios, since so far many IAMs do not have a comprehensive coverage of sustainable development goals (Rao et al. 2017a; van Soest et al. 2019). Figure 3.38 shows that mitigation likely leads to increased forest cover (SDG 15) and reduced mortality from ambient PM2.5 pollution (SDG 3) compared to reference scenarios. However, mitigation policies can also cause higher food prices and an increased population at risk of hunger (SDG 2) and relying on solid fuels (SDG 3 and SDG 7) as side effects. These trade-offs can be compensated through targeted support measures and/or additional SD policies (Cameron et al. 2016; Bertram et al. 2018; Fujimori et al. 2019; Soergel et al. 2021a).

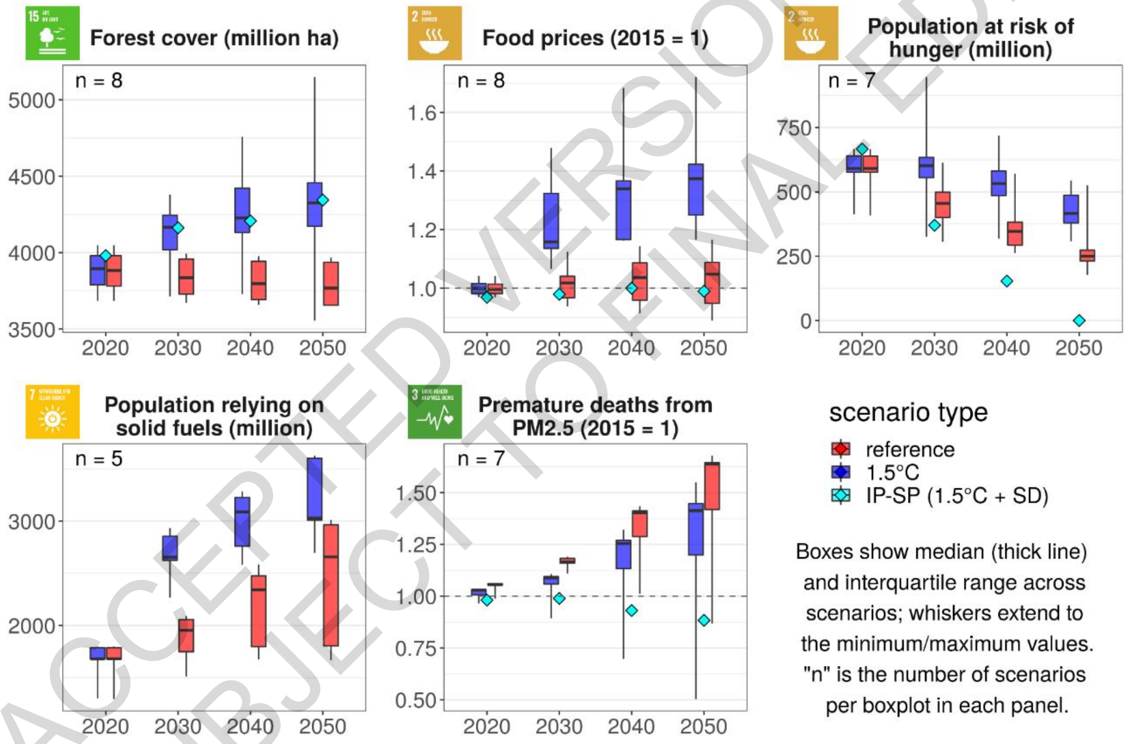


Figure 3.38: Effect of climate change mitigation on different dimensions of sustainable development: shown are mitigation scenarios compatible with 1.5°C target (blue) and reference scenarios (red). Blue boxplots contain scenarios that include narrow mitigation policies from different studies (see below). This is compared to a sustainable development scenario (*SP*, Soergel et al. (2021a), cyan diamonds) integrating mitigation and SD policies (e.g., zero hunger in 2050 by assumption). Scenario sources for boxplots: single scenarios from i) Fujimori et al. (2020a); ii) Soergel et al. (2021a); multi-model scenario set from CD-LINKS (McCollum et al. 2018b; Roelfsema et al. 2020; Fujimori et al. 2019). For associated methods, see also Cameron et al. (2016), Rafaj et al. (2021). The reference scenario for (Fujimori et al. 2020a) is no-policy baseline; for all other studies, it includes current climate policies. In the "Food prices" and "Risk of hunger" panels, scenarios from CD-LINKS include a price cap of 200 USD/tCO_2eq for land-use emissions (Fujimori et al. 2019). For the other indicators, CD-LINKS scenarios without price cap Roelfsema et al. (2020) are used due to SDG indicator availability. In the "Premature deaths" panel, a well-below 2°C scenario from Fujimori et al. (2020a) is used in place of a 1.5°C scenario due to data availability, and all scenarios are indexed to their 2015 values due to a spread in reported levels between models. SDG icons were created by the United Nations.

The synthesis of the interplay between climate mitigation and sustainable development is shown in Figure 3.39. The left panel shows the reduction in population affected by climate impacts at 1.5°C compared to 3°C according to sustainability domains (Byers et al. 2018). Reducing warming reduces the population impacted by all impact categories shown *(high confidence)*. The left panel does not take into account any side effects of mitigation efforts or policies to reduce warming: only reductions in climate impacts. This underscores that mitigation is an integral basis for comprehensive SD (Watts et al. 2015).

The middle and right panels of Figure 3.39 show the effects of 1.5°C mitigation policies compared to current national policies: narrow mitigation policies (averaged over several models, middle panel), and policies integrating sustainability considerations (right panel of Figure 3.39, based on the Illustrative Mitigation Pathway "Shifting Pathways" (***SP***) (Soergel et al. 2021a)). Policies integrating sustainability and mitigation (right panel) have far fewer trade-offs (red bars) and more co-benefits (green bars) than narrow mitigation policies (middle panel). Note that neither middle nor right panels include climate impacts.

Areas of co-benefits include human health, ambient air pollution and other specific kinds of pollution, while areas of trade-off include food access, habitat loss and mineral resources *(medium confidence)*. For example, action consistent with 1.5°C in the absence of energy demand reduction measures require large quantities of CDR, which, depending on the type used, are likely to negatively impact both food availability and areas for biodiversity (Fujimori et al. 2018; Ohashi et al. 2019; Roelfsema et al. 2020).

Mitigation to 1.5°C reduces climate impacts on sustainability (left). Policies integrating sustainability and mitigation (right) have far fewer trade-offs than narrow mitigation policies (middle).

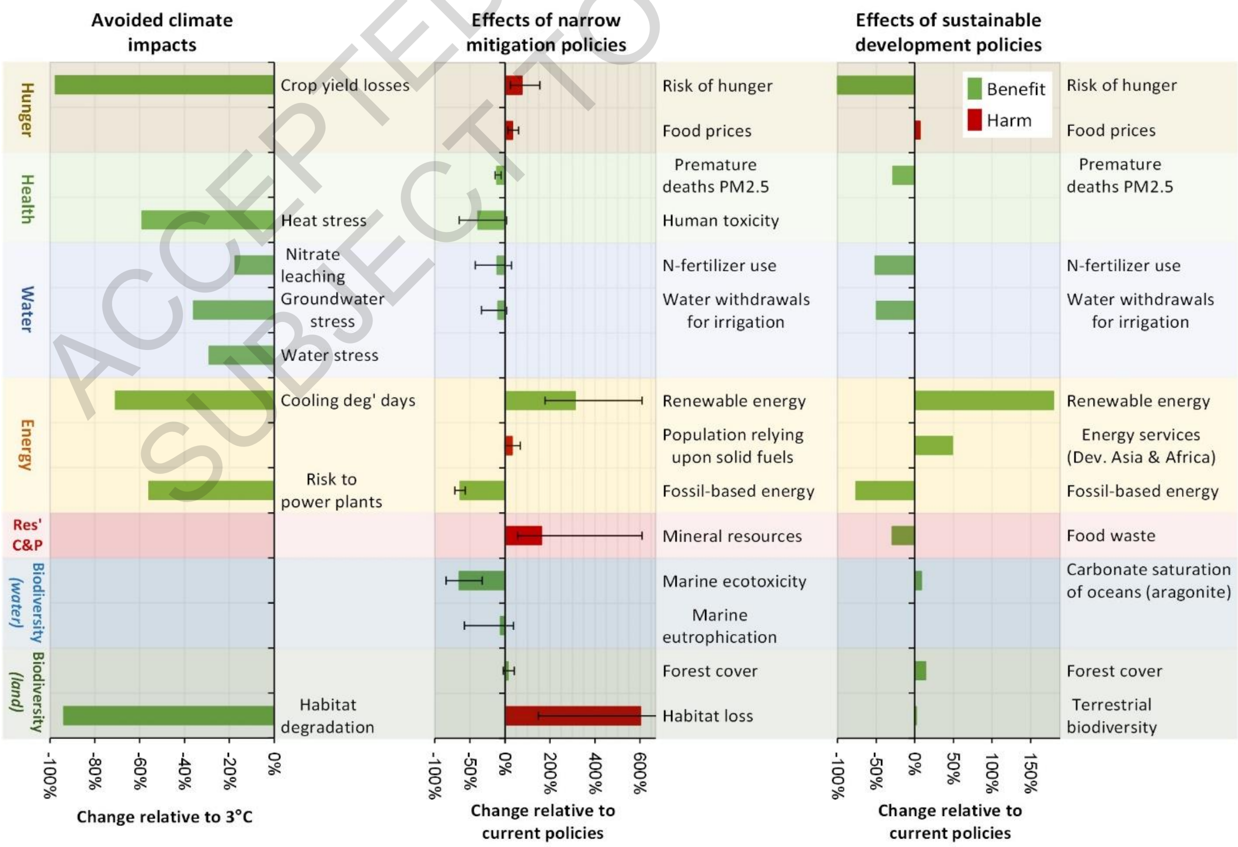


Figure 3.39: Sustainable development effects of mitigation to 1.5°C. Left: benefits of mitigation from avoided impacts. Middle: sustainability co-benefits and trade-offs of narrow mitigation policies (averaged over multiple models). Right: sustainability co-benefits and trade-offs of mitigation policies integrating sustainable development goals. Scale: 0% means no change compared to 3ºC (left) or current policies (middle and right). Green values correspond to proportional improvements, red values to proportional worsening. Note: only the left panel considers climate impacts on sustainable development; the middle and right panels do not. "Res' C&P" stands for Responsible Consumption and Production (SDG 12). Data are from Byers et al. (2018) (left), *SP*/Soergel et al. (2021a) (right). Methods used in middle panel: for biodiversity, Ohashi et al. (2019), for ecotoxicity and eutrophication, Arvesen et al. (2018) and Pehl et al. (2017), for energy access, Cameron et al. (2016). "Energy services" on the right is a measure of useful energy in buildings and transport. "Food prices" and "Risk of hunger" in the middle panel are the same as in Figure 3.38.

3.7.1.1 Policies combining mitigation and sustainable development

These findings indicate that holistic policymaking integrating sustainability objectives alongside mitigation will be important in attaining sustainable development goals (van Vuuren et al. 2015, 2018; Bertram et al. 2018; Fujimori et al. 2018; Hasegawa et al. 2018; Liu et al. 2020a; Honegger et al. 2021; Soergel et al. 2021a). Mitigation policies which target direct sector-level regulation, early mitigation action, and lifestyle changes have beneficial sustainable development outcomes across air pollution, food, energy and water (Bertram et al. 2018).

These policies include ones around stringent air quality (Kinney 2018; Rafaj et al. 2018; Soergel et al. 2021a); efficient and safe demand-side technologies, especially cook stoves (Cameron et al. 2016); lifestyle changes (Bertram et al. 2018; Grubler et al. 2018; Soergel et al. 2021a); industrial and sectoral policy (Bertram et al. 2018); agricultural and food policies (including food waste) (van Vuuren et al. 2019; Soergel et al. 2021a); international cooperation (Soergel et al. 2021a); as well as economic policies described in section 3.6. Recent research shows that mitigation is compatible with reductions in inequality and poverty (see Box 3.6 on poverty and inequality).

Lower demand – e.g., for energy and land-intensive consumption such as meat – represents a synergistic strategy for achieving ambitious climate mitigation without compromising sustainable development goals (Grubler et al. 2018; van Vuuren et al. 2018; Bertram et al. 2018; Kikstra et al. 2021b; Soergel et al. 2021a) *(high confidence)*. This is especially true for reliance on BECCS (Hickel et al. 2021; Keyßer and Lenzen 2021). Options that reduce agricultural demand (e.g., dietary change, reduced food waste) can have co-benefits for adaptation through reductions in demand for land and water (IPCC 2019a; Grubler et al. 2018; Bertram et al. 2018; Soergel et al. 2021a).

While the impacts of climate change on agricultural output are expected to increase the population at risk of hunger, there is evidence suggesting population growth will be the dominant driver of hunger and undernourishment in Africa in 2050 (Hall et al. 2017). Meeting SDG5 relating to gender equality and reproductive rights could substantially lower population growth, leading to a global population lower than the 95% prediction range of the UN projections (Abel et al. 2016). Meeting SDG5 (gender equality, including via voluntary family planning (O'Sullivan 2018)) could thus minimise the risks to SDG2 (hunger) that are posed by meeting SDG13 (climate action).

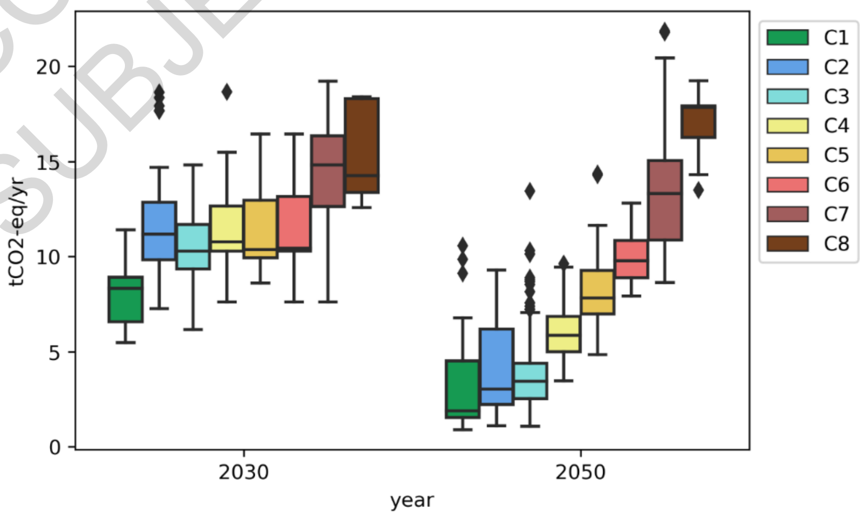
START BOX HERE

Box 3.6 Poverty and Inequality

There is high confidence *(medium evidence, high agreement)* that the eradication of extreme poverty and universal access to energy can be achieved without resulting in significant greenhouse gas emissions (Tait and Winkler 2012; Pachauri 2014; Chakravarty and Tavoni 2013; Rao 2014; Pachauri et al. 2013; Hubacek et al. 2017b; Poblete-Cazenave et al. 2021). There is also high agreement in the literature that a focus on wellbeing and decent living standards for all can reduce disparities in access to basic needs for services concurrently with climate mitigation (Chapter 5, 5.2). Mitigation pathways in which national redistribution of carbon pricing revenues is combined with international climate finance, achieve poverty reduction globally (Fujimori et al. 2020b; Soergel et al. 2021b). Carbon pricing revenues in mitigation pathways consistent with limiting temperature increase to 2°C could also contribute to finance investment needs for basic infrastructure (Jakob et al. 2016) and SDGs achievement (Franks et al. 2018).

Several studies conclude that reaching higher income levels globally, beyond exiting extreme poverty, and achieving more qualitative social objectives and well-being, are associated with higher emissions (Ribas et al. 2017, 2019; Scherer et al. 2018; Fischetti 2018; Hubacek et al. 2017b). Studies give divergent results on the effect of economic inequality reduction on emissions, with either an increase or a decrease in emissions (Berthe and Elie 2015; Lamb and Rao 2015; Grunewald et al. 2017; Hubacek et al. 2017a,b; Jorgenson et al. 2017; Knight et al. 2017; Mader 2018; Rao and Min 2018; Liu et al. 2019; Sager 2019; Baležentis et al. 2020; Liobikienė 2020; Liobikienė and Rimkuvienė 2020; Liu et al. 2020b; Millward-Hopkins and Oswald 2021). However, the absolute effect of economic inequality reduction on emissions remains moderate, under the assumptions tested. For instance, (Sager 2019) finds that a full redistribution of income leading to equality among US households in a counterfactual scenario for 2009 would raise emissions by 2.3%; and (Rao and Min 2018) limit to 8% the maximum plausible increase in emissions that would accompany the reduction of the global Gini coefficient from its current level of 0.55 to a level of 0.3 by 2050. Similarly, reduced income inequality would lead to a global energy demand increase of 7% (Oswald et al. 2021). Reconciling mitigation and inequality reduction objectives requires policies that take into account both objectives at all stages of policy making (Markkanen and Anger-Kraavi 2019), including focusing on the carbon intensity of lifestyles (Scherer et al. 2018), attention to sufficiency and equity (Fischetti 2018) and targeting the consumption of the richest and highest emitting households (Otto et al. 2019).

In modelled mitigation pathways, inequality in per capita emissions between regions are generally reduced over time, and the reduction is generally more pronounced in lower temperature pathways (Box 3.6 Figure 1). Already in 2030, if Nationally Determined Contributions from the Paris Agreement are fully achieved, inequalities in per capita GHG emissions between countries would be reduced (Benveniste et al. 2018).



Box 3.6 Figure 1: Difference in per capita emissions of Kyoto gases between the highest emitting and the lowest emitting of the 10 regions, in 2030 and 2050, by temperature category of pathways

Through avoiding impacts of climate change, which fall more heavily on low-income countries, communities and households and exacerbate poverty, mitigation reduces inequalities and poverty (see section 3.6.4.2).

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The remainder of this section covers specific domains of sustainable development: food (3.7.2), water (3.7.3), energy (3.7.4), health (3.7.5), biodiversity (3.7.6) and multisector - Cities, infrastructure, industry, production & consumption (3.7.7). These represent the areas with the strongest research connecting mitigation to sustainable development. The links to individual SDGs are given within these sections. Each domain covers the benefits of avoided climate impacts and the implications (synergies and trade-offs) of mitigation efforts.

3.7.2 Food

The goal of SDG2 is to achieve "zero-hunger" by 2030. According to the UN (2015), over 25% of the global population currently experience food insecurity and nearly 40% of these experience severe food insecurity, a situation worsened by the covid pandemic (Paslakis et al. 2021).

3.7.2.1 Benefits of avoided climate impacts along mitigation pathways

Climate change will reduce crop yields, increase food insecurity, and negatively influence nutrition and mortality (*high confidence*) (AR6 WGII Chapter 5). Climate mitigation will thus reduce these impacts, and hence reduce food insecurity (*high confidence*). The yield reduction of global food production will increase food insecurity and influence nutrition and mortality (Springmann et al. 2016a; Hasegawa et al. 2014). For instance, (Springmann et al. 2016a) estimate that climate change could lead to 315,000-736,000 additional deaths by 2050, though these could mostly be averted by stringent mitigation efforts. Reducing warming reduces the impacts of climate change, including extreme climates, on food production and risk of hunger (Hasegawa et al. 2014, 2021b).

3.7.2.2 Implications of mitigation efforts along pathways

Recent studies explore the effect of climate change mitigation on agricultural markets and food security (Hasegawa et al. 2018; Havlík et al. 2014; Fujimori et al. 2019; Doelman et al. 2019). Mitigation policies aimed at achieving 1.5-2°C, if not managed properly, could negatively affect the food security through changes in land and food prices *(high confidence)*, leading to increases in the population at risk of hunger by 80 to 280 million people compared to baseline scenarios. These studies assume uniform carbon prices on AFOLU sectors (with some sectoral caps) and do not account for climate impacts on food production.

Mitigating climate change while ensuring that food security is not adversely affected requires a range of different strategies and interventions (*high confidence*). (Fujimori et al. 2018) explore possible economic solutions to these unintended impacts of mitigation (e.g., agricultural subsidies, food aid, and domestic reallocation of income) with an additional small (<0.1%) change in global GDP. Targeted food-security support is needed to shield impoverished and vulnerable people from the risk of hunger that could be caused by the economic effects of policies narrowly focussed on climate objectives. Introducing more biofuels and careful selection of bioenergy feedstocks could also reduce negative impacts (FAO WFP, WHO 2017). Reconciling bioenergy demands with food and biodiversity, as well as competition for land and water, will require changes in food systems – agricultural intensification, open trade, less consumption of animal-products and reduced food losses – and advanced biotechnologies (Henry et al. 2018; Xu et al. 2019).

There are many other synergistic measures for climate mitigation and food security. Agricultural technological innovation can improve the efficiency of land use and food systems, thus reducing the pressure on land from increasing food demand (Foley et al. 2011; Humpenöder et al. 2018; Popp et al. 2014; Obersteiner et al. 2016; Doelman et al. 2019). Furthermore, decreasing consumption of animal products could contribute to SDG3.4 by reducing the risk of non-communicable diseases (Garnett 2016).

Taken together, climate changes will reduce crop yields, increase food insecurity and influence nutrition and mortality *(high confidence)* (see 3.7.2.1). However, if measures are not properly designed, mitigating climate change will also negatively impact on food consumption and security. Additional solutions to negative impacts associated with climate mitigation on food production and consumption include a transition to a sustainable agriculture and food system that is less resource intensive, more resilient to a changing climate, and in line with biodiversity and social targets (Kayal et al. 2019).

3.7.3 Water

Water is relevant to SDG 6 (clean water and sanitation), SDG 15 (ecosystem protection and water systems), and SDG Targets 12.4 and 3.9 (water pollution and health). This section discusses water quantity, water quality, and water-related extremes. See 3.7.5 for water-related health effects.

3.7.3.1 Benefits of avoided climate impacts along mitigation pathways

Global precipitation, evapotranspiration, runoff and water availability increase with warming (Hanasaki et al. 2013; Greve et al. 2018) (see also WGII Chapter 4). Climate change also affects the occurrence of and exposure to hydrological extremes *(high confidence)* (Arnell and Lloyd-Hughes 2014; Asadieh and Krakauer 2017; Dottori et al. 2018; IPCC 2019a; Naumann et al. 2018; Do et al. 2020) (see also WGII Chapter 4). Climate models project increases in precipitation intensity (*high confidence*), local flooding (*medium confidence*), and drought risk (*very high confidence*) (Arnell and Lloyd-Hughes 2014; Asadieh and Krakauer 2017; Dottori et al. 2018; IPCC 2019a) (see also WGII Chapter 4).

The effect of climate change on water availability and hydrological extremes varies by region (*high confidence*) due to differences in the spatial patterns of projected precipitation changes (Hanasaki et al. 2013; Koutroulis et al. 2019; Schewe et al. 2014; Schlosser et al. 2014; Asadieh and Krakauer 2017; Dottori et al. 2018; Naumann et al. 2018) (see also WGII Chapter 4). Global exposure to water stress is projected to increase with increased warming, but increases will not occur in all regions (Arnell and Lloyd-Hughes 2014; Gosling and Arnell 2016; Hanasaki et al. 2013; IPCC 2019a; Schewe et al. 2014).

Limiting warming could reduce water-related risks (*high confidence*) (O'Neill et al. 2017b; Byers et al. 2018; Hurlbert et al. 2019) (see also WGII Chapter 4) and the population exposed to increased water stress (Arnell and Lloyd-Hughes 2014; Gosling and Arnell 2016; Hanasaki et al. 2013; IPCC 2019a; Schewe et al. 2014).

The effect of climate change on water depends on the climate model, the hydrological model, and the metric (*high confidence*) stress (Arnell and Lloyd-Hughes 2014; Gosling and Arnell 2016; Hanasaki et al. 2013; IPCC 2019a; Schewe et al. 2014; Schlosser et al. 2014). However, the effect of socioeconomic development could be larger than the effect of climate change (*high confidence*) (Arnell and Lloyd-Hughes 2014; Schlosser et al. 2014; Graham et al. 2020).

Climate change can also affect water quality (both thermal and chemical) (Liu et al. 2017), leading to increases in stream temperature and nitrogen loading in rivers (Ballard et al. 2019).

3.7.3.2 Implications of mitigation efforts along pathways

The effect of mitigation on water demand depends on the mitigation technologies deployed (*high confidence*) (Bonsch et al. 2016; Chaturvedi et al. 2013a,b; Jakob and Steckel 2016; Hejazi et al. 2014; Kyle et al. 2013; Fujimori et al. 2017; Maïzi et al. 2017; Mouratiadou et al. 2016; Parkinson et al. 2019; Bijl et al. 2018; Cui et al. 2018; Graham et al. 2018; Hanasaki et al. 2013). Some mitigation options could increase water consumption (volume removed and not returned) while decreasing withdrawals (total volume of water removed, some of which may be returned) (Kyle et al. 2013; Mouratiadou et al. 2016; Fricko et al. 2016; Parkinson et al. 2019). Bioenergy and BECCS can increase water withdrawals and water consumption (*high confidence*) (Bonsch et al. 2016; Chaturvedi et al. 2013a; Hejazi et al. 2014; Jakob and Steckel 2016; Kyle et al. 2013; Fujimori et al. 2017; Maïzi et al. 2017; Mouratiadou et al. 2016; Parkinson et al. 2019; Yamagata et al. 2018; Séférian et al. 2018) (see also WGII Chapter 4). DACCS (Fuhrman et al. 2020) and CCS (Kyle et al. 2013; Fujimori et al. 2017) could increase water demand; however, the implications of CCS depend on the cooling technology and when capture occurs (Magneschi et al. 2017; Maïzi et al. 2017; Giannaris et al. 2020). Demand-side mitigation (e.g., dietary change, reduced food waste, reduced energy demand) can reduce water demand (Bajželj et al. 2014; Aleksandrowicz et al. 2016; Springmann et al. 2018; Green et al. 2018). Introducing specific measures (e.g., environmental flow requirements, improved efficiency, priority rules) can reduce water withdrawals (Bertram et al. 2018; Bijl et al. 2018; Parkinson et al. 2019).

The effect of mitigation on water quality depends on the mitigation option, its implementation, and the aspect of quality considered (*high confidence*) (McElwee et al. 2020; Smith et al. 2019; Sinha et al. 2019; Ng et al. 2010; Fuhrman et al. 2020; Flörke et al. 2019; Karlsson et al. 2020).

3.7.4 Energy

Energy is relevant to SDG7 on sustainable and affordable energy access. Access to sufficient levels of reliable, affordable and renewable energy is essential for sustainable development. Currently, over 1 billion people still lack access to electricity (Ribas et al. 2019).

3.7.4.1 Benefits of avoided climate impacts along mitigation pathways

Climate change alters the production of energy through changes in temperature (hydropower, fossil fuel, nuclear, solar, bioenergy, transmission and pipelines), precipitation (hydropower, fossil fuel, nuclear, bioenergy), windiness (wind, wave), and cloudiness (solar) *(high confidence)*. Increases in temperature reduce efficiencies of thermal power plants (e.g., fossil fuel and nuclear plants) with air-cooled condensers by 0.4-0.7% ºC increase in ambient temperature (Cronin et al. 2018a; Yalew, S. G. et al. 2020; Simioni and Schaeffer 2019). Potentials and costs for renewable energy technologies are also affected by climate change, though with considerable regional variation and uncertainty (Gernaat et al. 2021). Biofuel yields could increase or decrease depending on the level of warming, changes in precipitation, and the effect of CO_2 fertilization (Calvin et al. 2013; Kyle et al. 2014; Gernaat et al. 2021). Coastal energy facilities could potentially be impacted by sea-level rise (Brown et al. 2014).

The energy sector uses large volumes of water (Fricko et al. 2016), making it highly vulnerable to climate change (Tan and Zhi 2016) *(high confidence).* Thermoelectric and hydropower sources are the most vulnerable to water stress (van Vliet et al. 2016). Restricted water supply to these power sources can affect grid security and affordable energy access (Koch et al. 2014; Ranzani et al. 2018; Zhang et al. 2018d).The hydropower facilities from high mountain areas of Central Europe, Iceland, Western

US/Canada, and Latin America (Hock et al. 2019) as well as Africa and China (Bartos and Chester 2015; Eyer and Wichman 2018; Tarroja et al. 2016; Savelsberg et al. 2018; Ranzani et al. 2018; Zhang et al. 2018d; Conway et al. 2017; Zhou et al. 2018; Gaupp et al. 2015; Wang et al. 2019; Byers et al. 2018) have experienced changes in seasonality and availability.

3.7.4.2 Implications of mitigation efforts along pathways

Extending energy access to all in line with SDG7 is compatible with strong mitigation consistent with the Paris agreement *(high confidence)*. The Low Energy Demand (LED) scenario projects that these twin goals can be achieved by relying heavily on energy efficiency and rapid social transformations (Grubler et al. 2018). The IEA's Sustainable Development Scenario (IEA 2020a) achieves development outcomes but with higher average energy use, and bottom-up modelling suggests that decent living standards could be provided to all in 2040-2050 with roughly 150 EJ, or 40% of current final energy use (Kikstra et al. 2021b; Millward-Hopkins et al. 2020). The trade-offs between climate mitigation and increasing energy consumption of the world's poorest are negligible (Rao and Min 2018; Scherer et al. 2018).

The additional energy demand to meet the basic cooling requirement in Global South is estimated to be much larger than the electricity needed to provide basic residential energy services universally via clean and affordable energy, as defined by SDG7 (IEA 2019; Mastrucci et al. 2019) *(high confidence).* If conventional air conditioning systems are widely deployed to provide cooling, energy use could rise significantly (van Ruijven et al. 2019; Falchetta and Mistry 2021; Bezerra et al. 2021), thus creating a positive feedback further increasing cooling demand. However, the overall emissions are barely altered by the changing energy demand composition with reductions in heating demand occurring simultaneously (Isaac and van Vuuren 2009; Labriet et al. 2015; McFarland et al. 2015; Clarke et al. 2018). Some mitigation scenarios show price increases of clean cooking fuels, slowing the transition to clean cooking fuels (SDG 7.1) and leaving a billion people in 2050 still reliant on solid fuels in South Asia (Cameron et al. 2016).

In contrast, future energy infrastructure could improve reliability, thus lowering dependence on high-carbon, high-air pollution backup diesel generators (Farquharson et al. 2018) that are often used to cope with unreliable power in developing countries (Maruyama Rentschler et al. 2019). There can be significant reliability issues where mini-grids are used to electrify rural areas (Numminen and Lund 2019). A stable, sustainable energy transition policy that considers national sustainable development in the short- and long-term is critical in driving a transition to an energy future that addresses the trilemma of energy security, equity, and sustainability (La Viña et al. 2018).

3.7.5 Health

SDG 3 aims to ensure healthy lives and promote well-being for all at all ages. Climate change is increasingly causing injuries, illnesses, malnutrition, threats to mental health and well-being, and deaths (see WGII Chapter 7). Mitigation policies and technologies to reduce GHG emissions are often beneficial for human health on a shorter time scale than benefits in terms of slowing climate change (Limaye et al. 2020). The financial value of health benefits from improved air quality alone is projected to exceed the costs of meeting the goals of the Paris Agreement (Markandya et al. 2018).

3.7.5.1 Benefits of avoided climate impacts along mitigation pathways

The human health chapter of the WGII contribution to the AR6 concluded that climate change is increasingly affecting a growing number of health outcomes, with negative net impacts at the global scale and positive only in a few limited situations. There are few estimates of economic costs of increases in climate-sensitive health outcomes. In the U.S. in 2012, the financial burden in terms of deaths, hospitalizations, and emergency department visits for ten climate-sensitive events across 11 states were estimated to be USD 10.0 (2.7 – 24.6) billion in 2018 dollars (Limaye et al. 2019).

3.7.5.2 Implications of mitigation efforts along pathways

Transitioning toward equitable, low-carbon societies has multiple co-benefits for health and wellbeing (see WGII Chapter 7). Health benefits can be gained from improvements in air quality through transitioning to renewable energy and active transport (e.g., walking and cycling); shifting to affordable low-meat, plant-rich diets; and green buildings and nature-based solutions, such as green and blue urban infrastructure, as shown in Figure 3.40 (Iacobucci 2016).

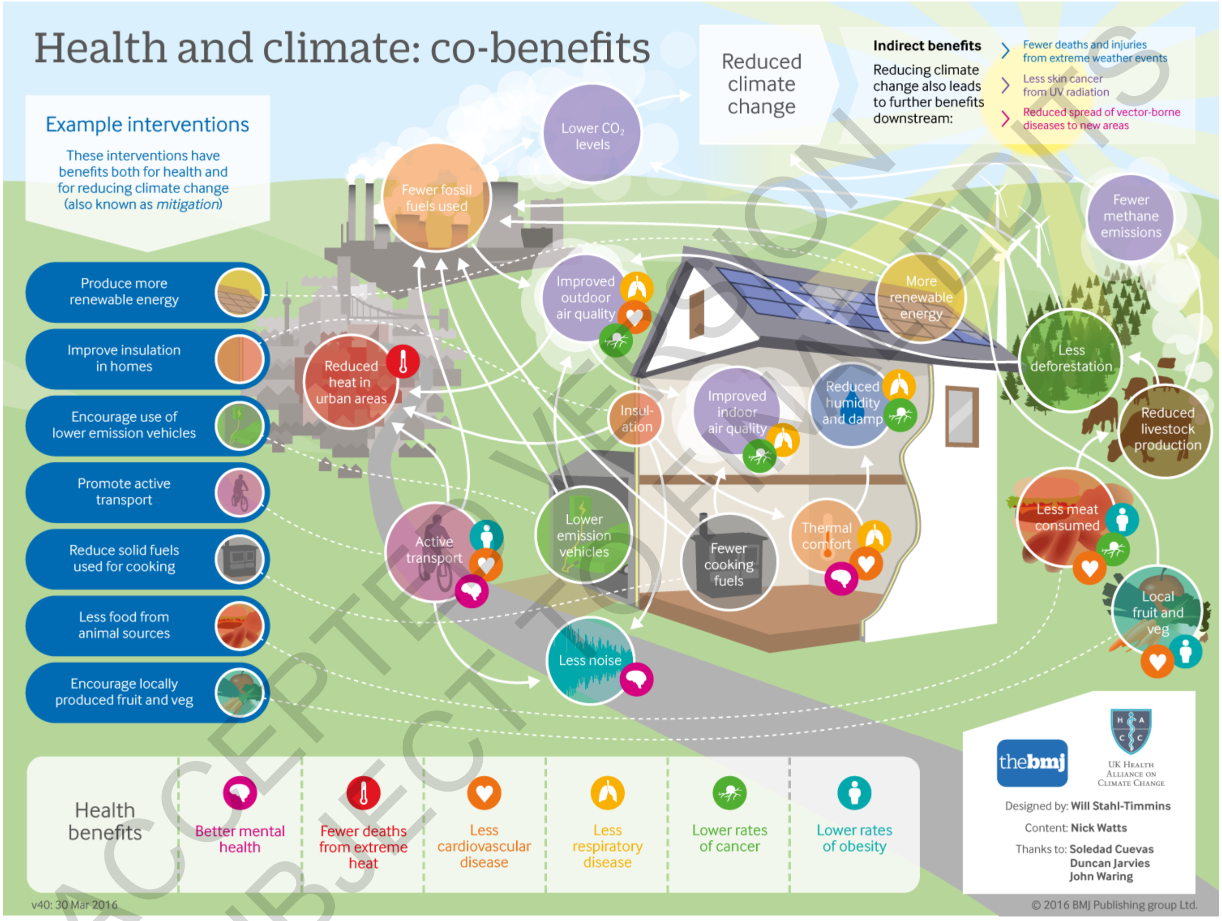

Figure 3.40: Diagram showing the co-benefits between health and mitigation (Iacobucci 2016)

The avoided health impacts associated with climate change mitigation can substantially offset mitigation costs at the societal level (Chang et al. 2017; Ščasný et al. 2015; Schucht et al. 2015; Markandya et al. 2018). Models of health co-benefits show that a 1.5 C pathway could result in 152 +/- 43 million fewer premature deaths worldwide between 2020 and 2100 in comparison to a business-as-usual scenario, particularly due to reductions in exposure to PM2.5 (Shindell et al. 2018; Rauner et al. 2020a; Rafaj et al. 2021). Some of the most substantial health, wellbeing, and equity benefits associated with climate action derive from investing in basic infrastructure: sanitation, clean drinking water, clean energy, affordable healthy diets, clean public transport, and improved air quality from transformative solutions across economic sectors including agriculture, energy, transport and buildings (Chang et al. 2017).

The health co-benefits of the NDCs for 2040 were compared for two scenarios, one consistent with the goal of the Paris Agreement and the SDGs and the other also placing health as a central focus of the policies (i.e., health in all climate policies scenario) (Hamilton et al. 2021), for Brazil, China, Germany, India, Indonesia, Nigeria, South Africa, the UK, and the USA. Modelling of the energy, food and agriculture, and transport sectors, and associated risk factors related to mortality, suggested the sustainable pathways scenario could result in annual reductions of 1.18 million air pollution-related deaths, 5.86 million diet-related deaths, and 1.15 million deaths due to physical inactivity. Adopting the more ambitious health in all climate policies scenario could result in further reductions of 462,000 annual deaths attributable to air pollution, 572,000 annual deaths attributable to diet, and 943,000 annual deaths attributable to physical inactivity. These benefits were attributable to the mitigation of direct greenhouse gas emissions and the commensurate actions that reduce exposure to harmful pollutants, as well as improved diets and safe physical activity.

Cost-benefit analyses for climate mitigation in urban settings that do not account for health may underestimate the potential cost savings and benefits (Hess et al. 2020). The net health benefits of controlling air pollution as part of climate mitigation efforts could reach trillions of dollars annually, depending on the air quality policies adopted globally (Markandya et al. 2018; Scovronick et al. 2019b). Air pollution reductions resulting from meeting the Paris Agreement targets were estimated to provide health co-benefits-to-mitigation ratios of between 1.4 and 2.5 (Markandya et al. 2018). In Asia, the benefit of air pollution reduction through mitigation measures were estimated to reduce premature mortality by 0.79 million, with an associated health benefit of USD2.8 trillion versus mitigation costs of USD840 billion, equating to 6% and 2% of GDP, respectively (Xie et al. 2018). Similarly, stabilizing radiative forcing to 3.4 W/m^2 in South Korea could cost USD1.3-8.5 billion in 2050 and could lead to a USD23.5 billion cost reduction from the combined benefits of avoided premature mortality, health expenditures, and lost work hours (Kim et al. 2020). The health co-benefits related to physical exercise and reduced air pollution largely offset the costs of implementing low CO_2 emitting urban mobility strategies in three Austrian cities (Wolkinger et al. 2018).

Just in the United States of America, over the next 50 years, a 2°C pathway could prevent roughly 4.5 million premature deaths, about 3.5 million hospitalizations and emergency room visits, and approximately 300 million lost workdays (Shindell 2020). The estimated yearly benefits of USD700 billion were more than the estimated cost of the energy transition.

3.7.6 Biodiversity (land and water)

Biodiversity covers Life Below Water (SDG 14) and Life On Land (SDG 15). Ecosystem services are relevant to the goals of Zero Hunger (SDG 2), Good Health and Well Being (SDG 3), Clean Water and Sanitation (SDG 6) and Responsible Consumption and Production (SDG 12), as well as being essential to human existence (Díaz et al. 2019).

3.7.6.1 Benefits of avoided climate impacts along mitigation pathways

3.7.6.1.1 Terrestrial and freshwater aquatic ecosystems

Climate change is a major driver of species extinction and terrestrial and freshwater ecosystems destruction (see WGII Chapter 2) *(high confidence)*. Analysis shows that approximately half of all species with long-term records have shifted their ranges in elevation and about two thirds have advanced their timing of spring events (Parmesan and Hanley 2015). Under 3.2 °C warming, 49% of insects, 44% of plants and 26% of vertebrates are projected to be at risk of extinction. At 2°C, this falls to 18% of insects, 16% of plants and 8% of vertebrates and at 1.5°C, to 6% of insects, 8% of plants and 4% of vertebrates (Warren et al. 2018). Incidents of migration of invasive species, including pests and diseases, are also attributable to climate change, with negative impacts on food security and vector-borne diseases. Moreover, if climate change reduces crop yields, cropland may expand – a primary driver of biodiversity loss – in order to meet food demand (Molotoks et al. 2020). Land restoration and halting land degradation under all mitigation scenarios has the potential for synergy between mitigation and adaptation.

3.7.6.1.2 Marine and coastal ecosystems

Marine ecosystems are being affected by climate change and growing non-climate pressures including temperature change, acidification, land-sourced pollution, sedimentation, resource extraction and habitat destruction *(high confidence)* (IPCC 2019b; Bindoff et al. 2019). The impacts of climate drivers and their combinations vary across taxa (WGII Chapter 3). The danger or warming and acidification to coral reefs, rocky shores and kelp forests is well established *(high confidence)* (WGII Chapter 3). Migration towards optimal thermal and chemical conditions (Burrows et al. 2019) contributes to large scale redistribution of fish and invertebrate populations, and major impacts on global marine biomass production and maximum sustainable yield (Bindoff et al. 2019).

3.7.6.2 Implications of mitigation efforts along pathways

Mitigation measures have the potential to reduce the progress of negative impacts on ecosystems, although it is unlikely that all impacts can be mitigated *(high confidence)* (Ohashi et al. 2019). The specifics of mitigation achievement are crucial, since large-scale deployment of some climate mitigation and land-based CDR measures could have deleterious impacts on biodiversity (Santangeli et al. 2016; Hof et al. 2018).

Climate change mitigation actions to reduce or slow negative impacts on ecosystems are likely to support the achievement of SDGs 2, 3, 6, 12, 14 and 15. Some studies show that stringent and constant GHG mitigation practices bring a net benefit to global biodiversity even if land-based mitigation measures are also adopted (Ohashi et al. 2019), as opposed to delayed action which would require much more widespread use of BECCS. Scenarios based on demand reductions of energy and land-based production are expected to avoid many such consequences, due to their minimized reliance on BECCS (Grubler et al. 2018; Conijn et al. 2018; Bowles et al. 2019; Soergel et al. 2021a). Stringent mitigation that includes reductions in demand for animal-based foods and food-waste could also relieve pressures on land-use and biodiversity *(high confidence)*, both directly by reducing agricultural land requirements (Leclère et al. 2020) and indirectly by reducing the need for land-based CDR (van Vuuren et al. 2018).

As environmental conservation and sustainable use of the earth's terrestrial species and ecosystems are strongly related, recent studies have evaluated interconnections among key aspects of land and show pathway to the global sustainable future of land (Erb et al. 2016; Humpenöder et al. 2018; Popp et al. 2014; Obersteiner et al. 2016). Most studies agree that many biophysical options exist to achieve global climate mitigation and sustainable land-use in future. Conserving local biodiversity requires careful policy design in conjunction with land-use regulations and societal transformation in order to minimize the conversion of natural habitats.

3.7.7 Cities and infrastructure

This subsection focuses upon SDG9, Industry, Innovation and Infrastructure and SDG11, Sustainable Cities and Communities.

3.7.7.1 Benefits of avoided climate impacts along mitigation pathways

By 2100, urban population will be almost double and more urban areas will be built (Jiang and O'Neill 2017), although Covid-19 may modify these trends (Kii 2021). Urbanization will amplify projected air temperature changes in cities, including amplifying heat waves (see WGI Chapter 10, Box 10.3). Benefits of climate mitigation in urban areas include reducing heat, air pollution and flooding. Industrial infrastructure and production-consumption supply networks also benefit from avoided impacts.

3.7.7.2 Implications of mitigation efforts along pathways

Many co-benefits to urban mitigation actions (see Chapter 8, Section 8.2.1) that improve the liveability of cities and contribute to achieving SDG11. In particular, compact, urban form, efficient technologies and infrastructure can play a valuable role in mitigation by reducing energy demand (Güneralp et al. 2017; Creutzig et al. 2016), thus averting carbon lock-in, while reducing land sprawl and hence increasing carbon storage and biodiversity (D'Amour et al. 2017). Benefits of mitigation include air quality improvements from decreased traffic and congestion when private vehicles are displaced by other modes; health benefits from increases in active travel; and lowered urban heat island effects from green-blue infrastructures (section 8.2.1).

However, increasing urban density or enlarging urban green spaces can increase property prices and reduce affordability (Section 8.2.1). Raising living conditions for slum dwellers & people living in informal settlements will require significant materials and energy; however, regeneration can be conducted in ways that avoid carbon-intense infrastructure lock-in (see Chapter 8 & 9). Cities affect other regions through supply chains (Marinova et al. 2020).

Sustainable production, consumption and management of natural resources are consistent with, and necessary for, mitigation (Chapters 5 & 11). Demand-side measures can lower requirements for upstream material and energy use (Chapter 5). In terms of industrial production, transformational changes across sectors will be necessary for mitigation (Chapter 11, sections 11.3 and 11.4).

Addressing multiple SDG arenas requires new systemic thinking in the areas of governance and policy, such as those proposed by (Sachs et al. 2019).

3.8 Feasibility of socio/techno/economic transitions

The objective of this section is to discuss concepts of feasibility in the context of the low carbon transition and pathways. We aim to identify drivers of low carbon scenarios feasibility and to highlight enabling conditions which cam ameliorate feasibility concerns.

3.8.1 Feasibility frameworks for the low carbon transition and scenarios

Effectively responding to climate change and achieving sustainable development requires overcoming a series of challenges to transition away from fossil-based economies. Feasibility can be defined in many ways (see also Chapter 1). The political science literature (Majone 1975a,b; Gilabert and Lawford-Smith 2012) distinguishes the feasibility of 'what' (i.e. emission reduction strategies),'when and where" (i.e. in the year 2050, globally) and "whom" (i.e. cities). It distinguishes desirability from political feasibility (von Stechow et al. 2015): the former represents a normative assessments of the compatibility with societal goals (i.e. SDGs) while the latter evaluate the plausibility of what can be attained given the prevailing context of transformation (Nielsen et al. 2020). Feasibility concerns are context and time dependent and malleable: enabling conditions can help overcome them. For example, public support for carbon taxes has been hard to secure but appropriate policy design and household rebates can help dissipate opposition (Carattini et al. 2019; Murray and Rivers 2015).

Regarding scenarios, the feasibility 'what' question is the one most commonly dealt with in the literature, though most of the studies have focused on expanding low carbon system, and yet political constraints might arise mostly from phasing out fossil fuel-based ones (Spencer et al. 2018; Fattouh et al. 2019). The 'when and where' dimension can also be related to the scenario assessment, but only insofar the models generating them can differentiate time and geographical contextual factors. Distinguishing mitigation potential by regional institutional capacity has a significant influence on the costs of stabilizing climate (Iyer et al. 2015c). The 'whom' question is the most difficult to capture by scenarios, given the multitude of actors involved as well as their complex interactions. The focus of socio-technical transition sciences on the co-evolutionary processes can shed light on the dynamics of feasibility (Nielsen et al. 2020).

The when-where-whom distinction allows depicting a feasibility frontier beyond which implementation challenges prevent mitigation action (Jewell and Cherp 2020). Even if the current feasibility frontier appears restraining in some jurisdictions, it is context-dependent and dynamic as innovation proceeds and institutional capacity builds up (Nielsen et al. 2020). The question is whether the feasibility frontier can move faster than the pace at which the carbon budget is being exhausted. Jewell et al. (2019) show that the emission savings from the pledges of premature retirement of coal plants is 150 times less than globally committed emissions from existing coal power plants. The pledges come from countries with high institutional capacity and relatively low shares of coal in electricity. Other factors currently limiting the capacity to steer transitions at the necessary speed include the electoral market orientation of politicians (Willis 2017), the status quo orientation of senior public officials (Geden 2016), path dependencies created by 'instrument constituencies' (Béland and Howlett 2016), or the benefits of deliberate inconsistencies between talk, decisions and actions in climate policy (Rickards et al. 2014). All in all, a number of different delay mechanisms in both science and policy have been identified to potentially impede climate goal achievement (Karlsson and Gilek 2020) - see also Chapter 13.

In addition to its contextual and dynamic nature, feasibility is a multi-dimensional concept. The IPCC 1.5°C special report distinguishes 6 dimensions of feasibility: geophysical, environmental-ecological, technological, economic, socio-cultural and institutional. At the individual option level, different mitigation strategies face various barriers as well as enablers (see Chapter 6 for the option-level assessment). However, a systemic transformation involves interconnections of a wide range of indicators. Model-based assessments are meant to capture the integrative elements of the transition and of associated feasibility challenges. However, the translation of model-generated pathways into feasibility concerns (Rogelj et al. 2018b) has developed only recently. Furthermore, multiple forms of knowledge can be mobilized to support strategic decision-making and complement scenario analysis (Turnheim and Nykvist 2019). We discuss both approaches next.

3.8.2 Feasibility appraisal of low carbon scenarios

Evaluating the feasibility of low carbon pathways can take different forms. In the narrowest sense, there is feasibility pertaining the reporting of model-generated scenarios: here an infeasible scenario is one which cannot meet the constraints embedded implicitly or explicitly in the models which attempted to generate it. Second, there is a feasibility that relates to specific elements or overall structure characterizing the low carbon transition compared to some specified benchmark.

3.8.2.1 Model solvability

In order to be generated, scenarios must be coherent with the constraints and assumptions embedded in the models (i.e., deployment potential of given technologies, physical and geological limits) and in the scenario design (i.e., carbon budget). Sometimes, models cannot solve specific scenarios. This provides a first, coarse indication of feasibility concerns. Specific vetting criteria can be imposed, such as carbon price values above which scenarios should not be reported, as in Clarke et al. (2009). However, model solvability raises issues of aggregation in model ensemble. Since model solving is not a random process, but a function of the characteristics of the models, analysing only reported outcomes leads to statistical biases (Tavoni and Tol 2010).

Although model-feasibility differs distinctly from feasibility in the real world, it can indicate the relative challenges of low carbon scenarios - primarily when performed in a model ensemble of sufficient size. Riahi et al. (2015) interpreted infeasibility across a large number of models as an indication of increased risk that the transformation may not be attainable due to technical or economic concerns. All models involved in a model comparison of 1.5°C targets (Rogelj et al. 2018b) (Table S1) were able to solve under favourable underlying socio-economic assumptions (SSP1), but none for the more challenging SSP3. This interpretation of feasibility was used to highlight the importance of socio-economic drivers for attaining climate stabilization. Gambhir et al. (2017) constrained the models to historically observed rates of change and found that it would no longer allow to solve for 2°C, highlighting the need for rapid technological change.

3.8.2.2 Scenario feasibility

Evaluating the feasibility of scenarios involves several steps (see Figure 3.41). First, one need to identify which dimensions of feasibility to focus on. Then, for each dimension, one needs to select relevant indicators for which sufficient empirical basis exists and which are an output of models (or at least of a sufficient number of them). Then, thresholds marking different levels of feasibility concerns are defined based on available literature, expert elicitations and empirical analysis based on appropriately chosen historical precedents. Finally, scenario feasibility scores are obtained for each indicator, and where needed aggregated up in time or dimensions, as a way to provide an overall appraisal of feasibility trade-offs, depending on the timing, disruptiveness and scale of transformation.

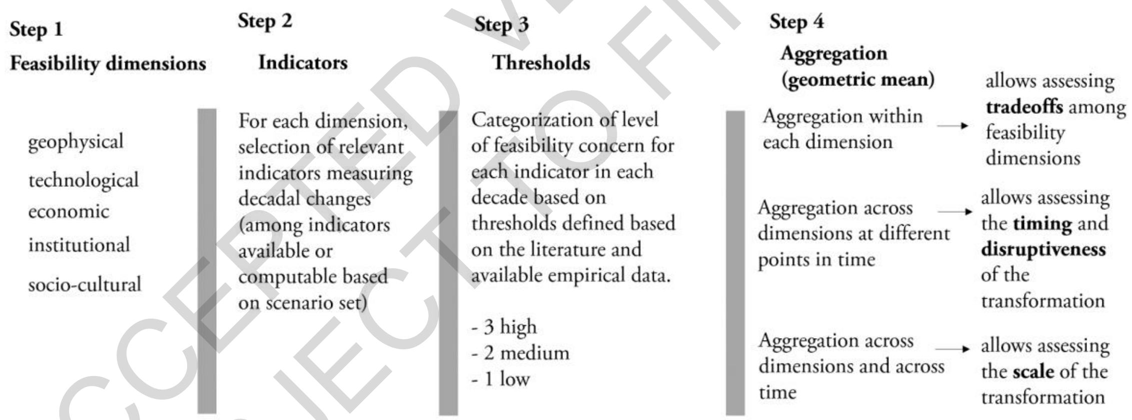

Figure 3.41: Steps involved in evaluating the feasibility of scenarios

Most of the existing literature has focused on the technological dimensions, given the technology focus of models and the ease of comparison. The literature points to varied findings. Some suggest that scenarios envision technological progress consistent with historical benchmarks (Loftus et al. 2015; Wilson et al. 2013). Others that scenarios exceed historically observed rates of low carbon technology deployment and of energy demand transformation globally (Napp et al. 2017; van der Zwaan et al. 2013; Semieniuk et al. 2021; Cherp et al. 2021), but not for all countries (Cherp et al. 2021). The reason for these discrepancies depends on the unit of analysis and the indicators used. Comparing a different kind of historical indicators, (van Sluisveld et al. 2015) find that indicators that look into the absolute change of energy systems remain within the range of historical growth frontiers for the next decade, but increase to unprecedented levels before mid-century. Expert assessments provide another way of benchmarking scenarios, though they have shown to be systematically biased (Wiser et al. 2021) and to underperform empirical methods (Meng et al. 2021). (van Sluisveld et al. 2018a) find that scenarios and experts align for baseline scenarios but differ for low carbon ones.

Scenarios rely more on conventional technologies based on existing infrastructure (such as nuclear and CCS) than what forecasted by experts. Overall, the technology assessment of the feasibility space highlights that Paris-compliant transformations would have few precedents, but not zero (Cherp et al. 2021).

Recent approaches have addressed multiple dimensions of feasibility, an important advancement since social and institutional aspects are as if not more important than technology ones (Jewell and Cherp 2020). Feasibility corridors of scenarios based on their scale, rate of change and disruptiveness have been identified (Kriegler et al. 2018b; Warszawski et al. 2021). The reality check shows that many 1.5°C compatible scenarios violate the feasibility corridors. The ones which didn't are associated with a greater coverage of the available mitigation levers (Warszawski et al. 2021).

Brutschin et al. (2021) proposed an operational framework covering all six dimensions of feasibility. They developed a set of multi-dimensional metrics capturing the timing, disruptiveness and the scale of the transformative change within each dimension (as in Kriegler et al. (2018b)). Thresholds of feasibility risks of different intensity are obtained through the review of the relevant literature and empirical analysis of historical data. Novel indicators include governance levels (Andrijevic et al. 2020a). The 17 bottom-up indicators are then aggregated up across time and dimension, as way to highlight feasibility trade-offs. Aggregation is done via compensatory approaches such as the geometric mean. This is employed, for instance, for the Human Development Index. A conceptual example of this approach as applied to the IPCC AR6 scenarios database is shown in Figure 3.42 and further described in the Annex.

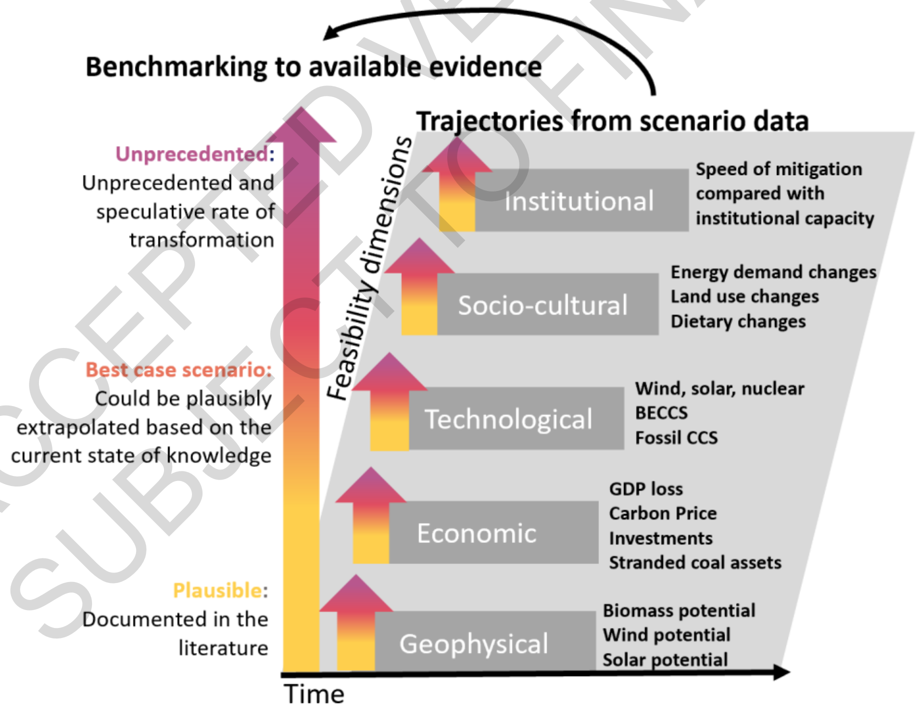

Figure 3.42: Example of multi-dimensional feasibility analysis and indicators used in the IPCC AR6 scenarios. The approach defines relevant indicators characterizing the key dimensions of feasibility. Indicators capture the timing, scale and disruptiveness challenges. Low, medium and high feasibility concerns are defined based on historical trends and available literature. Details about indicator and thresholds values can be found in Annex III

In Figure 3.43, we show the results of applying the methodology of Brutschin et al. (2021) to the AR6 scenarios database. The charts highlight the dynamic nature of feasibility risks, which are mostly concentrated in the decades before mid-century except for geophysical risks driven by CO_2 removals later in the century. Different dimensions pose differentiated challenges: for example, institutional feasibility challenges appear to be the most relevant, in line with the qualitative literature. Thus, feasibility concerns might be particularly relevant in countries with weaker institutional capacity. The Figure also highlights the key role of policy and technology, as enabling factors. In particular (Panel B), internationally coordinated and immediate emission reductions allow to smooth out feasibility concerns and reduce long term challenges compared to delayed policy action, as a result of a more gradual transition and lower requirements of CO_2 removals. For the same climate objective, different illustrative mitigation pathways entail somewhat different degrees and distributions of implementation challenges (panel C).

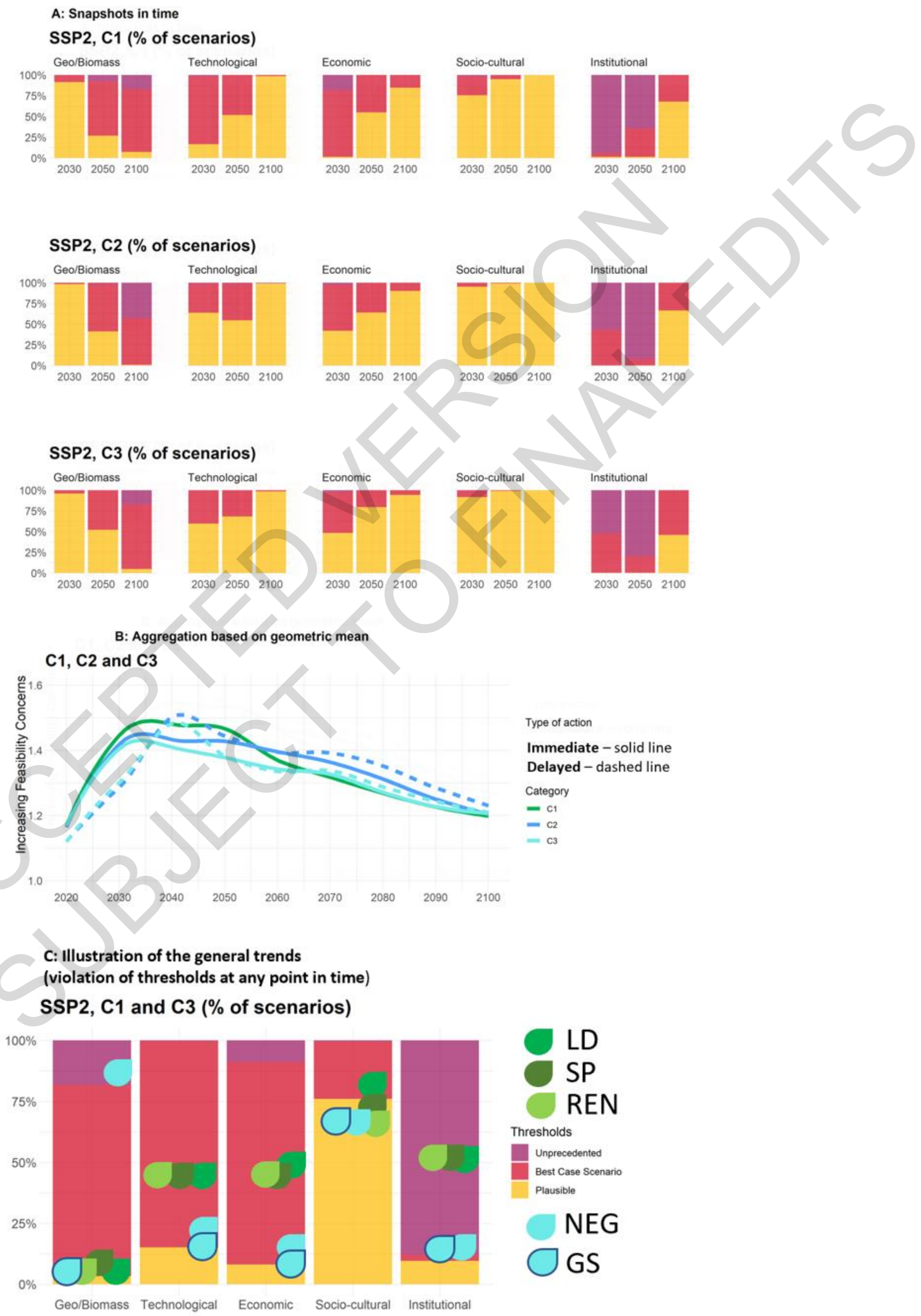

Figure 3.43: Feasibility characteristics of the Paris-consistent scenarios in AR6 scenarios database, applying the methodology by : Feasibility corridors for the AR6 scenarios database, applying the methodology by (Brutschin et al. 2021). Panel A: the fraction of scenarios falling within 3 categories of feasibility concerns (Plausible, Best Case, Unprecedented), for different times (2030, 2050, 2100), different climate categories consistent with the Paris Agreement and five dimensions. Panel B: composite feasibility score (obtained by geometric mean of underlying indicators) over time for scenarios with immediate and delayed global mitigation efforts, for different climate categories (C1-C2-C3. Note: no C1 scenarios has delayed participation). Panel C: Fraction of scenarios which in any point in time over the century exceed the feasibility concerns, for C1 and C3 climate categories. Overlayed are the Illustrative Mitigation Pathways (*LP*, *SP*, *Ren*: C1 category; *Neg*, *GS*: C3 category)

3.8.3 Feasibility in the light of socio-technical transitions

The limitations associated with quantitative low-carbon transition pathways stem from a predominant reliance on techno-economic considerations with a simplified or non-existent representation of the socio-political and institutional agreement. Accompanying the required deployment of low carbon technologies will be the formation of new socio-technical systems (Bergek et al. 2008). With a socio-technical system being defined as a cluster of elements comprising of technology, regulation, user practices and markets, cultural meaning, infrastructure, maintenance networks, and supply networks (Geels and Geels 2005; Hofman et al. 2004); the interrelationship between technological systems and social systems must be comprehensively understood. It is of vital importance that the pro-cess of technical change must considered in its institutional and social context so as to ascertain potential transition barriers which in turn provide an indication of pathway feasibility. In order to address the multitudinous challenges associated with low-carbon transition feasibility and governance, it has been opined that the robustness of evaluating pathways may be improved by the bridging of differing quantitative-qualitative analytical approaches (Haxeltine et al. 2008; Foxon et al. 2010; Hughes 2013; Wangel et al. 2013; Li et al. 2015; Turnheim et al. 2015; Geels et al. 2016a,b, 2018; Moallemi et al. 2017; De Cian et al. 2018; Li and Strachan 2019). The rationale for such analytical bridging is to rectify the issue that in isolation each disciplinary approach only can generate a fragmented comprehension of the transition pathway with the consequence being an incomplete identification of associated challenges in terms of feasibility. Concerning low-carbon transition pathways generated by IAMs, it has been argued that a comprehensive analysis should include social scientific enquiry (Geels et al. 2016a, 2018; van Sluisveld et al. 2018b). The normative analysis of IAM pathways assists in the generation of a vision or the formulation of a general plan with this being complemented by socio-technical transition theory (Geels et al. 2016a). Such an approach thereby allowing for the socio-political feasibility and the social acceptance and legitimacy of low-carbon options to be considered. Combining computer models and the multi-level perspective can help identify 'transition bottlenecks' (Geels et al. 2018). Similarly, increased resolution of integrated assessment models' actors has led to more realistic narratives of transition in terms of granularity and behaviour (McCollum et al. 2017; van Sluisveld et al. 2018b). Increased data availability of actual behaviour from smart technology lowers the barriers to representing behavioural change in computer simulations, and thus better represent crucial demand side transformations (Creutzig et al. 2018). Increasing the model resolution is a meaningful way forward. However, integrating a much broader combination of real-life aspects and dynamics into models could lead to an increased complexity that could restrict them to smaller fields of applications (De Cian et al. 2018).

Other elements of feasibility relate to social justice, which could be essential to enhance the political and public acceptability of the low carbon transition. Reviewing the literature, one study finds that employing social justice as an orienting principle can increase the political feasibility of low carbon policies (Patterson et al. 2018). Three elements are identified as key: i) protecting vulnerable people from climate change impacts, ii), protecting people from disruptions of transformation, iii), enhancing the process of envisioning and implementing an equitable post-carbon society.

3.8.4 Enabling factors

There is strong agreement that the climate policy institutional framework as well as technological progress have a profound impact on the attainability of low carbon pathways. Delaying international cooperation reduces the available carbon budget and locks into carbon intensive infrastructure exacerbating implementation challenges (Clarke et al. 2009; Bosetti et al. 2009; Krey and Riahi 2009; Boucher et al. 2009; Keppo and Rao 2007; van Vliet et al. 2009; Knopf et al. 2011; Luderer et al. 2013; Jakob et al. 2012; Aboumahboub et al. 2014; Bertram et al. 2021; Popp et al. 2014; Rogelj et al. 2013a; Riahi et al. 2015; Kriegler et al. 2014a; Gambhir et al. 2017). Similarly, technological availability influences the feasibility of climate stabilization, though differently for different technologies (Iyer et al. 2015a; Kriegler et al. 2014a; Riahi et al. 2015).

One of the most relevant factors affecting mitigation pathways and their feasibility is the rate and kind of socio-economic development. For example, certain socio-economic trends and assumptions about policy effectiveness preclude achieving stringent mitigation futures (Rogelj et al. 2018b). The risk of failure increases markedly in high growth, unequal and/or energy-intensive worlds - such as those characterized by the shared socio-economic pathways SSP3, SSP4 and SSP5. On the other hand, socio-economic development conducive to mitigation relieves the energy sector transformation from relying on large scale technology development: for example, the amount of biomass with CCS in SSP1 is one third of that in SSP5. The reason why socio-economic trends matter so much is that they both affect the CO_2 emissions in counterfactual scenarios as well as the mitigation capacity (Riahi et al. 2017; Rogelj et al. 2018b). Economic growth assumptions are the most important determinant of scenario emissions (Marangoni et al. 2017). De- and post-growth scenarios have been suggested as valuable alternatives to be considered (Hickel et al. 2021; Keyßer and Lenzen 2021), though substantial challenges remain regarding political feasibility (Keyßer and Lenzen 2021).

The type of policy instrument assumed to drive the decarbonization process also play a vital role for determining feasibility. The majority of scenarios exploring climate stabilization pathways in the past have focused on uniform carbon pricing as the most efficient instrument to regulate emissions. However, carbon taxation raises political challenges (Beiser-McGrath and Bernauer 2019), see also Chapter 13 and 14. Carbon pricing will transfer economic surplus from consumers and producers to the government. Losses for producers will be highly concentrated in those industries possessing fixed or durable assets with "high asset specificity" (Murphy 2002; Dolphin et al. 2020). These sectors have opposed climate jurisdictions (Jenkins 2014). Citizens are sensitive to rising energy prices, though revenue recycling can be used to increase support (Carattini et al. 2019). A recent model comparison project confirms findings from the extant literature: using revenues to reduce pre-existing capital or, to a lesser extent, labour taxes, reduces policy costs and eases distributional concerns (Mcfarland et al. 2018; Barron et al. 2018).

Nonetheless, winning support will require a mix of policies which go beyond carbon pricing, and include subsidies, mandates and feebates (Rozenberg et al. 2018; Jenkins 2014). More recent scenarios take into account a more comprehensive range of policies and regional heterogeneity in the near to medium term (Roelfsema et al. 2020). Regulatory policies complementing carbon prices could reduce the implementation challenges by increasing short term emission reduction, though they could eventually reduce economic efficiency (Bertram et al. 2015b; Kriegler et al. 2018a). Innovation policies such as subsidies to R&D have been shown to be desirable due to innovation market failures, and also address the dynamic nature of political feasibility (Bosetti et al. 2011).

3.9 Methods of assessment and gaps in knowledge and data

3.9.1 AR6 mitigation pathways

The analysis in this chapter relies on the available literature as well as an assessment of the scenarios contained in the AR6 scenarios database. Scenarios were submitted by research and other institutions following an open call (see Annex III Part II). The scenarios included in the AR6 scenarios database are an unstructured ensemble, as they are from multiple underlying studies and depend on which institutions chose to submit scenarios to the database. As noted in Section 3.2, they do not represent the full scenario literature or the complete set of possible scenarios. For example, scenarios that include climate change impacts or economic degrowth are not fully represented, as these scenarios, with a few exceptions, were not submitted to the database. Additionally, sensitivity studies, which could help elucidate model behaviour and drivers of change, are mostly absent from the database - though examples exist in the literature (Marangoni et al. 2017).

The AR6 scenarios database contains 3131 scenarios of which 2425 with global scope were considered by this chapter, generated by almost 100 different model versions, from more than 50 model families. Of the 1686 vetted scenarios, 1202 provided sufficient information for a climate categorization. Around 46% of the pathways are consistent with an end of century temperature of at least likely limiting warming to below 2°C. There are many ways of constructing scenarios that limit warming to a particular level and the choice of scenario construction has implications for the timing of both net zero CO_2 and GHG emissions and the deployment of CDR (Emmerling et al. 2019; Rogelj et al. 2019b; Johansson et al. 2020). The AR6 scenarios database includes scenarios where temperature is temporarily exceeded (40% of all scenarios in the database have median temperature in 2100 that is 0.1°C lower than median peak temperature). Climate stabilization scenarios are typically implemented by assuming a carbon price rising at a particular rate per year, though that rate varies across model, scenario, and time period. Standard scenarios assume a global single carbon price to minimize policy costs. Cost minimizing pathways can be reconciled with equity considerations through posterior international transfers. Many scenarios extrapolate current policies and include non-market, regulatory instruments such as technology mandates.

Scenarios are not independent of each other and not representative of all possible outcomes, nor of the underlying scenario generation process; thus, the statistical power of the database is limited. Dependencies in the data generation process originate from various sources. Certain model groups, and types, are over-represented. For example, 8 model teams contributed with 90% of scenarios. Second, not all models can generate all scenarios, and these differences are not random, thereby creating selection bias (Tavoni and Tol 2010). Third, there are strong model dependencies: the modelling scientific community shares code and data, and several IAMs are open source.

3.9.2 Models assessed in this chapter

The models assessed in this chapter differ in their sectoral coverage and the level of complexity in each sector. Models tend to have more detail in their representation of energy supply and transportation, than they do for industry (Section 3.4; Annex III). Some models include detailed land use models, while others exclude land models entirely and use supply curves to represent bioenergy potential (Bauer et al. 2018a). IAMs do not include all mitigation options available in the literature (Rogelj et al. 2018b; Smith et al. 2019). For example, most IAM pathways exclude many granular demand-side mitigation options and land-based mitigation options found in more detailed sectoral models; additionally, only a few pathways include CDR options beyond afforestation/reforestation and BECCS. Section 3.4 and Chapter 12 include some results and comparisons to non-IAM models (e.g., bottom-up studies and detailed sectoral models). These sectoral studies often include a more complete set of mitigation options but exclude feedbacks and linkages across sectors which may alter the mitigation potential of a given sector. There is an increasing focus in IAM studies on SDGs (Section 3.7), with some studies reporting the implications of mitigation pathways on SDGs (e.g., Bennich et al. (2020)) and others using achieving SDGs as a constraint on the scenario itself (van Vuuren et al. 2015; Soergel et al. 2021a). However, IAMs are still limited in the SDGs they represent, often focusing on energy, water, air pollution and land. On the economic side, the majority of the models report information on marginal costs (i.e., carbon price). Only a subset provides full economic implications measured by either economic activity or welfare. Also often missing, is detail about economic inequality within countries or large aggregate regions.

For further details about the models and scenarios, see Annex III.

Frequently Asked Questions (FAQs)

FAQ 3.1 – Is it possible to stabilize warming without net negative CO_2 and GHG emissions?

Yes. Achieving net zero CO2 emissions and sustaining them into the future is sufficient to stabilize the CO_2-induced warming signal which scales with the cumulative net amount of CO_2 emissions. At the same time, the warming signal of non-CO_2 GHGs can be stabilized or reduced by declining emissions that lead to stable or slightly declining concentrations in the atmosphere. For short-lived GHGs with atmospheric lifetimes of less than 20 years, this is achieved when residual emissions are reduced to levels that are lower than the natural removal of these gases in the atmosphere. Taken together, mitigation pathways that bring CO_2 emissions to net zero and sustain it, while strongly reducing non-CO_2 GHGs to levels that stabilize or decline their aggregate warming contribution, will stabilize warming without using net negative CO_2 emissions and with positive overall GHG emissions when aggregated using GWP100. A considerable fraction of pathways limiting warming to 1.5°C with no or limited overshoot and likely limiting warming to 2°C, respectively, do not or only marginally (<10 $GtCO_2$ cumulative until 2100) deploy net negative CO_2 emissions (26% and 46%, respectively) and do not reach net zero GHG emissions by the end of the century (48% and 70%, respectively). This is no longer the case in pathways that return warming to 1.5°C after a high overshoot (typically > 0.1°C). All of these pathways deploy net negative emissions on the order of 330 (26-623 $GtCO_2$) (median and 5^{th}-95^{th} percentile) and 87% achieve net negative GHGs emissions in AR6 GWP-100 before the end of the century. Hence, global net negative CO_2 emissions, and net zero or net negative GHG emissions, are only needed to decline, not to stabilize global warming. The deployment of carbon dioxide removal (CDR) is distinct from the deployment of net negative CO_2 emissions, because it is also used to neutralize residual CO_2 emissions to achieve and sustain net zero CO_2 emissions. CDR deployment can be considerable in pathways without net negative emissions and all pathways limiting warming to 1.5°C use it to some extent.

FAQ 3.2 – How can net zero emissions be achieved and what are the implications of net zero emissions for the climate?

Halting global warming in the long term requires, at a minimum, that no additional CO_2 emissions from human activities are added to the atmosphere (i.e., CO_2 emissions must reach "net" zero). Given that CO_2 emissions constitute the dominant human influence on global climate, global net zero CO_2 emissions are a prerequisite for stabilizing warming at any level. However, CO_2 is not the only greenhouse gas that contributes to global warming and reducing emissions of other greenhouse gases alongside CO_2 towards net zero emissions of all GHGs would lower the level at which global temperature would peak. The temperature implications of net zero GHG emissions depend on the bundle of gases that is being considered, and the emissions metric used to calculate aggregated GHG emissions and removals. If reached and sustained, global net zero GHG emissions using the 100-year Global Warming Potential (GWP-100) will lead to gradually declining global temperature.

Not all emissions can be avoided. Achieving net zero CO_2 emissions globally therefore requires deep emissions cuts across all sectors and regions, along with active removal of CO_2 from the atmosphere to balance remaining emissions that may be too difficult, too costly or impossible to abate at that time. Achieving global net zero GHG emissions would require, in addition, deep reductions of non-CO_2 emissions and additional CO_2 removals to balance remaining non-CO_2 emissions.

Not all regions and sectors must reach net zero CO_2 or GHG emissions individually to achieve global net zero CO_2 or GHG emissions, respectively; instead, positive emissions in one sector or region can be compensated by net negative emissions from another sector or region. The time each sector or region reaches net zero CO_2 or GHG emissions depends on the mitigation options available, the cost of those options, and the policies implemented (including any consideration of equity or fairness). Most modelled pathways that likely limit warming to 2°C above pre-industrial levels and below use land-based CO_2 removal such as afforestation/reforestation and BECCS to achieve net zero CO_2 and net zero GHG emissions even while some CO_2 and non-CO_2 emissions continue to occur. Pathways with more demand-side interventions that limit the amount of energy we use, or where the diet that we consume is changed, can achieve net zero CO_2, or net zero GHG emissions with less carbon dioxide removal. All available studies require at least some kind of carbon dioxide removal to reach net zero; that is, there are no studies where absolute zero GHG or even CO_2 emissions are reached by deep emissions reductions alone.

Total GHG emissions are greater than emissions of CO_2 only; reaching net zero CO_2 emissions therefore occurs earlier, by up to several decades, than net zero GHG emissions in all modelled pathways. In most modelled pathways that likely limit warming to 2°C above pre-industrial levels and below in the most cost-effective way, the AFOLU and energy supply sectors reach net zero CO_2 emissions several decades earlier than other sectors; however, many pathways show much reduced, but still positive net GHG emissions in the AFOLU sector in 2100.

FAQ 3.3 – How plausible are high emissions scenarios, and how do they inform policy?

IAMs are used to develop a wide range of scenarios describing future trajectories for greenhouse gas emissions based on a wide set of assumptions regarding socio-economic development, technological changes, political development and climate policy. Typically, the IAM-based scenarios can be divided into a) reference scenarios (describing possible trajectories in the absence of new stringent climate policies) and b) mitigation scenarios (describing the impact of various climate policy assumptions). Reference scenarios typically result in high emissions and, subsequently, high levels of climate change (in the order of 2.5-4 °C during the 21st century). The purpose of such reference scenarios is to explore the consequences of climate change and act as a reference for mitigation scenarios. The possible emission levels for reference scenarios diverge from stabilising and even slowly declining emissions (e.g., for current policy scenarios or SSP1) to very high emission levels (e.g., SSP5 and RCP8.5). The latter leads to nearly 5 °C of warming by the end of the century for medium climate sensitivity. Hausfather and Peters (2020) pointed out that since 2011, the rapid development of renewable energy technologies and emerging climate policy have made it considerably less likely that emissions could end up as high as RCP8.5. This means that reaching emissions levels as high as RCP8.5 has become less likely. Still, high emissions cannot be ruled out for many reasons, including political factors and, for instance, higher than anticipated population and economic growth. Climate projections of RCP8.5 can also result from strong feedbacks of climate change on (natural) emission sources and high climate sensitivity (see WGI Chapter 7). Therefore, their median climate impacts might also materialise while following a lower emission path (e.g., Hausfather and Betts (2020)). All-in-all, this means that high-end scenarios have become considerably less likely since AR5 but cannot be ruled out. High-end scenarios (like RCP8.5) can be very useful to explore high-end risks of climate change but are not typical ‘business-as-usual” projections and should therefore not be presented as such.

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Chapter 4: Mitigation and development pathways in the near- to mid-term

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Date of Draft: 27/11/2021

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Executive summary

This chapter focuses on accelerating mitigation and on shifting development pathways to increased sustainability, based on literature particularly at national scale. While previous WGIII assessments have discussed mitigation pathways, focus on development pathways is more recent. The timeframe is the near-term (now up to 2030) to mid-term (2030 to 2050), complementing Chapter 3 on the long-term (from 2050 onward).

An emissions gap persists, exacerbated by an implementation gap, despite mitigation efforts including those in near-universal nationally determined contributions (NDCs). The "emissions gap" is understood as the difference between the emissions with NDCs in 2030, and mitigation pathways consistent with the temperature goals. In general, the term "implementation gap" refers to the difference between goals on paper and how they are achieved in practice. In this report, the term refers to the gap between mitigation pledges contained in national determined contributions, and the expected outcome of existing policies. There is considerable literature on country-level mitigation pathways, including but not limited to NDCs. Country distribution of this literature is very unequal (*robust evidence, high agreement*). Current policies lead to median global GHG emissions of 57 $GtCO_2$-eq with a full range of 52-60 by 2030. NDCs with unconditional and conditional elements[1] lead to 53 (50-57) and 50 (47-55) $GtCO_2$-eq, respectively (*medium evidence, medium agreement*) (Table 4.3). This leaves estimated ***emissions gaps*** in 2030 between projected outcomes of unconditional elements of NDCs and emissions in scenarios that limit warming to 1.5°C with no or limited overshoot of 20-26 $GtCO_2$-eq, and 10-17 $GtCO_2$-eq for scenarios that *likely* limit warming to 2°C with immediate action. When conditional elements of NDCs are included, these gaps narrow to 16-24 GtCO2-eq and 7-14 $GtCO_2$-eq, respectively. {Cross-Chapter Box 4, Figure 1}

Studies evaluating up to 105 updated NDCs submitted by October 2021 indicate that emissions in conditional NDCs have been reduced by 4.5 (2.7-6.3) $GtCO_2$-eq, but only closes the emission gaps by about one-third to 2°C and about 20% to 1.5°C compared to the original NDCs submitted in 2015/16 (*medium evidence, medium agreement*). The magnitude of these emission gaps calls into question whether current development pathways and efforts to accelerate mitigation are adequate to achieve the Paris mitigation objectives. In addition, an ***implementation gap*** exists between the projected emissions of 'current policies' and the projected emissions resulting from the implementation of the unconditional and conditional elements of NDCs, and is estimated to be around 4 and 7 $GtCO_2$-eq in 2030, respectively (*medium evidence, medium agreement*), with many countries requiring additional policies and associated climate action to meet their autonomously determined mitigation targets as specified under the first NDCs (*limited evidence*). There is, furthermore, a potential difference between mitigation targets set in NDCs *ex ante* and what is achieved *ex post*. A limited number of studies assess the implementation gaps of conditional NDCs in terms of finance, technology and capacity building support. The disruptions triggered by the COVID-19 epidemic increase uncertainty over range of projections relative to pre-COVID-19 literature. As indicated by a growing number of studies at the national and global level, how large near- to mid-term emissions implications of the COVID-19 pandemic are, to a large degree depends on how stimulus or recovery packages are designed. {4.2, 4.2.2.5, Cross-Chapter Box 4}

Given the gaps, there is a need to explore accelerated mitigation (relative to NDCs and current policies). There is increasing understanding of the technical content of accelerated mitigation pathways, differentiated by national circumstances, with considerable though uneven literature at country-level (*medium evidence, high agreement*). Transformative technological and institutional changes for the

FOOTNOTE[1] See section 4.2.1 for description of 'unconditional' and 'conditional' elements of NDCs.

near-term include demand reductions through efficiency and reduced activity, rapid decarbonisation of the electricity sector and low-carbon electrification of buildings, industry and transport (*robust evidence, medium agreement*). A focus on energy use and supply is essential, but not sufficient on its own – the land sector and food systems deserve attention. The literature does not adequately include demand-side options and systems analysis, and captures the impact from non-CO_2 GHGs with medium confidence . Countries and regions will have different starting points for transition pathways. Some factors include climate conditions resulting in different heating and cooling needs, endowments with different energy resources, patterns of spatial development, and political and economic conditions. {4.2.5}

Accelerated mitigation alone may run into obstacles. If such obstacles are rooted in underlying structural features of society, then transforming such structures helps remove obstacles, which amounts to shifting development pathways. Various actors have developed an increasing number of mitigation strategies up to 2050 (mid-term). A growing number of such strategies aim at net zero GHG or CO_2 emissions, but it is not yet possible to draw global implications due to the limited size of sample (*medium evidence; low agreement*). Non-state actors are also engaging in a wide range of mitigation initiatives. When adding up emission reduction potentials, sub-national and non-state international cooperative initiatives could reduce up to about 20 $GtCO_2$-eq in 2030 (*limited evidence, medium agreement*). Yet perceived or real conflicts between mitigation and other Sustainable Development Goals (SDGs) can impede such action. If undertaken without precaution, accelerated mitigation is found to have significant implications for development objectives and macroeconomic costs at country level. For example, most country-level mitigation modelling studies in which GDP is an endogenous variable report negative impacts of mitigation on GDP in 2030 and 2050, relative to the reference. In all reviewed studies, however, GDP continues to grow even with mitigation (*robust evidence, high agreement*). The literature finds that employment effect of mitigation policies tends to be limited on aggregate, but can be significant at sectoral level (*limited evidence, medium agreement*). Detailed design of mitigation policies is critical for distributional impacts and avoiding lock-in (*robust evidence, high agreement*), though further research is needed in that direction. {4.2.3, 4.2.4, 4.2.6}

Shifting development pathways towards sustainability offers ways to (i) broaden the range of levers and enablers that a society can use to provide enabling conditions and accelerate mitigation; and (ii) increase the chances of advancing at the same time towards mitigation and towards other development goals. The way countries develop determines their capacity to accelerate mitigation and achieve other sustainable development objectives simultaneously (*medium-robust evidence, medium agreement*). Yet meeting ambitious mitigation and development goals cannot be achieved through incremental change, hence the focus on shifting development pathways (*robust evidence, medium agreement*). Though development pathways result from the actions of a wide range of actors, it is possible to shift development pathways through policies and enhancing enabling conditions (*limited evidence, medium agreement*). For example, policies such as those listed in Table 4.12 are typically associated with broader objectives than greenhouse gas mitigation. They are generally conceived and implemented in the pursuit of overall societal development objectives, such as job creation, macro-economic stability, economic growth, and public health and welfare. In some countries, such policies are framed as part of a just transition. However, they can have major influence on mitigative capacity, and hence can be seen as tools to broaden mitigation options, as illustrated by the Illustrative Mitigation Pathway "Shifting Pathways" (*medium evidence, medium agreement*). There are practical options to shift development pathways in ways that advance mitigation and other sustainable development objectives, supporting political feasibility, increase resources to meet multiple goals, and reduce emissions (*limited evidence, high agreement*). Concrete examples assessed in this chapter include high employment and low emissions structural change, fiscal reforms for mitigation and social contract, combining housing policies to deliver both housing and transport mitigation, and change economic, social and spatial patterns of development of the agriculture sector provide the basis for sustained reductions in emissions from deforestation. These examples differ by context. Examples in other chapters include transformations in energy, urban, building, industrial, transport, and land-based systems, changes in behaviour and social practices, as well as transformational changes across whole economies and societies. Coordinated policy mixes would need to coordinate multiple actors—individuals, groups and collectives, corporate actors, institutions and infrastructure actors—to deepen decarbonisation and shift pathways towards sustainability. Shifts in one country may spill over to other countries. Shifting development pathways can jointly support mitigation and adaptation. Some studies explore the risks of high complexity and potential delay attached to shifting development pathways. {4.3, 4.3.1, 4.3.2, 4.4.2, 4.4.3, 4.4.1.7-4.4.1.10, Figure 4.7, Cross-Chapter Box 5, 5.8, Box 6.2, 8.2, 8.3.1, 8.4, 9.8.1, 9.8.2, 10.4.1, Cross-Chapter Box 5, Cross-Chapter Box 7, Cross-Chapter Box 12}

The literature identifies a broad set of enabling conditions that can both foster shifting development pathways and accelerated mitigation, along five categories. (*medium evidence, high agreement*). Policy integration is a necessary component of shifting development pathways, addressing multiple objectives. To this aim, mobilising a range of policies is preferable to single policy instruments (*robust evidence, high agreement*). Governance for climate mitigation and shifting development pathways is enhanced when tailored to national and local contexts. Improved institutions and governance enable ambitious climate action and help bridge implementation gaps (*medium evidence, high agreement*). Given that strengthening institutions may be a long term endeavour, it needs attention in the near-term. Accelerated mitigation and shifting development pathways necessitates both re-directing existing financial flows from high- to low-emissions technologies and systems and to provide additional resources to overcome current financial barriers. (*robust evidence, high agreement*). Opportunities exist in the near-term to close the finance gap. At the national level, public finance for actions promoting the SDG agenda helps broaden the scope of mitigation (*medium evidence, medium agreement*). Changes in behaviour and lifestyles are important to move beyond mitigation as incremental change, and when supporting shifts to more sustainable development pathways will broadening the scope of mitigation (*medium evidence, medium agreement*). The direction of innovation matters (*robust evidence, high agreement*) . The necessary transformational changes are likely to be more acceptable if rooted in the development aspirations of the economy and society within which they take place. {4.4.1, 4.4.1.2, 4.4.1.3, 4.4.1.4, 4.4.1.5, 4.4.1.6, Figure 4.8, 15.2.2}

Equity can be an important enabler of deeper ambition for accelerated mitigation, dealing with the distribution of costs and benefits and how these are shared as per social contracts, national policy and international agreements. Transition pathways have distributional consequences such as large changes in employment and economic structure (*robust evidence, high agreement*). In that regard, the just transition concept has become an international focal point tying together social movements, trade unions, and other key stakeholders to ensure equity is better accounted for in low-carbon transitions . Effectiveness of cooperative action and the perception of fairness of such arrangements are closely related, in that pathways that prioritise equity and allow broad stakeholders participation can enable broader consensus for the transformational change implied by deeper mitigation efforts (*robust evidence, medium agreement*). Hence, equity is a concept that is instrumentally important. {4.5, Figure 4.9}

In sum, this Chapter suggests that the immediate tasks are to broaden and deepen mitigation in the near-term if the global community is to deliver emission reductions at the scale required to keep temperature well below 2°C and pursue efforts at 1.5°C. Deepening mitigation means more rapid decarbonisation. Shifting development pathways to increased sustainability (SDPS) broadens the scope of mitigation. Putting the enabling conditions above in place supports both. Depending on context, some enabling conditions such as shifting behaviour may take time to establish, underscoring the importance of early action. Other enabling conditions, such as improved access to financing, can be put in place in a relatively short time frame, and can yield results rapidly.

Accelerating mitigation: The literature points to well-understood policy measures and technologies for accelerating mitigation, though the balance depends on country specificities: 1) decarbonising electricity supply to produce net zero CO_2, including renewable energy, 2) radically more efficient use of energy than today; 3) electrification of end-uses including transport; 4) dramatically lower use of fossil fuels than today; 5) converting other uses to low- or zero-carbon fuels (e.g., hydrogen, bioenergy, ammonia) in hard-to-decarbonise sectors; 6) promote bioenergy, demand reduction, dietary changes, and policies, incentives, and rules for mitigation in the land sector; 7) setting and meeting ambitious targets to reduce methane and other short-lived climate forcers. Charting just transitions to net zero may provide a vision, which policy measures can help achieve. Though there is increasing experience with pricing carbon directly or indirectly, decision-makers might consider a broader toolbox of enablers and levers that is available in domains that have not traditionally been climate policy. {4.5, Annex II Part IV Section 11}

Broadening opportunities by focusing on development pathways and considering how to shift them: Some of the policy measures may yield rapid results, whereas other, larger transformations may take longer. If we are to overcome obstacles, a near-term priority is to put in place the enabling conditions to shifting development pathways to increased sustainability. Learning from the examples above, focusing on SDPS also provides a broader set of tools to accelerating mitigation and achieve other sustainable development goals. Consider climate whenever you make choices about development, and *vice versa*. {4.4.1}

4.1 Introduction

The recent IPCC Report on Global Warming of 1.5°C (SR15) made clear that the next three decades are critical if we are to achieve the long-term mitigation goal of the Paris Agreement (IPCC 2018a). The present Chapter assesses the literature on mitigation and development pathways over that timeframe, in the near- (up to 2030) and mid-term (up to 2050).

It considers three questions: (1) Where are we heading now? That is, what is the current state of affairs with respect to climate mitigation and how did we get here? (2) Where do we want to go? I.e., what state of affairs would meet the objectives of the Paris Agreement and achieving the Sustainable Development Goals (SDGs)? and (3) How do we bring about this shift? I.e., what interventions are at societies' disposal to bring about the necessary change in an equitable manner?

Where are we heading now? Despite the drop in emissions due to the COVID-19 crisis, the gap between projected emissions based on Nationally Determined Contributions (NDCs) in 2030 and emissions pathways compatible with the long term temperature goal set in the Paris Agreement remains large (4.2.2). In addition to this persistent emissions gap, we face an implementation gap, as current policies are insufficient to achieve mitigation targets in NDCs, and sufficient international support is not yet available to developing countries who have requested and quantified support needs. Continuing along a development pathway characterized by the same underlying drivers, structural obstacles and insufficient enabling conditions that led to high emissions will not address the problem (*robust evidence, high agreement*).

The analysis of the gap is conducted together with Chapter 3 (see Cross-Chapter Box 4). Chapter 3 is working backward, assessing mitigation in the long-term (beyond 2050 up to 2100) to draw the near- and mid-term implications of long-term temperature and mitigations goals. Chapter 4, on the other hand, works forward from current and planned mitigation (including NDCs) (4.2.1, 4.2.2) and from current development paths to assess the implications for near- and mid-term Greenhouse Gases (GHG) emissions and development goals. Some countries, regions, cities, communities and non-state actors are taking leadership in implementing more ambitious action (4.2.3). This chapter also assesses national low emission development strategies (4.2.4).

Where do we want to go? Technical alternatives and policy options exist to bridge the emissions and implementation gaps, and the literature illustrates these with a wide range of accelerated techno-economic pathways that deepen decarbonisation closer to the pace and scale required (4.2.5), and examines their impacts on other development objectives (4.2.6). In practice, however, scaling up at the broader, deeper, and faster level required to meet climate goals while advancing other development objectives regularly faces prohibitive obstacles (4.2.7). Mitigation policies grafted on to existing development pathways are unlikely to achieve rapid and deep emission reductions.

Secondly, even if carefully designed, climate policies to accelerate mitigation may have adverse consequences for other development objectives. As a complement to mitigation action, taking action to shift development pathways towards sustainability broadens the range of mitigation options, while increasing the possibility to meet other development priorities at the same time (*medium evidence, high agreement*).

Development pathways and shifting them to increased sustainability are introduced in Chapter 1, and constitute a thread throughout the report (see glossary entry on development pathways). The WGII Report highlights the related concept of *climate resilient development pathways* (Chapter 18). Cross-Chapter Box 5 on shifting sustainable pathway towards sustainability elaborates on the concept. The influence of development pathways on emissions and mitigative capacity is discussed in Chapter 2. Chapter 3 assesses modelling of shifts in development pathways, illustrated by the illustrative mitigation pathway called "shifting pathways". The importance of behavioural change as societies make decisions that intentionally shift their future development pathway is emphasized in Chapter 5. The systems Chapters (6-12) take sectoral perspectives, while pathways that are sustainable are the specific focus of Chapter 17.

How can one shift development pathway and accelerate mitigation? The literature does not provide a complete handbook for shifting development pathways and accelerating mitigation. The literature does, however, shed light on some of the underlying dynamics. Shifting development pathways can be necessitated by the existence of pervasive obstacles that prove prohibitive to reaching mitigation and other development objectives (4.2.7). Deliberate measures taken to facilitate the shifting of development pathways and accelerated mitigation involve putting in place key enabling conditions that help overcome those obstacles (see Figure 4.6)—improving governance and institutional capacity, fostering behavioural change and technological innovation, designing and implementing adequate policy, and finance. Just transitions, while they will differ by context, are critical to identifying and avoiding or addressing inequitable distributive consequences (*robust evidence, high agreement*).

Enabling conditions necessary to accelerate mitigation and shift development pathways are discussed in depth in Chapters 5, 13, 14, 15 and 16. In addition, Chapters 13 and 14 detail the policy instruments that could help shift development pathways and accelerate the scale and pace of mitigation, while Chapter 4 describes those in broad strategies terms. Chapter 13 adds more texture on institutional and governance machinery; policy choice, design and implementation; as well as policy formulation processes, actors and structure across scales.

Since development pathways and mitigation options depend to large extent on national objectives and circumstances, this chapter is primarily concerned with literature at national level (or in the case of the European Union, at regional level), while Chapter 3 is primarily concerned with literature at global scale. The national scale selected in this Chapter requires attention as national mitigation pathways cannot be linked directly to global mitigation goals (see Box 4.2). This chapter is also concerned mostly with economy-wide development and mitigation pathways, as distinct from detailed sectoral work that is assessed in the systems chapters 6 to 12. The present chapter also assesses literature on non-state action.

Chapter 4 draws on five major strands of literature: (1) an emerging literature on development pathways—conceptual, empirical, and model-based, including at the national and sub-national scales; (2) a rapidly expanding, model-based, literature on mitigation pathways in the near- and mid-term (Lepault and Lecocq 2021); (3) studies of NDCs and mid-century strategies; (4) a broader literature on transformation and shifts in development pathways, including from non-climate literatures; and (5) a significant literature on equity, including just transitions. This is supported by a database of country-level mitigation scenarios at country level assembled for the preparation of this Chapter (Annex III, Table I.10 and I.11).

The Chapter builds on past IPCC reports. In AR5, all mitigation pathways were assessed in a single chapter (Clarke et al. 2014), which focused mostly on the long-term. SR1.5 included a chapter on mitigation pathways compatible with the temperature goal in the Paris Agreement (Rogelj et al. 2018a), mostly at the global level. It also considered strengthening mitigation (de Coninck et al. 2018) in the context of poverty, inequality and sustainable development (Roy et al. 2018). Development pathways have also been explored, albeit less frequently, in past IPCC reports starting with the Special Report on Emissions Scenarios (Nakicenovic et al. 2000). Some early framing of development pathways was included in the Third Assessment Report (William R. Moomaw et al. 2001), further developed in the Fourth Assessment Report (Sathaye et al. 2007). An extended discussion of climate change and equity was conducted in AR5 (Fleurbaey et al. 2014).

Chapter 4 examines mitigation within the broader context of development pathways, and examines how shifting development pathways can have a major impact on mitigative capacity and broadening mitigation options. It is organized as follows.

Section 4.2 demonstrates that collective mitigation actions fall short of pathways that keep in reach the Paris temperature goals in the long-term. Section 4.3 introduces development pathways (given its relative novelty in IPCC assessments), considers the implications of mitigation for development and *vice versa*, and articulates an approach on *both* accelerating mitigation *and* shifting development pathways.

Section 4.4 discusses how to shift development pathway and accelerate the scale and pace of mitigation, what levers are available to policy makers, and how policies may intersect with adaptation goals. It points out that development pathways also drive adaptation and adaptative capacity, and discusses various risks associated with shifting development pathways and accelerated mitigation strategies.

Finally, equity and just transitions are recurring themes in the Chapter, specifically in relation to accelerating mitigation and shifting development pathways toward sustainability. In section 4.2.2.7, equity is discussed in the context of Parties' assertions regarding the fairness of their NDCs, alongside reflections from academic scholarship on the ethical underpinnings of these assertions and of various quantitative analyses of equitable effort-sharing. Section 4.2.6 discusses certain distributional implications of domestic mitigation efforts, such as shifts in employment. Sections 4.2.7 and 4.3 note the relevance of potential distributional impacts as an obstacle to climate action, as well as the inequitable distribution of decision-making authority. Finally, section 4.5 recognizes the structural relationship between equity and climate, explores just transitions as an international focal point tying together social movements, trade unions, and other stakeholders, and thus an instrumental role in establishing consensus.

4.2 Accelerating mitigation actions across scales

4.2.1 Mitigation targets and measures in nationally determined contributions

A central instrument of the Paris Agreement is the NDCs, submitted by each country, and reflecting national efforts to reduce GHG emissions and build resilience to the impacts of climate change. Every five years, collective progress will be compared against long-term goals of the Paris Agreement. Considering the outcome of a global stocktake, countries will prepare subsequent NDCs, showing progression in their ambition and enhancing international cooperation (UNFCCC 2015a).

Prior to COP21, in 2015, most countries submitted their INDCs (Intended Nationally Determined Contributions), which included mitigation targets for 2025 or 2030. INDCs become first NDCs on ratification and/or after national governments' revision, and by 11 October 2021, the official NDC registry contained 194 first NDCs with 105 new and updated NDCs from 132 Parties to the Paris Agreement, covering 53% of the total global emissions in 2019 of 52.4 $GtCO_2$-eq without LULUCF, and 13 second NDCs. Most of the Parties that submitted new or updated NDCs have demonstrated increased ambition in addressing climate change. Moreover, though some countries like China have not submitted their updated NDCs yet, they have already announced their updated NDC goals somewhere. Countries will take the first stock in 2023 based on their progression towards achieving the objectives of Paris Agreement (UNFCCC 2015a, 2018a; SB Chairs 2021) (14.3.2.5).

Submitted NDCs vary in content, scope and background assumptions. First NDCs contain mitigation targets, and in many cases also provisions about adaptation. The mitigation targets range from economy-wide absolute emission reduction targets to strategies, plans and actions for low-emission development. Baseline years vary from 1990 to 2015 and in almost all NDCs the targeted time frame is 2030, with a few specified periods of until 2025, 2035, 2040 or 2050. Around 43% of the mitigation targets in first NDCs are expressed in terms of deviation below business-as-usual by a specified target year, either for the whole economy or for specific sectors, while around 35% include fixed-level targets (either reductions or limitations compared to base years), and another 22% refer to intensity targets (in terms of GHG, CO_2 or energy) or policies and measures, with an increasing number of Parties moving to absolute emission reduction targets in their new or updated NDCs (UNFCCC 2016a, 2021). Some developing countries' NDCs include unconditional elements, while others include conditional ones, the latter with higher ambition if finance, technology and capacity building support from developed countries is provided (UNFCCC 2016a).[2] In some NDCs, the additional mitigation is quantified, in others not (Figure 14.2).

Most first NDCs cover all specific sectors, including LULUCF, and communicate specific targets for individual sub-sectors to support their overall mitigation targets. Concrete actions and priority areas are more detailed in the energy sector, with increased share of renewable energies and energy efficiency being highlighted in the majority of NDCs. Given the uncertainty behind LULUCF emission and removal accounting (Grassi et al. 2017; Jian et al. 2019), several countries state that their accounting framework will only be defined in later NDCs. The GHG included and the global warming potentials (GWPs) used to aggregate emissions also vary across NDCs. Most countries only refer to carbon dioxide, methane and nitrous oxide emissions aggregated based on IPCC AR2 or AR4 metrics, while few NDCs also include fluorinated gases and use IPCC AR5 GWPs. The shares of Parties that indicate possible use of at least one type of voluntary cooperation and set qualitative limits on their use have both nearly doubled in new or updated NDCs.

There is considerable literature on country-level mitigation pathways, including but not limited to NDCs. Country distribution of this literature is very unequal (*robust evidence, high agreement*). In particular, there is a growing literature on (I)NDCs, with a wide scope which includes estimate of emissions levels of NDCs (see section 4.2.2.2); alignment with sustainable development goals (Caetano et al. 2020; Campagnolo and Davide 2019; Fuso Nerini et al. 2019; Antwi-Agyei et al. 2018); ambition (Höhne et al. 2018; Vogt-Schilb and Hallegatte 2017; Hermwille et al. 2019); energy development (Scott et al. 2018); and the legality of downgrading NDCs (Rajamani and Brunnée 2017). Other studies note that many NDCs contain single-year mitigation targets, and suggest that a multi-year trajectory is important for more rigorous monitoring (Elliott et al. 2017; Dagnet et al. 2017).

The literature also points out that beyond the 'headline numbers', information in (I)NDCs is difficult to analyse (Pauw et al. 2018). Information for 'clarity, transparency and understanding' is to be communicated with NDCs, although initial guidance was not specific (UNFCCC 2014). While the adoption of the Paris rule-book provided some greater specificity (UNFCCC 2018b,c), the information included in the NDCs remains uneven. Many NDCs omit important mitigation sectors and do not adequately provide details on costs and financing of implementation (Pauw et al. 2018). Countries are also invited to explain how their NDCs are fair and ambitious, though the way this has been done so far has been criticised as insufficiently rigorous (Winkler et al. 2018).

FOOTNOTE[2] "Unconditional" NDCs refer to abatement efforts pledged without any conditions (this terminology is used by the literature, not by the Paris Agreement). They are based mainly on domestic abatement actions, although countries can use international cooperation to meet their targets. (2) "Conditional" NDCs require international cooperation, for example bilateral agreements under article 6, financing or monetary and/or technological transfers (14.3.2).

4.2.2 Aggregate effects of NDCs and other mitigation efforts relative to long-term mitigation pathways

4.2.2.1 Introduction

Near-term mitigation targets submitted as part of NDCs to the UNFCCC, as well as currently implemented policies, provide a basis for assessing potential emissions levels up to 2030 at the national, regional and global level. The following sections present an evaluation of the methods used for assessing projected emissions under NDCs and current policies (4.2.2.2), and the results of these assessments at global, regional and national level assessing a broad available literature based on first NDC submissions from 2015/16 and pre-COVID economic projections (4.2.2.3). The impacts of the COVID-19 pandemic and related government responses on emissions projections are then discussed in 4.2.2.4 and the implications of updated NDCs submitted in 2020/21 on emissions follow in 4.2.2.5. Section 0 presents an assessment of the so-called "implementation gap" between what currently implemented policies are expected to deliver and what the ambitions laid out under the full implementation of the NDCs are projected to achieve. Finally, a comparison of ambitions across different countries or regions (4.2.2.7) is presented and the uncertainties of projected emissions associated with NDCs and current policies are estimated, including a discussion of measures to reduce uncertainties in the specification of NDCs (4.2.2.8).

The literature reviewed in this section includes globally comprehensive assessments of NDCs and current policies, both peer-reviewed and non-peer-reviewed (but not unpublished model results) as well as synthesis reports by the UNFCCC Secretariat, government reports and national studies.

The aggregate effects of NDCs provide information on where emissions might be in 2025/2030, working forward from their recent levels. Chapter 3 of this report works backwards from temperature goals, defining a range of long-term global pathways consistent with 1.5°C, 2°C and higher temperature levels. By considering the two together, it is possible to assess whether NDCs are collectively consistent with 1.5°C, 2°C and other temperature pathways (Cross-Chapter Box 4, p.4-22).

4.2.2.2 Methods to project emissions under NDCs and current policies

A variety of different methods are used to assess emissions implications of NDCs and current policies over the time horizon to 2025 or 2030. Some of these projections were explicitly submitted as part of an official communication to UNFCCC (e.g., Biennial Report, Biennial Update Reports or National Communications) while the majority is from independent studies.

Methods that are used in independent studies (but that can also underlie the official communications) can broadly be separated into two groups,

(i) system modelling studies which analyse policies and targets in a comprehensive modelling framework such an integrated assessment, energy systems or integrated land-use model to project emissions (or other indicators) of mitigation targets in NDCs and current policies, either at the national or global scale (noting some differences in the systems), and

(ii) hybrid approaches that typically start out with emissions pathways as assessed by other published studies (e.g., the IEA World Energy Outlook, national emissions pathways such as those specified in some NDCs) and use these directly or apply additional modifications to them.

System modelling studies are conducted at global, regional and national scales. Global models provide an overview, are necessary for assessment of global phenomena (e.g., temperature change), can integrate climate models and trade effects. National models typically include more details on sectors, technology, behaviour and intersectoral linkages, but often use simplifying assumptions for international trade (e.g., the Armington elasticity approach). Critically, they can also better reflect local socio-economic and political conditions and their evolution (i.e., national development pathways). A variety of modelling paradigms are found, including optimisation and simulation models, myopic and with foresight, monolithic and modular (see Annex III: Scenarios and modelling methods).

Among the hybrid approaches, three broader categories can be distinguished, (i) direct use of official emission projection as part of submitted NDC or other communication to UNFCCC, (ii) historical trend extrapolation of emissions based on inventory data, possibly disaggregated by sector and emission species, and (iii) use of Reference/Business-As-Usual pathways from an independent published study (e.g., IEA WEO). In all cases, the reductions are then estimated on top of the resulting emission trajectory. Note that globally comprehensive studies may vary the approach used depending on the country.

Beyond the method applied, studies also differ in a number of dimensions, including (i) their spatial resolution and coverage, (ii) their sectoral resolution and coverage, (iii) the GHGs that are included in the assessment, the GWPs (or other metrics) to aggregate them, the emissions inventory (official vs. independent inventory data) and related accounting approaches used as a starting point for the projections, (iv) the set of scenarios analysed (Reference/Business-As-Usual, Current Policies, NDCs, etc.), and (v) the degree to which individual policies and their impact on emissions are explicitly represented (Table 4.1).

First, the studies are relevant to different spatial levels, ranging from macro-scale regions with globally comprehensive coverage to national level (4.2.2.3) and subnational and company level in a few cases (4.2.3). It is important to recognise that globally comprehensive studies typically resolve a limited number of countries individually, in particular those that contribute a high share to global emissions, but have poor resolution of remaining countries or regions, which are assessed in aggregate terms. Conversely, studies with high resolution of a particular country tend to treat interactions with the global scale in a limited way. The recent literature includes attempts to provide a composite global picture from detailed national studies (Bataille et al. 2016a; Deep Decarbonization Pathways Project 2015; Roelfsema et al. 2020).

A second dimension in which the studies are different is their comprehensiveness of covering different emitting sectors. Some studies focus on the contribution of a single sector, for example the Agriculture, Forestry and Other Land Use (AFOLU) sector (Fyson and Jeffery 2019; Grassi et al. 2017) or the energy system (including both energy supply and demand sectors), to emission reductions as specified in the NDC. Such studies give an indication of the importance of a given sector to achieving the NDC target of a country and can be used as a benchmark to compare to comprehensive studies, but adding sectoral contributions up represents a methodological challenge.

Third, GHG coverage is different across studies. Some focus on CO_2 only, while others take into account the full suite of Kyoto gases (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6, see glossary). For the latter, different metrics for aggregating GHGs to a CO_2-equivalent metric are being used, typically GWP 100 from different IPCC assessments (Table 4.1)

Fourth, studies typically cover a set of scenarios, though how these scenarios are defined varies widely. The literature reporting IAM results often includes *Nationally Determined Contribution* (NDC), which are officially communicated, and *Current Policies* (CP) as interpreted by modellers. Studies based on national modelling, by contrast, tend to define scenarios reflecting very different national contexts. In both cases, modellers typically include so-called *No Policy Baseline* scenarios (alternatively referred to as *Reference* or *Business-as-Usual scenarios)* which do not necessarily reflect currently implemented policies and thus are not assessed as reference pathways (see section 4.2.6.1). There are also various approaches to considering more ambitious action compared to the CP or NDC projections that are covered in addition.

Fifth, studies differ in the way they represent policies (current or envisioned in NDCs), depending on their internal structure. For example, a subsidy to energy efficiency in buildings may be explicitly modelled (e.g., in a sectoral model that represents household decisions relative to building insulation), represented by a proxy (e.g., by an exogenous decrease in the discount rate households use to make choices), or captured by its estimated outcome (e.g., by an exogenous decrease in the household demand for energy, say in an energy system model or in a compact CGE). Detailed representations (such as the former example) do not necessarily yield more accurate results than compact ones (the latter example), but the set of assumptions that are necessary to represent the same policy will be very different.

Finally, policy coverage strongly varies across studies with some just implementing high level targets specified in policy documents and NDCs while others represent the policies with the largest impact on emissions and some looking at very detailed measures and policies at subnational level. In addition, in countries with rapidly evolving policy environments, slightly different cut-off dates for the policies considered in an emission projection can make a significant difference for the results (Dubash et al. 2018).

The challenges described above are dealt with in the assessment of quantitative results in Section 4.2.2.3 by (i) comparing national studies with country-level results from global studies to understand systematic biases, (ii) comparing economy-wide emissions (incl. AFOLU) as well as energy-related emissions, (iii) using different emission metrics including CO_2 and Kyoto GHG emissions where the latter have been harmonized to using AR6 GWP100 metrics, and (iv) tracking cut-off dates of implemented policies and NDCs used in different references (Table S4.1). The most notable differences in quantitative emission estimates related to current policies and NDCs relate to the COVID-19 pandemic and its implications and to the updated NDCs mostly submitted since early 2020 which are separately dealt with in Sections 4.2.2.4 and 4.2.2.5, respectively.

In addition to assessing the emissions outcomes of NDCs, some studies report development indicators, by which they mean a wide diversity of socio-economic indicators (Altieri et al. 2016; Jiang et al. 2013; Benavides et al. 2015; Chai and Xu 2014; Delgado et al. 2014; La Rovere et al. 2014a; Paladugula et al. 2018; Parikh et al. 2018; Zevallos et al. 2014; Zou et al. 2016; Yang et al. 2021; Bataille et al. 2016a), share of low-carbon energy (Bertram et al. 2015; Riahi et al. 2015), renewable energy deployment (Roelfsema et al. 2018), production of fossil fuels (SEI et al. 2020) or investments into low-carbon mitigation measures (McCollum et al. 2018) to track progress towards long-term temperature goals.

4.2.2.3 Projected emissions under NDCs and current policies by 2025/2030

The emissions projections presented in this section relate to the first NDCs, as communicated in 2015 and 2016, and on which an extensive literature exists. New and updated NDCs, mostly submitted since the beginning of 2020, are dealt with in Section 4.2.2.5. Similarly, the implications of COVID-19 and the related government responses on emissions projections is specifically dealt with in Section 4.2.2.4.

Table 4.1 presents the evidence base for the assessment of projected emissions of original NDCs and current policies until 2030. It covers 31 countries and regions responsible for about 82% of global GHG emission (excluding FOLU CO_2 emissions) and draws quantitative estimates from more than 40 studies (see Table S4.1 in the Supplementary Material to Chapter 4). The table allows comparing emission projections from national and globally comprehensive studies as well as official communications by countries to the UNFCCC at the national/regional level. The global aggregates presented in Table 4.1 derive from globally comprehensive studies only and are not the result of aggregating country projections up to the global level. As different studies report different emission indicators, the table includes four different indicators: CO_2 and GHG emissions, in- or excluding AFOLU emissions. Where possible, multiple indicators are included per study.

Globally comprehensive studies.

The UNFCCC Secretariat has assessed the aggregate effect of NDCs multiple times. The first report considered the intended NDCs in relation to 2°C (UNFCCC 2015b), whereas the second considered NDCs also in relation to 1.5°C (UNFCCC 2016b). New submissions and updates of NDCs in 2020/21 are assessed in Section 4.2.2.5. A number of globally comprehensive studies (den Elzen et al. 2016; Luderer et al. 2016; Rogelj et al. 2016, 2017; Vandyck et al. 2016; Rose et al. 2017; Baumstark et al. 2021) which estimate aggregate emissions outcomes of NDCs and current policies have previously been assessed in Cross-Chapter-Box 11 of IPCC SR1.5.

According to the assessment in this report, studies projecting emissions of current policies based on pre-COVID assumptions lead to median global GHG emissions of 60 $GtCO_2$-eq with a full range of 54-68 by 2030 and original unconditional and conditional NDCs submitted in 2015/16 to 57 (49-63) and 54 (50-60) $GtCO_2$-eq, respectively (*robust evidence*, *medium agreement*) (Table 4.1). Globally comprehensive and national-level studies project emissions of current policies and NDCs to 2025 and 2030 and, in general, are in good agreement about projected emissions at the country level.

These estimates are close to the ones provided by the IPCC SR1.5, Cross-Chapter-Box 11, and the UNEP emissions gap report (UNEP 2020a)[3].

National studies

A large body of literature on national and regional emissions projections, including official communications of as part of the NDC submissions and independent studies exist. A subset of this literature provides quantitative estimates for the 2030 timeframe. As highlighted in Section 4.2.1, the number of independent studies varies considerably across countries with an emphasis on the largest emitting countries. This is reflected in Table 4.1 (see also Table S4.1). Despite smaller differences between globally comprehensive and national studies for a few countries, there is generally good agreement between the different types of studies, providing evidence that these quantitative estimates are fairly robust.

Sectoral studies

Sectoral studies are essential to understand the contributions of concrete measures of NDCs and current policies. For example, approximately 98% of NDCs include the energy sector in their mitigation contributions, of which nearly 50% include a specific target for the share of renewables, and about 5% aim at increasing nuclear energy production (Stephan et al. 2016). Transport is covered explicitly in 75% of NDCs, although specific targets for the sector exist in only 21% of NDCs (PPMC and SLoCaT 2016). Measures or targets for buildings are referred to explicitly in 27% of NDCs (GIZ 2017). 36% of NDCs include targets or actions that are specific to the agriculture sector (FAO 2016). LULUCF (mitigation) is included in 80 % of all submitted NDCs, while 59 % include adaptation and 29 % refer to REDD+.

Greater sectoral expertise and involvement will be critical to accomplishing development and climate goals due to enhanced availability of information and expertise on specific sectoral options, greater ease of aligning the NDCs with sectoral strategies, and greater awareness among sector-level decision-makers and stakeholders (NDC Partnership 2017; Fekete et al. 2015). Sector-specific studies are assessed in the sectoral Chapters (6-11) of this report.

FOOTNOTE[3] Note that the statistical metrics reported are slightly different across the reports. For example, IPCC SR1.5 reported the 25th to 75th range while the UNEP emissions gap report uses median and 10th to 90th percentile ranges. In addition, this report applies 100-year GWPs from AR6 to aggregate across different GHG emission species, whereas 100-year GWPs from AR4 were applied in IPCC SR1.5 and UNEP 2020. The application of AR6 GWPs on average leads to increase of estimates by about 1.3% and ranges are wider due to the difference in statistical error metrics.

Table 4.1 Assessment of projected 2030 emissions of current policies based on pre-COVID assumptions and original NDCs submitted in 2015/16 for 28 individual countries/regions and the world. The table compares projected emissions from globally comprehensive studies, national studies and, when available, official communications to UNFCCC using different emission sources (fossil fuels, AFOLU sector) and different emission metrics (CO_2, Kyoto GHGs). The comparison allows identifying potential biases across the ranges and median estimates projected by the different sets of studies.

Region[a]	GHG share [%][b]	Type[c]	# estimates[d]	Current Policies 2030 emissions			NDC 2030 emissions (conditional/unconditional)		
				CO_2 only [$GtCO_2$] median (min - max)[f]		Kyoto GHGs[e] [$GtCO_2$-eq] median (min - max)[f]	CO_2 only [$GtCO_2$] median (min - max)[f]		Kyoto GHGs[e] [$GtCO_2$-eq] median (min - max)[f]
				incl. AFOLU[g]	fossil fuels	incl. AFOLU[g]	incl. AFOLU[g]	fossil fuels	incl. AFOLU[g]
World	100	global	93	43 (38 - 51)	37 (33 - 45)	60 (54 - 68)	40 (35 - 45)/37 (35 - 39)	32 (26 - 39)/31 (27 - 37)	54 (50 - 60)/57 (49 - 63)
CHN	27	global	76	12 (9.7 - 15)	11 (8.4 - 14)	15 (12 - 18)	- /11 (9.8 - 13)	- /8.8 (6.9 - 13)	- /14 (13 - 16)
		national	13	12 (12 - 12)	11 (9.2 - 13)	15 (13 - 15)	- /12 (11 - 12)	- /11 (10 - 11)	- /15 (13 - 16)
USA[h]	12	global	71	4.9 (4.4 - 6.6)	4.6 (3.5 - 6.5)	5.9 (4.9 - 6.6)	- /3.8 (3.3 - 4.1)	- /3.9 (3.1 - 5.3)	- /4.6 (4 - 5.1)
		national	5	4.1	4.5 (4.1 - 4.9)	5.9 (5.2 - 6.7)	- /3.4	- /3.5	- /4.3
EU[i]	8.1	global	24	2.7 (2.1 - 3.5)	2.6 (2.1 - 3.3)	3.4 (2.6 - 4.7)	- /2.6 (2.1 - 2.8)	- /2.4 (2.1 - 2.7)	- /3.2 (2.6 - 3.7)
		national	3	3.1	2.6		- /2.5		
		official	3			3.2 (2.8 - 3.7)			
IND	7.1	global	79	3.7 (3 - 4.5)	3.2 (2.5 - 4.5)	4.7 (4.1 - 6.4)	3.3 (3.1 - 4.4)/4	3.3 (2.4 - 5.6)/3.8 (2.9 - 5.6)	5 (4.2 - 6.4)/5.8 (4.9 - 6.1)
		national	9	3.4 (3.3 - 4)	3.4 (2.9 - 3.9)	5.5 (5 - 5.7)	3.4 (3.2 - 3.6)/3.2	3.4 (3.2 - 3.5)/2.9	5.1/4.9
RUS	4.5	global	66	1.7 (0.84 - 2)	1.6 (1.5 - 2)	2.3 (1.6 - 3.3)	- /1.7 (0.85 - 1.9)	- /1.6 (1.2 - 1.9)	- /2.6 (1.9 - 3.1)
		national	6		1.5 (1.5 - 1.5)	2.6		- /1.5 (1.5 - 1.5)	- /2.5
		official	2			2.1			- /2.7
BRA	2.5	global	69	1.1 (0.79 - 1.7)	0.5 (0.28 - 1.1)	1.8 (1.4 - 2.7)	- /0.94 (0.52 - 1.5)	- /0.38 (0.097 - 0.86)	- /1.3 (1.2 - 2.5)
		national	4	0.59	0.47	1.8	- /0.51	- /0.47	- /1.2
		official	1						- /1.2
JPN	2.4	global	66	1.2 (0.94 - 1.3)	1.1 (0.67 - 1.3)	1.2 (0.95 - 1.3)	- /1 (0.9 - 1.2)	- /0.83 (0.65 - 1.2)	- /1 (0.95 - 1.2)
		national	16	1.1 (1.1 - 1.6)	1.1 (1.1 - 1.5)	1.3 (1.2 - 1.7)	- /0.93 (0.91 - 1.2)	- /0.93 (0.87 - 1.1)	- /1 (1 - 1.3)
		official	1						- /1

IDN	2.2	global	25	1.1 (0.79 - 2)	0.62 (0.51 - 0.89)	1.7 (1.4 - 2.4)	0.93 (0.76 - 1.4)/0.99	0.53 (0.45 - 0.66)/0.68 (0.6 - 0.77)	1.8 (1.3 - 2.1)/2.1 (1.5 - 2.2)
		official	2						1.9 (1.8 - 1.9)/2.2
CAN	1.5	global	67	0.58 (0.4 - 0.8)	0.43 (0.38 - 0.72)	0.68 (0.51 - 1)	- /0.43 (0.34 - 0.67)	- /0.43 (0.31 - 0.64)	- /0.53 (0.49 - 0.82)
		national	2	0.54		0.71	- /0.41		- /0.54
		official	2			0.67			
MEX	1.5	global	31	0.61 (0.54 - 1.3)	0.48 (0.3 - 0.56)	0.82 (0.72 - 1.7)	0.54 (0.48 - 1)/0.46	0.43 (0.27 - 0.54)/0.33 (0.26 - 0.42)	0.65 (0.62 - 1.4)/0.73 (0.63 - 0.79)
		official	2						0.62/0.76
SAU	1.5	global	6	0.7 (0.57 - 0.82)	0.61 (0.48 - 0.74)	1 (0.7 - 1.1)	0.7 (0.58 - 0.82)/ -	0.62 (0.49 - 0.74)/ -	0.83 (0.7 - 0.96)/ -
KOR	1.4	global	64	0.69 (0.55 - 0.76)	0.67 (0.42 - 0.91)	0.72 (0.68 - 0.81)	- /0.57 (0.5 - 0.65)	- /0.4 (0.26 - 0.61)	- /0.57 (0.5 - 0.69)
		national	4	0.78 (0.75 - 0.81)	0.73 (0.7 - 0.76)	0.86 (0.83 - 0.89)	- /0.62 (0.51 - 0.72)	- /0.58 (0.49 - 0.67)	- /0.68 (0.56 - 0.8)
		official	1						
AUS	1.1	global	16	0.42 (0.34 - 0.49)	0.34 (0.28 - 0.46)	0.54 (0.46 - 0.69)	- /0.36 (0.28 - 0.43)	- /0.3 (0.24 - 0.41)	- /0.44 (0.39 - 0.52)
		national	3			0.55			
		official	2			0.52 (0.51 - 0.52)			
TUR	1.1	global	18	0.44 (0.44 - 0.49)	0.4 (0.34 - 0.43)	0.6 (0.51 - 0.83)	- /0.44 (0.44 - 0.49)	- /0.4 (0.27 - 0.43)	- /0.94 (0.55 - 1)
		official	1						- /0.93
ZAF	1.1	global	26	0.49 (0.35 - 0.62)	0.36 (0.23 - 0.56)	0.64 (0.45 - 0.85)	- /0.4 (0.27 - 0.55)	- /0.35 (0.21 - 0.44)	0.41/0.58 (0.39 - 0.65)
		official	1						- /0.52 (0.41 - 0.64)
VNM	0.92	global	2						0.61/0.77
		national	4	0.36	0.28		0.32 (0.28 - 0.36)/0.36	0.26 (0.24 - 0.28)/0.28	
GBR	0.86	global	4	0.37	0.33 (0.3 - 0.37)		- /0.37	- /0.33 (0.3 - 0.37)	
FRA	0.85	global	4	0.22	0.32 (0.24 - 0.4)		- /0.22	- /0.32 (0.24 - 0.4)	
THA	0.84	global	5			0.41 (0.41 - 0.41)			0.44/0.47
		national	3	0.43	0.4	0.58	0.35/0.36	0.32/0.34	0.43/0.46
ARG	0.76	global	22	0.33 (0.17 - 0.52)	0.2 (0.15 - 0.35)	0.51 (0.33 - 0.75)	0.25 (0.17 - 0.46)/0.25	0.21 (0.18 - 0.23)/0.15 (0.14 - 0.16)	0.39 (0.32 - 0.69)/0.51 (0.33 - 0.52)
		national	2			0.42 (0.41 - 0.43)		- /0.19	
		official	2						0.4/0.52
KAZ	0.71	global	3			0.45			0.28/0.32

UKR	0.52	global	2			0.42 (0.42 - 0.42)			- /0.54
PHL	0.48	global	3			0.24			0.082/ -
COL	0.4	global	5			0.23 (0.23 - 0.23)			0.26 (0.26 - 0.26)/0.29 (0.29 - 0.29)
ETH	0.31	global	5		0.022	0.23 (0.19 - 0.27)		- /0.023	0.16 (0.15 - 0.16)/ -
MAR	0.21	global	5			0.11 (0.087 - 0.13)			0.13 (0.1 - 0.15)/0.13 (0.1 - 0.15)
KEN	0.18	global	5		0.022	0.13 (0.11 - 0.14)		- /0.023	0.11 (0.11 - 0.11)/ -
SWE	0.13	global	4	-0.012	0.03 (0.029 - 0.031)		- /-0.012	- /0.03 (0.028 - 0.032)	
PRT	0.12	global	2	0.045	0.036		- /0.045	- /0.036	
		national	1					- /0.023	
CHE	0.094	global	1						- /0.026
		national	1	0.027	0.025				
MDG	0.065	global	1						0.033/ -
		national	3	0.071	0.0059		0.07 (0.068 - 0.071)/ -	0.0043 (0.0026 - 0.0059)/ -	

Notes: [a] Countries are abbreviated by their ISO 3166-1 alpha-3 letter codes. EU denotes the European Union. [b] 2018 Share of global Kyoto GHG emissions, excluding FOLU emissions, based on 2019 GHG emissions from Chapter 2 (Minx et al. 2021; Crippa et al. 2021). [c] Type distinguishes between independent globally comprehensive studies (that also provide information at the country/region level), independent national studies and official communications via Biennial Reports, Biennial Update Reports or National Communications. [d] Different estimates from one study (e.g., data from multiple models or minimum and maximum estimates) are counted individually, if available. [e] GHG emissions expressed in CO_2-eq emission using AR6 100-year GWPs (see Section 2.2.2 for a discussion of implications for historical emissions). GHG emissions from scenario data is recalculated from individual emission species using AR6 100-year GWPs. GHG emissions from studies that do provide aggregate GHG emissions using other GWPs are rescaled using 2019 GHG emissions from Chapter 2 (Minx et al. 2021; Crippa et al. 2021). [f] If more than one value is available, a median is provided and the full range of estimates (in parenthesis). To avoid a bias due to multiple estimates provided by the same model, only one estimate per model, typically the most recent update, is included in the median estimate. In the full range, multiple estimates from the same model might be included, in case these reflect specific sensitivity analyses of the "central estimate" (e.g., (Baumstark et al. 2021; Rogelj et al. 2017)). [g] Note that AFOLU emissions from national GHG inventories and global/national land use models are generally different due to different approaches to estimate the anthropogenic CO_2 sink (Grassi et al. 2018, 2021)(7.2.3 and Cross-Chapter Box 6). [h] The estimates for the USA are based on the first NDC submitted prior to the withdrawal from the Paris Agreement, but not including the updated NDC submitted following its re-entry. [i] The EU estimates are based on the 28 member states up until 31 January 2020, i.e. including the UK.

4.2.2.4 Estimated impact of COVID-19 and governmental responses on emissions projections

The impacts of COVID-19 and national governments' economic recovery measures on current (see 2.2.2) and projected emissions of individual countries and globally under current policies scenarios until 2030 may be significant, although estimates are highly uncertain and vary across the few available studies. The analyses published to date (October 2021) are based on limited information about how COVID-19 has affected the economy and hence GHG emissions across countries so far in 2020, and also based on assumptions about COVID-19's longer term impact. Moreover, the comparison of pre- and post-COVID-19 projections captures the impact of COVID-19 as well as other factors such as the consideration of recently adopted policies not related to COVID-19, as well as methodological changes.

Across different studies (Kikstra et al. 2021; IEA 2020; Dafnomilis et al. 2021; Pollitt et al. 2021; UNEP 2020a; Climate Action Tracker 2020; Keramidas et al. 2021; Dafnomilis et al. 2020), the impact of the general slowdown of the economy due to the COVID-19 pandemic and its associated policy responses would lead to a reduced estimate of global GHG emissions in 2030 of about 1 to 5 $GtCO_2eq$, equivalent to 1.5 to 8.5 per cent, compared to the pre-COVID-19 estimates (see Table S4.2 for details). Nascimento et al. (2021) analyse the impacts of COVID-19 on current policy emission projections for 26 countries and regions and find a large range of emission reduction—between -1% and -21%—across these.

As indicated by a growing number of studies at the national and global level, how large near- to mid-term emissions implications of the COVID-19 pandemic are to a large degree depends on how stimulus or recovery packages are designed (Wang et al. 2020; Gillingham et al. 2020; Forster et al. 2020; Malliet et al. 2020; Le Quéré et al. 2020; Obergassel et al. 2021; IEA 2020; UNEP 2020a; Pollitt et al. 2021).

Four studies (Climate Action Tracker 2021; den Elzen et al. 2021; JRC 2021; Riahi et al. 2021) provide an update of the current policies assessment presented in Section 4.2.2.3 by taking into account the effects of COVID-19 as well as potential updates of policies. The resulting GHG emissions in 2030 are estimated to be 57 $GtCO_2$-eq with a full range of 52 to 60 $GtCO_2$-eq (Table 4.2). This is a reduction of about 3 $GtCO_2$-eq or 5% compared to the pre-COVID estimates from Section 4.2.2.3.

Table 4.2 Projected global GHG emissions of current policies by 2030.

	Kyoto GHGs[a] [$GtCO_2$-eq] median (min - max)[b]	References
Climate Action Tracker	54 (52-56)	(Climate Action Tracker 2021)
PBL	58	(den Elzen et al. 2021; Nascimento et al. 2021)
JRC GECO	57	(JRC 2021)
ENGAGE[c]	57 (52-60)	(Riahi et al. 2021)
Total[d]	57 (52-60)	

Notes: [a] GHG emissions expressed in CO_2-eq emission using AR6 100-year GWPs. GHG emissions from studies that provide aggregate GHG emissions using other GWPs are rescaled using 2019 GHG emissions from Chapter 2 (Minx et al. 2021; Crippa et al. 2021). [b] If a range is available from a study, a median is provided in addition to the range. [c] Range includes estimates from four models GEM-E3, MESSAGEix-GLOBIOM, POLES, REMIND-MAgPIE based on sensitivity analysis. [d] To avoid a bias due to multiple estimates provided by the same model, only one estimate per model, typically the most recent update, is included in the median estimate for the total.

4.2.2.5 Estimated impact of new and updated NDCs on emissions projections

The number of studies estimating the emissions implications of new and updated NDCs and announced mitigation pledges that can be used for the quantitative assessment is limited to four (Table 4.3) (Climate Action Tracker 2021; den Elzen et al. 2021; Meinshausen et al. 2021; JRC 2021). One other study includes a limited number of NDC updates (Riahi et al. 2021) and another (UNFCCC 2021) excludes LULUCF emissions. They are therefore not directly comparable to the other two. In addition, the UNEP

Emissions Gap Report 2021 (UNEP 2021) in itself is assessment of almost the same studies included here. The evidence base for the updated NDC assessment is thus considerably smaller compared to that of the assessment of emissions implications of original NDCs presented in Section 4.2.2.3. However, it is worthwhile to note that the earlier versions of the studies summarized in Table 4.2 and Table 4.3 are broadly representative for the emissions range implied by the pre-COVID-19 current policies and original NDCs of the full set of studies shown in Table 4.1, therefore building confidence in estimates.

An additional challenge lies in the fact that these studies do not all apply the same cut-off date for NDC updates, potentially leading to larger systematic deviations in the resulting emission estimates. Another complication is the fact that publicly announced mitigation pledges on global 2030 emissions that have not been officially submitted to the UNFCCC NDC registry yet, have been included in several of the studies to anticipate their impact on emission levels (see notes to Table 4.3). In addition to the updates of NDC targets, most of the new studies also include impacts of COVID-19 on future emission levels (as discussed in 4.2.2.4) which may have led to considerable downward revisions of emission trends unrelated to NDCs. Table 4.3 presents the emission estimates of the four studies that form the basis of the quantitative assessment presented here and three other studies to compare with.

Table 4.3 Projected global GHG emissions of new and updated NDCs by 2030.

Study	Cut-off date	Kyoto GHGs[a] [$GtCO_2$-eq] historical 2015	historical 2019	median (min - max)[b] 2030 Unconditional NDCs	median (min - max)[b] 2030 Conditional NDCs	References
Climate Action Tracker[c]	5/2021	51	52	50	47	(Climate Action Tracker 2021)
PBL[d]	9/2021	52	54	53 (51-55)	52 (49-53)	(den Elzen et al. 2021; Nascimento et al. 2021)
JRC – GECO[e]	10/2021	51			48	(JRC 2021)
Meinshausen et al.[f]	10/2021	54	56	55 (54-57)	53 (52-55)	(Meinshausen et al. 2021)
Total[g]				53 (50-57)	50 (47-55)	
Other studies for comparison						
UNEP EGR[h]	9/2021			53 (50-55)	50 (47-53)	(UNEP 2017a)
UNFCCC Secretariat[i]	7/2021			57 (55-58)	54 (52-56)	(UNFCCC 2021)
ENGAGE[j]	3/2021				51 (49-53)	(Riahi et al. 2021)

Notes: [a] GHG emissions expressed in CO_2-eq emission using AR6 100-year GWPs. GHG emissions from studies that provide aggregate GHG emissions using other GWPs are rescaled using 2019 GHG emissions from Chapter 2 (Minx et al. 2021; Crippa et al. 2021). Note that due to slightly different system boundaries across historical emission datasets as well as data uncertainties (see Chapter 2, SM2.2 for details) relative change compared to historical emissions should be calculated vis-à-vis the historical emissions data used by a particular study. [b] If a range is available from a study, a median is provided in addition to the range. [c] announced mitigation pledges on global 2030 emissions of China and Japan included. [d] announced mitigation pledges of China, Japan, Republic of Korea included. [e] announced mitigation pledge of Korea not included. [f] announced mitigation pledges of China and Republic of Korea not included, emissions from international aviation and shipping not included. [g] Ranges across four studies are calculated using the median and the full range including the minimum and maximum of studies if available. [h] UNEP EGR 2021 estimate listed for comparison, but since largely relying on the same studies not included in range estimate. [i] NDCs submitted until 30 July included, announcements not included, excluding LULUCF emissions. [j] NDC updates of Brazil, EU and announcement of China included as a sensitivity analysis compared to original NDCs.

Comparing the emission levels implied by the new and updated NDCs as shown in Table 4.3 with those estimated by the original NDCs from the same studies (as included in Table 4.1), a downward revision of 3.8 (3.0-5.3) $GtCO_2$-eq of the central unconditional NDC estimates and of 4.5 (2.7-6.3) $GtCO_2$-eq of the central conditional NDC estimate emerges (*medium evidence, medium agreement*). The emissions gaps between temperature limits and new and updated NDCs are assessed in Cross-Chapter Box 4 below. New and updated unconditional NDC reduce the median gap with 2°C emissions pathways in 2030 by slightly more than 20%, from a median gap of 17 $GtCO_2$-eq (9-23) to 13 (10-17). New and updated conditional NDC reduce the median gap with 2°C emissions pathways in 2030 by about one third, from 14 $GtCO_2$-eq (10-20) to 10 (7-14). New and updated unconditional NDC reduce the median gap with 1.5°C emissions pathways in 2030 by about 15%, from a median gap of 27 $GtCO_2$-eq (19-32) to 23 $GtCO_2$-eq (20-26). New and updated conditional NDC reduce the median gap with 1.5°C emissions pathways in 2030 by about 20%, from a median gap of 24 $GtCO_2$-eq (20-29) to 19 $GtCO_2$-eq (16-24). Box 4.1 discusses the adaptation gap.

Globally, the implementation gap between projected emissions of current policies and the unconditional and conditional new and updated NDCs is estimated to be around 4 and 7 $GtCO_2$eq in 2030, respectively (Table 4.2 and 4.3) (*medium evidence, medium agreement*), with many countries requiring additional policies and associated climate action to meet their mitigation targets as specified under the NDCs (*limited evidence*) (see 4.2.2.6 for more details). It should be noted that the implementation gap varies considerably across countries, with some having policies in place estimated to be sufficient to achieve the emission targets their NDCs, some where additional policies may be required to be sufficient, as well as differences between the policies in place and action on the ground.

4.2.2.6 Tracking progress in implementing and achieving NDCs

Under the Enhanced Transparency Framework, countries will transition from reporting biennial reports (BRs) and biennial update reports (BURs) to reporting biennial transparency reports (BTRs) starting, at the latest, by December 2024. Each Party will be required to report information necessary to track progress made in implementing and achieving its NDC under the Paris Agreement (UNFCCC 2018b). Thus, no official data exists yet on tracking progress of individual NDCs.

Meanwhile, there is some literature at global and national level that aims at assessing whether countries are on track or progressing towards implementing their NDCs and to which degree the NDCs collectively are sufficient to reach the temperature targets of the Paris agreement (Quéré et al. 2018; Höhne et al. 2018; Roelfsema et al. 2020; Rogelj et al. 2016; den Elzen et al. 2019; Höhne et al. 2020). Most of these studies focus on major emitters such as G20 countries and with the aim to inform countries to strengthen their ambition regularly, e.g., through progress of NDCs and as part of the global stocktake (Höhne et al. 2018; Peters et al. 2017). However, a limited number of studies assess the implementation gaps of conditional NDCs in terms of finance, technology and capacity building support. Some authors conclude that finance needed to fulfil conditional NDCs exceeds available resources or the current long-term goal for finance (USD100 billion yr^{-1}) (Pauw et al. 2019); others assess financial resources needed for forest-related activities (Kissinger et al. 2019) (15.4.2). The literature suggests that consistent and harmonised approach to track progress of countries towards their NDCs would be helpful (den Elzen et al. 2019; Höhne et al. 2018; Peters et al. 2017), and negotiations on a common tabular format are expected to conclude during COP26 in November 2021.

With an implementation gap in 2030 of 4 to 7 $GtCO_2$-eq (4.2.2.5), many countries will need to implement additional policies to meet their self-determined mitigation targets as specified under the NDCs. Studies that assess the level of projected emissions under current policies indicate that new policies (that have been implemented since the first assessment of the NDCs in 2015 and are thus covered in more recent projections) have reduced projections, by about 2 $GtCO_2$-eq since the adoption of the Paris Agreement in 2015 to 2019 (Climate Action Tracker 2019; UNEP 2020a; den Elzen et al. 2019).

4.2.2.7 Literature on fairness and ambition of NDCs

Most countries provided information on how they consider their NDCs to be fair and ambitious in the NDCs submitted to UNFCCC and many of these NDCs refer to specific national circumstances such as social, economic and geographical factors when outlining why they are fair and ambitious. Further, several Parties provided information on specific criteria for evaluating fairness and ambition, including criteria relating to: responsibility and capability; share of emissions; development and/or technological capacity; mitigation potential; cost of mitigation actions; the degree of progression or stretching beyond the current level of effort; and the link to objectives and global goals (UNFCCC 2016a).

According to its Article 2.2, the Paris Agreement will be implemented to reflect equity and the principle of common but differentiated responsibilities and respective capabilities, in the light of different national circumstances, the latter clause being new, added to the UNFCCC principle (Rajamani 2017; Voigt and Ferreira 2016). Possible different interpretations of equity principles lead to different assessment frameworks (Lahn 2018; Lahn and Sundqvist 2017).

Various assessment frameworks have been proposed to analyse fair share ranges for NDCs. The literature on equity frameworks including quantification of national emissions allocation is assessed in section 4.5 (see 13.4.2, 14.3.2 and 14.5.3). Recent literature has assessed equity, analysing how fairness is expressed in NDCs in a bottom-up manner (Cunliffe et al. 2019; Mbeva and Pauw 2016; Winkler et al. 2018). Some studies compare NDC ambition level with different effort sharing regimes and which principles are applied to various countries and regions (Robiou du Pont and Meinshausen 2018; Robiou Du Pont et al. 2017; Holz et al. 2018; Peters et al. 2015; Pan et al. 2017; van den Berg et al. 2019). Others propose multi-dimensional evaluation schemes for NDCs that combine a range of indicators, including the NDC targets, cost-effectiveness compared to global models, recent trends and policy implementation into consideration (Aldy et al. 2017; Höhne et al. 2018). Yet other literature evaluates NDC ambition against factors such as technological progress of energy efficiency and low-carbon technologies (Jiang et al. 2017; Wakiyama and Kuramochi 2017; Kuramochi et al. 2017), synergies with adaptation plans (Fridahl and Johansson 2017), the obligations to deploy carbon dioxide removal technologies like BECCS in the future implied by their near-term emission reductions where they are not reflected on in the first NDCs (Fyson et al. 2020; Pozo et al. 2020; Peters and Geden 2017; Mace et al. 2021). Others identify possible risks of unfairness when applying GWP* as emissions metric at national scale (Rogelj and Schleussner 2019). A recent study on national fair shares draws on principles of international environmental law, excludes approaches based on cost and grandfathering, thus narrowing the range of national fair shares previously assessed, and apply this to the quantification of national fair share emissions targets (Rajamani et al. 2021).

4.2.2.8 Uncertainty in estimates

There are many factors that influence the global aggregated effects of NDCs. There is limited literature on systematically analysing the impact of uncertainties on the NDC projections with some exception (Benveniste et al. 2018; Rogelj et al. 2017). The UNEP Gap Report (UNEP 2017a) discusses uncertainties of NDC estimates in some detail. The main factors include variations in overall socio-economic development; uncertainties in GHG inventories; conditionality; targets with ranges or for single years; accounting of biomass; and different GHG aggregation metrics (e.g., GWP values from different IPCC assessments). In addition, when mitigation effort in NDCs is described as measures that do only indirectly translate into emission reductions, assumptions necessary for the translation come into play (Doelle 2019). For a more elaborate discussion of uncertainties in NDCs see Section 14.3.2.

Some studies assume successful implementation of all of the NDCs' proposed measures, sometimes including varying assumptions to account for some of the NDC features which are subject to assumed conditions related to finance and technology transfer. Countries "shall pursue domestic mitigation measures" under Article 4.2 of the Paris Agreement (UNFCCC 2015c), but they are not legally bound to the result of reducing emissions (Winkler 2017a). Some authors consider this to be a lack of a strong guarantee that mitigation targets in NDCs will be implemented (Nemet et al. 2017). Others point to growing extent of national legislation to provide a legal basis for action (Iacobuta et al. 2018) (13.2). These factors together with incomplete information in NDCs mean there is uncertainty about the estimates of anticipated 2030 emission levels.

The aggregation of targets results in large uncertainty (Benveniste et al. 2018; Rogelj et al. 2017). In particular, clarity on the contributions from the land use sector to NDCs is needed "to prevent high LULUCF uncertainties from undermining the strength and clarity of mitigation in other sectors" (Fyson and Jeffery 2019). Methodological differences in the accounting of the LULUCF anthropogenic CO_2 sink between scientific studies and national GHG inventories (as submitted to UNFCCC) further complicate the comparison and aggregation of emissions of NDC implementation (Grassi et al. 2018, 2021) (Section 7.2.3 and Cross-Chapter Box 6). This uncertainty could be reduced with clearer guidelines for compiling future NDCs, in particular when it comes to mitigation efforts not expressed as absolute economy-wide targets (Doelle 2019), and explicit specification of technical details, including energy accounting methods, harmonised emission inventories (Rogelj et al. 2017) and finally, increased transparency and comparability (Pauw et al. 2018).

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Cross-Chapter Box 4 Comparison of NDCs and current policies with the 2030 GHG emissions from long-term temperature pathways

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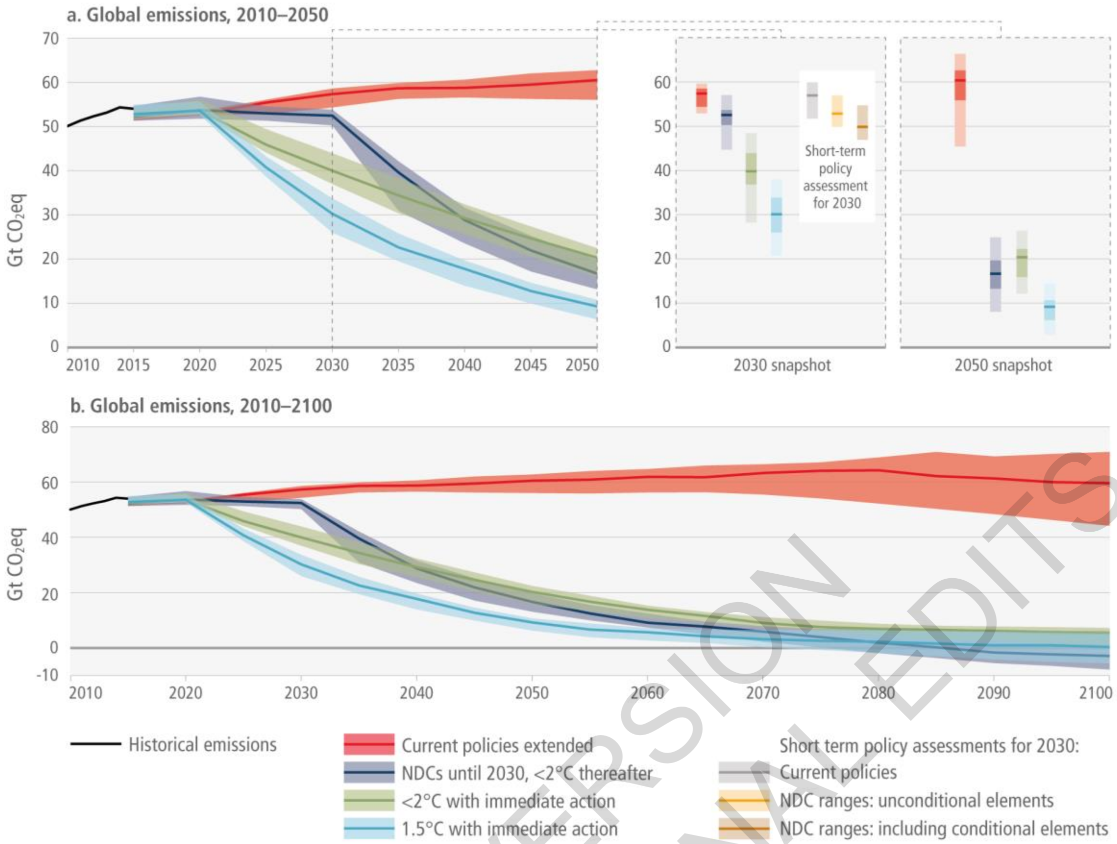
Introduction

The Paris Agreement (PA) sets a long-term goal of holding the increase of global average temperature to 'well below 2°C above pre-industrial levels' and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels. This is underpinned by the 'aim to reach global peaking of greenhouse gas emissions as soon as possible' and 'achieve a balance between anthropogenic emissions by sources and removals by sinks of GHG in the second half of this century' (UNFCCC 2015d). The PA adopts a bottom-up approach in which countries determine their contribution to reach the PA's long-term goal. These national targets, plans and measures are called 'nationally determined contributions' or NDCs.

The NDCs are a central instrument of the PA to achieve its long-term goal. It thus combines a global goal with a country-driven (bottom-up) instrument to a hybrid climate policy architecture to strengthen the global response to climate change. All signatory countries committed to communicating nationally determined contributions including mitigation targets, every five years. While the NDCs mostly state targets, countries are also obliged to pursue domestic mitigation measures to achieve the objectives. The literature examines the emissions outcome of the range of policies implemented to reach these targets.



Cross-Chapter Box 4, Figure 1 Aggregate GHG emission outcomes of NDCs and long-term mitigation pathways consistent with global temperature limits. Shown are emission ranges that would emerge when assuming the full implementation of current unconditional and conditional NDCs (grey bars, median and full range) and global pathways from the AR6 scenario database that can be grouped into four types: pathways with near-term emissions developments in line with (1) current policies and extended with comparable ambition levels beyond 2030; (2) pathways holding warming below 2°C (66% chance) with near term emissions developments reflecting ambition levels in current NDCs until 2030; and mitigation pathways undertaking immediate action after 2020 towards (3) holding warming below 2°C (66% chance) and (4) limiting warming to 1.5°C by 2100 (>50% chance) with no or limited (<0.1°C) overshoot, respectively. The upper panel shows the emission pathways until 2050 (median and 25th-75th percentiles) with their emissions ranges in 2030 and 2050 broken out in full (median and 5th-95th percentiles). The lower panel shows the ranges (25th -75th percentiles) for the four types of emissions pathways over the 21st century.

Notes: GHG emissions are expressed in CO_2-equivalent based on 100-year GWPs from AR6. Projected emissions for the current policies and NDCs scenarios from Section 4.2.2 (Tables 4.2/3) show median and full range. The studies on current policies include post-COVID effects up until 2021(Table 4.2). Note that NDC estimates include updates submitted up until October 2021 as well as pledge announcements (Table 4.3). Historical emissions are from the RCMIP historical compiled dataset comprising various sources and methods, as described in (Nicholls et al. 2020).

Emissions gap

A comparison between the projected emission outcomes of current policies, the NDCs (which include unconditional and conditional elements, see Section 4.2.1) and mitigation pathways acting immediately, i.e. from 2020 onwards, on reaching different temperature goals in the long-term (see Section 3.3.3) allows identifying different 'emission gaps' in 2030 (Figure 1). First, the implementation gap between 'current policies' and unconditional and conditional NDCs is estimated to be around 4 and 7 $GtCO_2eq$ in 2030, respectively (Section 4.2.2 and Tables 4.2 and 4.3). Second, the comparison of unconditional

(conditional) NDCs and long-term mitigation pathways likely limit warming to 2 °C or lower; giving rise to a 2030 median emissions gap of 20-26 $GtCO_2eq$ (16-24 $GtCO_2eq$) for limiting end-of-century warming to 1.5°C (50% chance) with no or limited overshoot and 10-17 $GtCO_2eq$ (7-14 $GtCO_2eq$) for limiting warming to 2°C (66% chance)[4]. GHG emissions of NDCs are broadly consistent with 2030 emission levels of cost-effective long-term pathways staying below 2.5°C.

Other 'gap indicators'

Beyond the quantification of different GHG emissions gaps, there is an emerging literature that identifies gaps between current policies, NDCs and long-term temperature in terms of other indicators, including for example the deployment of low-carbon energy sources, energy efficiency improvements, fossil fuel production levels or investments into mitigation measures (Roelfsema et al. 2020; McCollum et al. 2018; SEI et al. 2020).

A 2030 gap in the contribution of low-carbon energy sources to the energy mix in 2030 between current policies and cost-effective long-term temperature pathways is calculated to be around 7%-points (2°C) and 13%-points (1.5°C) by Roelfsema et al. (Roelfsema et al. 2020). The same authors estimate an energy intensity improvement gap 10% and 18% for 2030 between current policies pathways and 2°C and 1.5°C pathways, respectively. SEI et al. (2020) estimates the 'fossil fuel production gap', i.e. the level of countries' planned fossil fuel production expressed in their carbon content to be 120% and 50% higher compared to the fossil fuel production consistent with 1.5°C and 2°C pathways, respectively, as assessed in IPCC SR1.5 (Rogelj et al. 2018a). The methodology used for this estimation is very similar to how emissions gaps are derived (SEI et al. 2019). The gap of global annual average investments in low-carbon energy and energy efficiency in 2030 between following current policy on the one hand and achieving the NDCs, the 2°C and 1.5°C targets on the other hand, is estimated to be approximately USD 130, 320, or 480 billion per year (McCollum et al. 2018).

It is important to note that such comparisons are less straight forward as the link between long-term temperature goals and these indicators is less pronounced compared to the emission levels themselves; they are therefore associated with greater uncertainty compared to the emissions gap.

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Box 4.1 Adaptation Gap and NDCs

NDCs have been an important driver of national adaptation planning, with cascading effects on sectors and sub-national action, especially in developing countries. Yet, only 40 developing countries have quantifiable adaptation targets in their current NDCs; 49 countries include quantifiable targets in their national legislation (UNEP 2018a).

Working Group II contribution to this Assessment finds that the overall extent of adaptation-related responses in human systems is low (*high confidence)* and that there is limited evidence on the extent to which adaptation-related responses in human systems are reducing climate risk (O'Neill et al. 2020). Thus there is an adaptation gap (UNEP 2018a), and bridging that gap requires enablers including institutional capacity, planning and investment (UNEP 2016). Estimates of adaptation costs vary greatly across studies. Recent studies based on climate change under RCP8.5 report adaptation costs for

FOOTNOTE [4] The emission gap ranges provided here is calculated as the difference between minimum and maximum emissions estimates of NDCs and the median of the 1.5 and 2°C pathways.

developing countries of up to 400 (300 in RCP2.6) billion USD2005 in 2030 (New et al. 2020). Of the NDCs submitted in 2015, fifty countries estimated adaptation costs of USD 39 billion annually. Both public and private finance for adaptation is increasing, but remains insufficient and constitutes a small fraction (4-8%) of total climate finance which is mostly aimed at mitigation. The pledge of developed countries of mobilising finance for developing countries to address adaptation needs globally as part of the Paris Agreement are insufficient. By 2030 the adaptation needs are expected to be 3 to 6 times larger than what is pledged, further increasing towards 2050 (UNEP 2016; New et al. 2020).

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4.2.3 Mitigation efforts in subnational and non-state action plans and policies

The decision adopting the Paris Agreement stresses the importance of "stronger and more ambitious climate action" by non-government and subnational stakeholders, "including civil society, the private sector, financial institutions, cities and other subnational authorities, local communities and indigenous peoples" (UNFCCC 2015e). The Marrakech Partnership for Global Action, launched in the 2016 UNFCCC Conference of Parties by two "high-level champions," further formalized the contributions of non-government and subnational actors taking action through seven thematic areas (e.g., energy, human settlements, industry, land-use, etc.) and one cross-cutting area (resilience). Since then, non-state actors, e.g., companies and civil society, and subnational actors, e.g. cities and regions, have emerged to undertake a range of largely voluntary carbon mitigation actions (Hsu et al. 2019, 2018) both as individual non-state actors (NSA in the following) and through national and international cooperative initiatives (ICIs) (Hsu et al. 2018). ICIs take a variety of forms, ranging from those that focus solely on non-state actors to those that engage national and even local governments. They can also range in commitment level, from primarily membership-based initiatives that do not require specific actions to those that require members to tackle emissions reductions in specific sectors or aim for transformational change.

Quantification of the (potential) impact of these actions is still limited. Almost all studies estimate the potential impact of the implementation of actions by NSA and ICI, but do not factor in that they may not reach their targets. The main reason for this is that there is very limited data currently available from individual actors (e.g., annual GHG inventory reports) and initiatives to assess their progress towards their targets. A few studies have attempted to assess progress of initiatives by looking into the initiatives' production of relevant outputs (Chan et al. 2018). Quantification does not yet cover all commitments and only a selected number of ICIs are analysed in the existing literature. Most of these studies exclude commitments that are not (self-)identified as related to climate change mitigation, those that are not connected to international networks, or those that are communicating in languages other than English.

Non state action could make significant contributions to achieving the Paris climate goals (*limited evidence, high agreement*). However, efforts to measure the extent to which non-state and subnational actors go beyond national policy are still nascent (Kuramochi et al. 2020; Hsu et al. 2019) and we do not fully understand the extent to which ambitious action by non-state actors is additional to what national governments intend to do. Subnational and non-state climate action may also have benefits in reinforcing, implementing, or piloting national policy, in place of or in addition to achieving additional emissions reductions (Broekhoff et al. 2015; Heidrich et al. 2016; Hsu et al. 2017).

Quantification of commitments by individual NSAs are limited to date. Attempts to quantify aggregate effects in 2030 of commitments by individual non-state and subnational actors are reported by (Kuramochi et al. 2020; Hsu et al. 2019). (Kuramochi et al. 2020) estimate potential mitigation by more than 1,600 companies, around 6,000 cities and many regions (cities assessed have a collective population of 579 million, and regions 514 million). Individual commitments by these subnational regions, cities and companies could reduce GHG emissions in 2030 by 1.2 to 2.0 $GtCO_2$-eq yr^{-1} compared to current national policies scenario projections, reducing projected emissions by 3.8%–5.5% in 2030, if commitments are fully implemented and do not lead to weaker mitigation actions by others (Figure 4.1 left). In several countries, NSA commitments could potentially help meet or exceed national mitigation targets.

Quantification of potential emission reductions from international cooperative initiatives have been assessed in several studies, and recently synthesised (Hsu et al. 2020; Lui et al. 2021), with some initiatives reporting high potential. In Table 4.4 and Figure 4.1, we report estimates of the emissions reductions from 19 distinct sub-national and non-state initiatives to mitigate climate change. The table shows wide ranges of potential mitigation based on current, target or potential membership, as well as a wide diversity of actors and membership assumptions. Current membership reflects the number of non-state or subnational actors that are presently committed to a particular initiative; while targeted or potential membership represents a membership goal (e.g., increasing from 100 to 200 members) that an initiative may seek to achieve (Kuramochi et al. 2020). When adding up emission reduction potentials, sub-national and non-state international cooperative initiatives could reduce up to about 20 Gt of CO_2-eq in 2030 (*limited evidence*, *medium agreement*). Chapter 8 also presents data on the savings potential of cities and it suggests that these could reach 2.3 $GtCO_2$-eq annually by 2030 and 4.2 $GtCO_2$-eq annually for 2050.

Table 4.4 Emissions reduction potential for sub-national and non-state international cooperative initiatives by 2030

Sector	**Leading Actor**	**Name**	**Scale**	**Target(s)**	**2030 emissions reduction potential compared to no policy, current policies or NDC baseline ($GtCO_2$-eq yr^{-1})**		**Membership assumptions**
					Min	***Max***	
Energy efficiency	Intergovernmental (UNEP)	United for Efficiency (U4E)	Global (focus on developing countries)	Members to adopt policies for energy-efficient appliances and equipment	0.6	1.25	Current membership
Energy efficiency	Intergovernmental	Super-efficient Equipment and Appliance Deployment (SEAD) Initiative	Global	Members to adopt current policy best practices for energy efficiency product standards	0.5	1.7 (excl. China)	Current membership
Buildings	Business	Architecture 2030	Global (focus on North America)	New buildings and major renovations shall be designed to meet an energy consumption performance standard of 70% below the regional (or country) average/median for that building type and to go carbon- neutral in 2030	0.2	0.2	Current membership
Transport	Business (aviation sector)	Collaborative Climate Action Across the Air Transport World (CAATW)	Global	Two key objectives: 1) 2% annual fuel efficiency improvement through 2050, 2) Stabilise net carbon emissions from 2020	0.3	0.6	Current membership
Transport	Business	Lean and Green	Europe	Member companies to reduce CO_2 emissions from logistics and freight activity by at least 25% over a five-year period	0.02	0.02	Current membership
Transport	Hybrid	Global Fuel Economy Initiative (GFEI)	Global	Halve the fuel consumption of the LDV fleet in 2050 compared to 2005	0.5	1.0	Current membership

Transport	Business	Below50 LCTPi [1)]	Global	Replace 10% of global transportation fossil fuel use with low-carbon transport fuels by 2030	0.5	0.5	Scaled-up global potential
Renewable energy	Business	European Technology & Innovation Platform Photovoltaic (ETIP PV)	Europe	Supply 20% of electricity from solar Photovoltaic PV technologies by 2030	0.2	0.5	Current membership
Renewable energy	Intergovernmental (African Union)	Africa Renewable Energy Initiative (AREI)	Africa	Produce 300 GW of electricity for Africa by 2030 from clean, affordable and appropriate forms of energy	0.3	0.8	Current membership
Renewable energy	Hybrid	Global Geothermal Alliance (GGA)	Global	Achieve a five-fold growth in the installed capacity for geothermal power generation and a more than two-fold growth in geothermal heating by 2030	0.2	0.5	Targeted capacity
Renewable energy	Business	REscale LCTPi [1)]	Global	Support deployment of 1.5 TW of additional renewable energy capacity by 2025 in line with the IEA's 2°C scenario	5	5	Scaled-up global potential
Renewable energy	Business	RE100 initiative	Global	2,000 companies commit to source 100% of their electricity from renewable sources by 2030	1.9	4	Targeted membership
Forestry	Hybrid	Bonn Challenge / Governors' Climate and Forests Task Force (GCFTF) / New York Declaration on Forests (NYDF)	Global	End forest loss by 2030 in member countries and restore 150 million hectares of deforested and degraded lands by 2020 and an additional 200 million hectares by 2030	3.8	8.8	Scaled-up global potential
Non-CO_2 emissions	Government	Climate & Clean Air Coalition (CCAC)	Global	Members to implement policies that will deliver substantial short-lived climate forcers (SLCP) reductions in the near- to medium-term (i.e., by 2030) for HFCs and methane	1.4	3.8	Current membership
Non-CO_2 emissions	Intergovernmental	Zero Routine Flaring	Global	Eliminate routine flaring no later than 2030	0.4	0.4	Current membership

	(World Bank)						
Multisectoral	Cities and regions	Under2 Coalition	Global	Local governments (220 members) aim to limit their GHG emissions by 80 to 95% below 1990 levels by 2050	4.6	5	Current membership
Multisectoral	Cities and regions	Global Covenant of Mayors for Climate & Energy (GCoM)	Global	Member cities have a variety of targets (+9,000 members)	1.4	1.4	Current membership
Multisectoral	Cities and regions	C40 Cities Climate Leadership Group (C40)	Global	94 member cities have a variety of targets, aiming for 1.5°C compatibility by 2050. The network carries two explicit goals: 1) to have every C40 city develop a climate action plan before the end of 2020 (Deadline 2020), which is "deliver action consistent with the objectives of the Paris Agreement" and 2) to have cities achieve emissions neutrality by 2050	1.5	3	Current membership
Agriculture	Business	Climate Smart Agriculture (CSA) LCTPi [1)]	Global	Reducing agricultural and land-use change emissions from agriculture by at least 50% by 2030 and 65% by 2050. 24 companies and 15 partners	3.7	3.7	Scaled-up global potential
Multisectoral	Business	Science Based Targets initiative (SBTi)	Global	By 2030, 2,000 companies have adopted a science- based target in line with a 2°C temperature goal	2.7	2.7	Targeted membership

21 Source: (Hsu et al. 2020)

22 Note [1] As of December 2020 most of the Low Carbon Technology Partnerships (LCTPi) initiatives are defunct, except the Climate Smart Agriculture programme

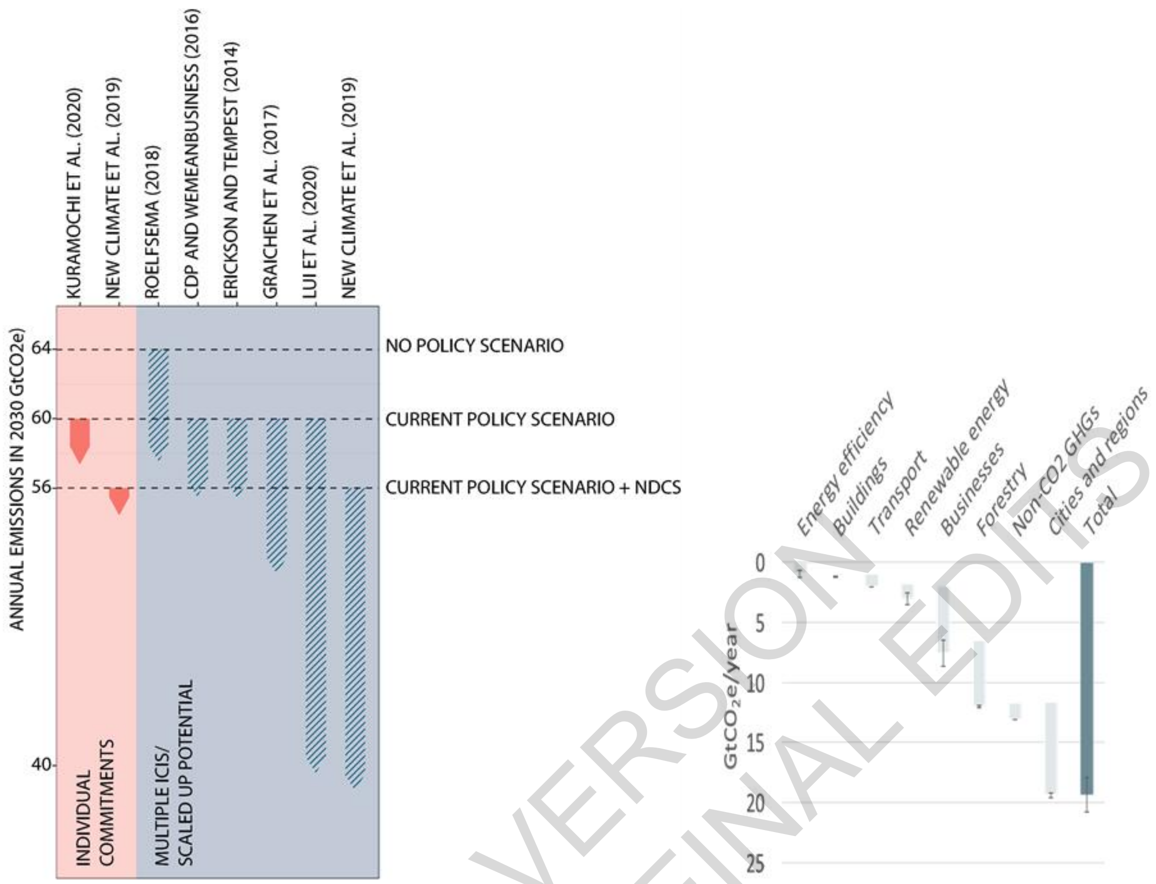

Figure 4.1 Emissions reduction potential for non-state and sub-national actors by 2030

Source: Data in left panel from Hsu et al. (2020), right panel from Lui et al. (2020).

Non-state action may be broader than assessed in the literature so far, though subject to uncertainty. The examples in Table 4.4 and Figure 4.1 do not include initiatives that target the emissions from religious organisations, colleges and universities, civic and cultural groups, and, to some extent, households, and in this sense may underestimate sub-national potential for mitigating emissions, rather than overestimate it. That said, the estimates are contingent on assumptions that subnational and non-state actors achieve commitments—both with respect to mitigation and in some cases membership—and that these actions are not accounted for in nor lead to weakening of national actions.

Care is to be taken not to depict these efforts as additional to action within national NDCs, unless this is clearly established (Broekhoff et al. 2015). There are potential overlaps between individual NSA and ICI, and across ICIs. Kuramochi et al. (2020) propose partial and conservative partial effect methods to avoid double counting when comparing ambition, a matter that merits further attention. As the diversity of actions increased, the potential to count the same reductions multiple times increases.

Equally important to note here is that none of the studies reviewed in Figure 4.1 quantified the potential impact of financial sector actions, e.g., divestment from emission intensive activities (see Section 15.3 for a more detailed discussion of how financial actors and instruments are addressing climate change). Moreover, only a limited number of studies on the impact of actions by diverse actors go beyond 2050 (see Table 4.4), which may reflect analysts' recognition of the increasing uncertainties of longer time horizons. Accurate accounting methods can help to avoiding counting finance multiple times, and methods across mitigation and finance would consider counting carbon market flows and the tons reduced. As Table 4.4 and Figure 4.1 indicate, activities by businesses have potential to significantly contribute to global mitigation efforts. For example, the SBTi (Science-Based Targets Initiative) encourages companies to pledge to reduce their emissions at rates which according to SBTI would be compatible with global pathways to well below 2°C or 1.5°C, with various methodologies being proposed (Andersen et al. 2021; Faria and Labutong 2019). Readers may note, however, that the link between emissions by individual actors and long-term temperature goals cannot be inferred without additional assumptions (see Box 4.2). In the energy sector, some voluntary initiatives are also emerging to stop methane emissions associated with oil and gas supply chains. The Oil and Gas Methane Partnership (OGMP) is a voluntary initiative lead by the Climate and Clean Air Coalition, which has recently published a comprehensive framework for methane detection, measurement and reporting (UNEP 2020b).

Initiatives made up of cities and subnational regions have an especially large potential to reduce emissions, due to their inclusion of many actors, across a range of different geographic regions, with ambitious emissions reduction targets, and these actors' coverage of a large share of emissions (Kuramochi et al. 2020). Hsu et al. (2019) find largest potential in that area. Several subnational regions like California and Scotland have set zero emission targets (Höhne et al. 2019), supported by short- and medium-term interim goals (Scottish Government 2020; State of California 2018). Sharing of effort across global and sub-global scales has not been quantified, though one study suggests that non-state actors have increasingly adopted more diverse framings, including vulnerability, human rights and transformational framings of justice (Shawoo and McDermott 2020). Initiatives focused on forestry have high emissions reduction potential due to the current high deforestation rates, and due to the ambitious targets of many of these forestry initiatives, such as the New York Declaration on Forests' goal to end deforestation by 2030 (Höhne et al. 2019; Lui et al. 2021), although the Initiative acknowledges that insufficient progress has to-date been made towards this goal (NYDF Assessment Partners 2020). On the other hand, uncertainties in global forest carbon emissions (and therefore potential reductions) are high and despite a multitude of initiatives in the sector, actually measured deforestation rates have not declined since the initiative was announced in 2014 (7.2, 7.3.1). Moreover, not all initiatives are transparent about how they plan to reach their goals and may also rely on offsets.

Initiatives focused on non-CO_2 emissions, and particularly on methane, can achieve sizable reductions, in the order of multiple $GtCO_2$-eq yr^{-1} (see Table 4.4). The Global Cement and Concrete Association (formerly the Cement Sustainability Initiative), has contributed to the development of consistent energy and emissions reporting from member companies. The CSI also suggested possible approaches to balance GHG mitigation and the issues of competitiveness and leakage (Cook and Ponssard 2011). The member companies of the GCCA (CSI) have become better prepared for future legislation on managing GHG emissions and developed management competence to respond to climate change compared to non-member companies in the cement sector (Busch et al. 2008; Global Cement and Concrete Association 2020). Accordingly, the cement industry has developed some roadmaps to reach net zero GHG around 2050 (Sanjuán et al. 2020).

It is also important to note that individual NSA and ICI that commit to GHG mitigation activities are often scarce in many crucial and 'hard-to-abate' sectors, such as iron and steel, cement and freight transport (see Chapters 10 and 11). Subnational and non-state action efforts could help these sectors meet an urgent need to accelerate the commercialisation and uptake of technical options to achieve low zero emissions (Bataille 2020).

4.2.4 Mid-century low-emission strategies at the national level

An increasing amount of literature describes mitigation pathways for the mid-term (up to 2050). We assess literature reflecting on the UNFCCC process (4.2.4.1), other official plans and strategies (4.2.4.2) and academic literature on mid-century low-emission pathways at the national level (4.2.4.3). After the Paris Agreement and the IPCC SR1.5 Report, the number of academic papers analysing domestic emission pathways compatible with the 1.5°C limit has been increasing. Governments have developed an increasing number of mitigation strategies up to 2050. Several among these strategies aim at net zero CO_2 or net zero GHG, but it is not yet possible to draw global implications due to the limited size of sample (*limited evidence, limited agreement)*.

START BOX 4.2 HERE

Box 4.2 Direct links between an individual actor's mitigation efforts in the near-term and global temperature goals in the long-term cannot be inferred; making direct links requires clear distinctions of spatial and temporal scales (Robertson 2021; Rogelj et al. 2021) **and explicit treatment of ethical judgements made** (Holz et al. 2018; Klinsky et al. 2017a; Rajamani et al. 2021; Klinsky and Winkler 2018).

The literature frequently refers to *national* mitigation pathways up to 2030 or 2050 using long-term temperature limits in the Paris Agreement (i.e., "2°C" or "1.5°C scenario"). Without additional information, such denomination is incorrect. Working Group I reaffirmed "with high confidence the AR5 finding that there is a near-linear relationship between cumulative anthropogenic CO_2 emissions and the global warming they cause" (WGI SPM AR6). It is not the function of any single country's mitigation efforts, nor any individual actor's. Emission pathways of *individual* countries or sectors in the near- to mid-term can only be linked to a long-term temperature with additional assumptions specifying (i) the GHG emissions and removals of other countries up the mid-term; and (ii) the GHG emissions and removals of all countries beyond the near- and mid-term. For example, a national mitigation pathway can be labelled "2°C compatible" if it derives from a global mitigation pathway consistent with 2°C via an explicit effort sharing scheme across countries (see 4.2.2.6 and 4.5).

END BOX 4.2 HERE

4.2.4.1 GHG Mitigation target under UNFCCC and Paris Agreement

The Paris Agreement requests that Parties should strive to formulate and communicate long-term low GHG development strategies by 2020. (Note that by "long-term", the UNFCCC means 2050, which is the end point of the "mid-term" horizon range in the present report.) As of August 25, 2021, 31 countries and the European Union had submitted low-emissions development strategies (LEDS) (Table 4.5).

By 2018, most long-term strategies targeted 80% emissions reduction in 2050 relative to a reference (1990, 2000 or 2005). After IPCC SR1.5 was published, the number of the countries aiming at net zero CO_2 or GHG emissions has been increasing.[5]

FOOTNOTE[5] Specifying gases aids clarity, see Cross-Chapter Boxes 2 and 3. Some countries refer to net zero GHG emissions as 'climate neutrality' or 'carbon neutrality'; the more precise terms are used where supported by the information assessed in this report.

Table 4.5 Countries having submitted long-term low GHG emission development strategy (as of August 25, 2021)

Country	Date submitted	GHG reduction target
USA	Nov. 16, 2016	80% reduction of GHG in 2050 compared to 2005 level
Mexico	Nov. 16, 2016	50% reduction of GHG in 2050 compared to 2000 level
Canada	Nov. 17, 2016	80% reduction of GHG in 2050 compared to 2005 level
Germany	Nov. 17, 2016 Rev. Apr. 26, 2017 Rev. May 4, 2017	Greenhouse gas neutrality by 2050 (Old target: 80-95% reduction of GHG in 2050 compared to 1990 level)
France	Dec. 28, 2016 Rev. Apr. 18, 2017 Rev. Feb. 8, 2021	Achieving net zero GHG emissions by 2050 (Old target: 75% reduction of GHG in 2050 compared to 1990 level)
Benin	Dec. 12, 2016	Resilient to climate change and low carbon intensity by 2025
Czech Republic	Jan. 15, 2018	80% reduction of GHG in 2050 compared to 1990 level
UK	April 17, 2018	80% reduction of GHG in 2050 compared to 1990 level
Ukraine	July 30, 2018	66-69% reduction of GHG in 2050 compared to 1990 level
Republic of the Marshall Islands	Sept. 25, 2018	Net zero greenhouse gas emissions by 2050
Fiji	Feb. 25, 2019	Net zero carbon by 2050 as central goal, and net negative emissions in 2041 under a Very High Ambition scenario
Japan	June 26, 2019	80% reduction of GHG in 2050, and decarbonized society as early as possible in the 2nd half of 21st century
Portugal	Sept. 20, 2019	Carbon neutrality by 2050
Costa Rica	Dec. 12, 2019	Decarbonized economy with net zero emissions by 2050
European Union	March 6, 2020	Net zero GHG emissions by 2050
Slovakia	March 30, 2020	Climate neutrality by 2050, with decarbonisation targets implying reduction of at least 90% compared to 1990 (not taking into account removals)
Singapore	March 31, 2020	Halving emissions from its peak to 33 $MtCO_2$-e by 2050, with a view to achieving net zero emissions as soon as viable in the second half of the century.
South Africa	Sep. 23, 2020	Net zero carbon economy by 2050
Finland	Oct.5, 2020	Carbon neutrality by 2035; 87.5-90% reduction of GHG in 2050 to 1990 level (excluding land use sector)
Norway	Nov. 25, 2020	Being a low-emission society by 2050
Latvia	Dec. 9, 2020	Climate neutrality by 2050 (non-reducible GHG emissions are compensated by removals in the LULUCF sector)

Spain	Dec. 10, 2020	Climate neutrality by 2050
Belgium	Dec. 10, 2020	Carbon neutrality by 2050 (Walloon Region);Full climate neutrality (Flemish Region), and the European target of carbon neutrality by 2050 (Brussels-Capital Region)
Austria	Dec. 11, 2020	climate-neutral by no later than 2050
Netherlands	Dec. 11, 2020	Reduction of GHG emissions by 95% by 2050 compared to 1990 level.
Sweden	Dec. 11, 2020	Zero net emissions of GHG into the atmosphere latest by 2045
Denmark	Dec. 30, 2020	Climate neutrality by 2050
Republic of Korea	Dec. 30, 2020	Carbon neutrality by 2050
Switzerland	Jan. 28, 2021	2050 net zero GHG
Guatemala	July 6, 2021	59% reduction of projected emissions by 2050
Indonesia	July 22, 2021	540 $MtCO_2$-e by 2050, and with further exploring opportunity to rapidly progress towards net zero emission in 2060 or sooner
Slovenia	Aug. 23, 2021	Net zero emissions or climate neutrality by 2050

4.2.4.2 Other national emission pathways to mid-century

At the 2019 Climate Action Summit, 77 countries indicated their aim to reach net zero CO_2 emissions by 2050, more the number of countries having submitted LEDS to the UNFCCC. Table 4.6 lists the countries that have a national net zero by 2050 target in laws, strategies or other documents (The Energy and Climate Intelligence Unit 2019). Bhutan and Suriname already have achieved net negative emissions. France second "low-carbon national strategy" adopted in 2020 has an objective of GHG neutrality by 2050. Net zero is also the basis of the recent revision of the official notional price of carbon for public investment in France (Quinet et al. 2019). The Committee on Climate Change of the UK analyses sectoral options and concludes that delivering net zero GHG by 2050 is technically feasible but highly challenging (Committee on Climate Change 2019). For Germany, three steps to climate neutrality by 2050 are introduced: First, a 65% reduction of emissions by 2030; second, a complete switch to climate- neutral technologies, leading to a 95% cut in emissions, all relative to 1990 levels by 2050; and third balancing of residual emissions through carbon capture and storage (Görz et al. 2020). In addition to the countries in Table 4.6, EU reported the net zero GHG emission pathways by 2050 under Green Deal (European Commission 2019). China and South Korea, have made announcements of carbon neutrality by 2060 and net zero GHG emission by 2050, respectively (UN 2020a,b). In the case of Japan, the new target to net zero GHG emission by 2050 was announced in 2020 (UN 2020c). As of August 25, 2021, a total 121 countries participate in the 'Climate Ambition Alliance: Net Zero 2050, together with businesses, cities and regions.

Table 4.6 Countries with a national net zero CO_2 or GHG target by 2050 (as of August 25, 2021)

Country	Target year	Target status	Source
Suriname		Achieved	Suriname INDC
Bhutan		Achieved	Royal Government of Bhutan National Environment Commission

Germany	2045	In Law	KSG
Sweden	2045	In Law	Climate Policy Framework
European Union	2050	In Law	European Climate Law
Japan	2050	In Law	Japan enshrines PM Suga's 2050 carbon neutrality promise into law
United Kingdom	2050	In Law	The Climate Change Act
France	2050	In Law	Energy and Climate Law
Canada	2050	In Law	Canadian Net Zero Emissions Accountability Act
Spain	2050	In Law	New Law
Denmark	2050	In Law	The Climate Act
New Zealand	2050	In Law	Zero Carbon Act
Hungary	2050	In Law	Climate Ambition Alliance: Net Zero 2050
Luxembourg	2050	In Law	Climate Ambition Alliance: Net Zero 2050
South Korea	2050	Proposed Legislation	Speeches and Statements by the President
Ireland	2050	Proposed Legislation	Climate Action and Low Carbon Development (Amendment) Bill 2021
Chile	2050	Proposed Legislation	Chile charts path to greener future
Fiji	2050	Proposed Legislation	Draft Climate Law

Note: In addition to the above list, the numbers of "In Policy Document" and "Target Under discussion" as Target status are 37 countries and 79 countries, respectively.

4.2.4.3 Mid-century low emission strategies at the national level in the academic literature

Since the 2000s, an increasing number of studies have quantified the emission pathways to mid-century by using national scale models. In the early stages, the national emission pathways were mainly assessed in the developed countries such as Germany, UK, France, the Netherlands, Japan, Canada, and USA. For example, the Enquete Commission in Germany identified robust and sustainable 80% emission reduction pathways (Deutscher Bundestag 2002). In Japan, 2050 Japan Low-Carbon Society scenario team (2008) assessed the 70% reduction scenarios in Japan, and summarized the necessary measures to "Dozen Actions towards Low-Carbon Societies."

Among developing countries, China, India, South Africa assessed their national emission pathways. For example, detailed analysis was undertaken to analyse pathways to China's goal for carbon neutrality (EFC 2020). In South Africa, a Scenario Building Team (2007) quantified the Long Term Mitigation Scenarios for South Africa.

Prior to COP21, most of the literature on mid-century mitigation pathways at the national level was dedicated to pathways compatible with a 2°C limit (see Box 4.2 for a discussion on the relationship between national mitigation pathways and global, long-term targets). After COP21 and the IPCC SR15, literature increasingly explored just transition to net zero emissions around 2050. This literature reflects on low-emissions development strategies (cognate with SDPS, see 4.3.1) and policies to get to net zero CO_2 or GHG emissions (Waisman et al. 2021)(Cross-Chapter Box 5).

Figure 4.2 provides a snapshot of this literature. For a selected set of countries, it shows the mid-century emission pathways at national scale that have been registered in the IIASA national mitigation scenario database built for the purpose of this Report (Annex III.3.3). Overall, the database contains scenarios for 50 countries. Total GHG emission are the most comprehensive information to assess the pathways on climate mitigation actions, but energy-related CO_2 emissions are the most widely populated data in the scenarios. As a result, Figure 4.2 shows energy-related CO_2 emission trajectories. Scenarios for EU countries show reduction trends even in the reference scenario, whereas developing countries and non-European developed countries such as Japan and USA show emissions increase in the reference. In most countries plotted on Figure 4.2, studies have found that reaching net zero energy related CO_2 emissions by 2050 is feasible, although the number of such pathways is limited.

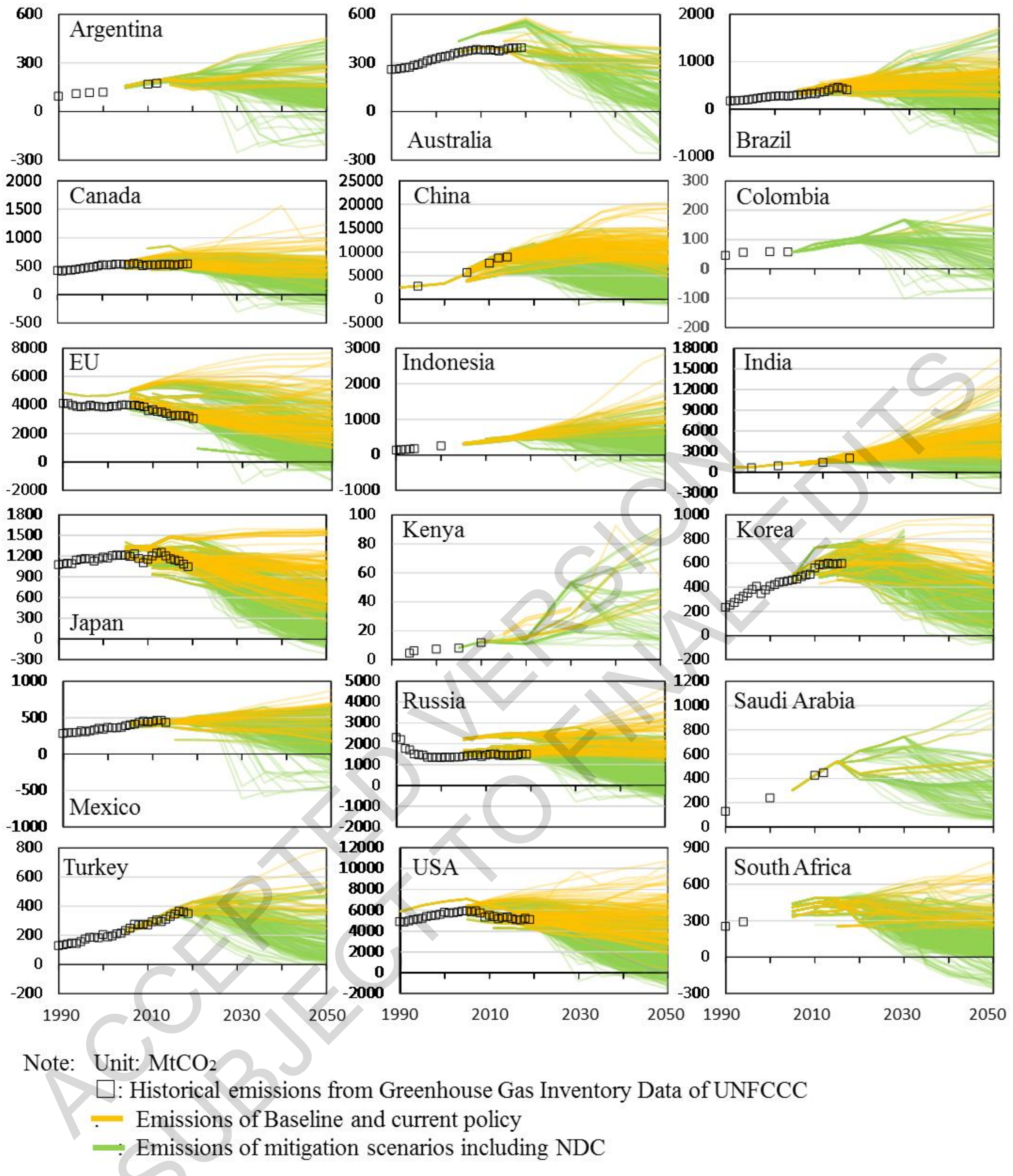

Figure 4.2 Energy related CO_2 emission pathways to mid-century from existing studies
Source of the historical data: Greenhouse Gas Inventory Data of UNFCCC
(https://di.unfccc.int/detailed_data_by_party)

The literature underlines the differences induced by the shift from "2°C scenarios" (typically assumed to imply mitigation in 2050 around 80% relative to 1990) to "1.5°C scenarios" (typically assumed to imply net zero CO_2 or GHG emissions in 2050) (Box 4.2). For Japan, Oshiro et al. (2018) shows the difference between the implications of a 2°C scenario (80% reduction of CO_2 in 2050) and a 1.5 °C scenario (net zero CO_2 emission in 2050), suggesting that for a net zero CO_2 emission scenario, BECCS is a key technology. Their sectoral analysis aims in 2050 at negative CO_2 emissions in the energy sector, and near-zero emissions in the buildings and transport sectors, requiring energy efficiency improvement and electrification. To do so, drastic mitigation is introduced immediately, and, as a result, the mitigation target of Japan's current NDC is considered not sufficient to achieve a 1.5°C scenario. Jiang et al. (2018) also show the possibility of net negative emissions in the power sector in China by 2050, indicating that biomass energy with CCS must be adopted on a large scale by 2040. Samadi et al. (2018) indicate the widespread use of electricity-derived synthetic fuels in end-use sectors as well as behavioural change for the 1.5 degree scenario in Germany.

In addition to those analyses, Vishwanathan et al. (2018b), Chunark and Limmeechokchai (2018) and Pradhan et al. (2018b) build national scenarios in India, Thailand and Nepal, respectively, compatible with a global 1.5°C. Unlike the studies mentioned in the previous paragraph, they translate the 1.5°C goal by introducing in their model a carbon price trajectory estimated by global models as sufficient to achieve the 1.5°C target. Because of the high economic growth and increase of GHG emissions in the reference case, CO_2 emissions in 2050 do not reach zero. Finally, the literature also underlines that to achieve a 1.5°C target, mitigation measures relative to non-CO_2 emissions become important, especially in developing countries where the share of non-CO_2 emissions is relatively high. (La Rovere et al. 2018) treat mitigation actions in AFOLU sector.

Chapter 3 reported on multi-model analyses, comparison of results using different models, of global emissions in the long term. At the national scale, multi-model analyses are still limited, though such analyses are growing as shown in Table 4.7. By comparing the results among different models and different scenarios in a country, the uncertainties on the emission pathways including the mitigation measures to achieve a given emission target can be assessed.

Table 4.7 Examples of research projects on country-level mitigation pathways in the near- to medium-term under the multi-national analyses

Project name	Features
DDPP (Deep Decarbonisation Pathways Project)	16 countries participated and estimated the deep decarbonisation pathways from the viewpoint of each country's perspective using their own models (Waisman et al. 2019).
COMMIT (Climate Policy assessment and Mitigation Modelling to Integrate national and global Transition pathways)	This research project assessed the country contributions to the target of the Paris Agreement (COMMIT 2019).
MAPS (Mitigation Action Plans and Scenarios)	The mitigation potential and socio-economic implications in Brazil, Chile, Colombia and Peru were assessed (La Rovere et al. 2018; Benavides et al. 2015; Zevallos et al. 2014; Delgado et al. 2014). The experiences of the MAPS programme suggests that co-production of knowledge by researchers and stakeholders strengthens the impact of research findings, and in depth studies of stakeholder engagement provide lessons (Boulle et al. 2015; Kane and Boulle 2018; Raubenheimer et al. 2015), which can assist building capacity for long-term planning in other contexts (Calfucoy et al. 2019).
CD-LINKS (Linking Climate and Development Policies – Leveraging International Networks and Knowledge Sharing)	The complex interplay between climate action and development at both the global scale and some national perspectives were explored. The climate policies for G20 countries up to 2015 and some levels of the carbon budget are assessed for short-term and long-term, respectively (Rogelj et al. 2017).

APEC Energy Demand and Supply Outlook	Total 21 APEC countries assessed 2 degree scenario which follows the carbon emissions reduction pathway included in the IEA Energy Technology Perspectives (IEA 2017) by using the common framework (APERC 2019).
Low-Carbon Asia Research Project	The low carbon emission scenarios for several countries and cities in Asia were assessed by using the same framework (Matsuoka et al. 2013). The mitigation activities were summarised into 10 actions toward Low Carbon Asia to show a guideline to plan and implement the strategies for an LCS in Asia (Low-Carbon Asia Research Project 2012).
CLIMACAP–LAMP	This is an inter-model comparison exercise that focused on energy and climate change mitigation in Latin America (Clarke et al. 2016).
DDPP-LAC (Latin American Deep Decarbonisation Pathways project)	6 countries in Latin America analysed the activities in AFOLU (agriculture, forestry and land use) commonly (Bataille et al. 2020).
MILES (Modelling and Informing Low-Emission Strategies)	This is an international research project which covers 5 countries and 1 region in order to build capacity and knowledge on low-emissions development strategies both at a national and global level, by investigating the concrete implications of INDCs for the low-carbon transformation by and beyond 2030 (Spencer et al. 2015).

Another type of multi-model analysis is international, i.e., different countries join the same project and use their own national models to assess a pre-agreed joint mitigation scenario. By comparing the results of various national models, such projects help highlight specific features of each country. More robust mitigation measures can be proposed if different types of models participate. These activities can also contribute to capacity building in developing countries.

4.2.5 What is to be done to accelerate mitigation?

4.2.5.1 Overview of accelerated mitigation pathways

The literature reports an increasing number of accelerated mitigation pathways that are beyond NDCs in different regions and countries. There is increasing understanding of the technical content of such pathways, though the literature remains limited on some dimensions, such as demand-side options, systems analysis, or mitigation of AFOLU non-CO_2 GHGs. The present section describes insights from this literature.

Overall, the literature shows that pathways considered consistent with likely below 2˚C or 1.5˚C (see Box 4.2)—including inter alia 80% reduction of GHG emissions in 2050 relative to 1990 or 100% renewable electricity scenarios—are technically feasible (Esteban et al. 2018; Esteban and Portugal-Pereira 2014; Lund and Mathiesen 2009; Young and Brans 2017; Mathiesen et al. 2011; Hansen et al. 2019; Child et al. 2019). They entail increased end-use energy efficiency, significant increases in low-carbon energy, electrification, other new and transformative technologies in demand sectors, adoption of carbon capture and sequestration (CCS) to reduce gross emissions, and contribution to net negative emissions through carbon dioxide removal (CDR) and carbon sinks. For these pathways to be realized, the literature assumes higher carbon prices, combined in policy packages with a range of other policy measures.

The most recent literature also reflects on accelerated mitigation pathways aiming at reaching net zero CO_2 emissions or net zero GHG emissions by 2050 (4.2.4, Table 4.6) (see glossary entries on net zero CO_2 emissions and net zero GHG emissions). Specific policies, measures and technologies are needed to reach such targets. These include, broadly, decarbonising electricity supply, including through low carbon energy, radically more efficient use of energy than today; electrification of end-uses (including transport / electric vehicles); dramatically lower use of fossil fuels than today; converting other uses to low- or zero-carbon fuels (e.g., hydrogen, bioenergy, ammonia) in hard-to-decarbonise sectors; and setting ambitious targets to reduce methane and other short-lived climate forcers (SLCFs).

Accelerated mitigation pathways differ by countries, depending *inter alia* on sources of emissions, mitigation opportunities and economic context. In China, India, Japan and other Southeast Asian countries, more aggressive action related to climate change is also motivated by regional concerns over health and air quality related to air pollutants and SLCFs (Ashina et al. 2012; Aggarwal 2017; Dhar et al. 2018; Xunzhang et al. 2017; Khanna et al. 2019; China National Renewable Energy Centre 2019; Energy Transitions Commission and Rocky Mountain Institute 2019; Oshiro et al. 2018; Jiang et al. 2018; Kuramochi et al. 2017). Studies of accelerated mitigation pathways in North America tend to focus on power sector and imported fuel decarbonisation in the US , and on electrification and demand-side reductions in Canada (Hammond et al. 2020; Vaillancourt et al. 2017; Jayadev et al. 2020; Hodson et al. 2018; Victor et al. 2018; Bahn and Vaillancourt 2020). In Latin America, many pathways emphasise supply-side mitigation measures, finding that replacing thermal power generation and developing bioenergy (where resources are available) utilisation offers the greatest mitigation opportunities (Nogueira de Oliveira et al. 2016; Lap et al. 2020; Herreras Martínez et al. 2015; Arango-Aramburo et al. 2019; Delgado et al. 2020). The European Union-28's recently announced 2050 climate neutrality goal is explored by pathways that emphasise complete substitution of fossil fuels with electricity generated by low-carbon sources, particularly renewables; demand reductions through efficiency and conservation, and novel fuels and end-use technologies (Capros et al. 2019; Zappa et al. 2019; Louis et al. 2020; Duscha et al. 2019; Prognos Öko-Institut Wuppertal-Institut 2020). The limited literature so far on Africa's future pathways suggest those could be shaped by increasing energy access and mitigating the air pollution and health effects of relying on traditional biomass use, as well as cleaner expansion of power supply alongside end-use efficiency improvements (Hamilton and Kelly 2017; Oyewo et al. 2020, 2019; Wright et al. 2019; Ven et al. 2019; Forouli et al. 2020).

Though they differ across countries, accelerated mitigation pathways share common characteristics as follows. First, energy efficiency, conservation, and reducing energy use in all energy demand sectors (buildings, transport, and industry) are included in nearly all literature that addresses future demand growth (Jiang et al. 2016; Saveyn et al. 2012; Hanaoka and Masui 2018; Thepkhun et al. 2013; Chilvers et al. 2017; Chiodi et al. 2013; Schmid and Knopf 2012; Oshiro et al. 2017a; Shahiduzzaman and Layton 2017; Fragkos et al. 2017; Elizondo et al. 2017; Ouedraogo 2017; Lee et al. 2018; Schiffer 2015; Deetman et al. 2013; Zhou et al. 2019; McNeil et al. 2016; Lefèvre et al. 2018; Sugiyama et al. 2019; Kato and Kurosawa 2019; Jacobson et al. 2019, 2017; Dioha and Kumar 2020; Dioha et al. 2019; Nieves et al. 2019; Jiang et al. 2013; Altieri et al. 2016; Oshiro et al. 2018; Ashina et al. 2012; Vaillancourt et al. 2017; Khanna et al. 2019; Victor et al. 2018; Duscha et al. 2019; Hodson et al. 2018; Capros et al. 2019; Nogueira de Oliveira et al. 2016; Kuramochi et al. 2017)

Similarly, electrification of industrial processes (up to 50% for EU and China) and transport (e.g., 30-60% for trucks in Canada), buildings, and district heating and cooling are commonplace (Ashina et al. 2012; Chiodi et al. 2013; Deetman et al. 2013; Fragkos et al. 2017; Massetti 2012; Mittal et al. 2018; Oshiro et al. 2017b; Oshiro et al. 2018; Saveyn et al. 2012; Vaillancourt et al. 2017; Zhou et al. 2019; Xunzhang et al. 2017; Hammond et al. 2020; Jiang et al. 2018; Capros et al. 2019).

Third, lower emissions sources of energy, such as nuclear, renewables, and some biofuels, are seen as necessary in all pathways. However, the extent of deployment depends on resource availability. Some countries have set targets of up to 100% renewable electricity, while others such as Brazil rely on increasing biomass up to 40-45% of total or industry energy consumption by 2050.

Fourth, CCS and CDR are part of many of the national studies reviewed (Ashina et al. 2012; Chilvers et al. 2017; Jiang et al. 2013; Kuramochi et al. 2018; Herreras Martínez et al. 2015; Massetti 2012; Mittal et al. 2018; Oshiro et al. 2018; Xunzhang et al. 2017; Roberts et al. 2018b; Solano Rodriguez et al. 2017; Thepkhun et al. 2013; Vishwanathan et al. 2018b; Kato and Kurosawa 2019; van der Zwaan et al. 2016). CCS helps reduce gross emissions but does not remove CO_2 from the atmosphere, unless combined with bioenergy (BECCS). CO_2 removal from sources with no identified mitigation measures is considered necessary to help achieve economy-wide net negative emissions (Deetman et al. 2013; Massetti 2012; Solano Rodriguez et al. 2017).

Each option is assessed in more detail in the following sections.

4.2.5.2 Accelerated decarbonisation of electricity through renewable energy

Power generation could decarbonise much faster with scaled up deployment of renewable energy and storage. Both technologies are mature, available, and fast decreasing in costs, more than for many other mitigation options. Models continuously underestimate the speed at which renewables and storage expand. Higher penetration of renewable energy in the power sector is a common theme in scenarios. Some studies provide cost optimal electricity mix under emission constraints, while others explicitly explore a 100% renewables or 100% emission free electricity sector (Box 4.3).

Figure 4.3 shows an increasing share of renewable electricity in most countries historically, with further increases projected in many decarbonisation pathways. Targets for very high shares of renewable electricity generation—up to 100%—are shown for a number of countries, with the global share projected to range from 60% to 70% for 1.5°C with no overshoot (C0) to below 2°C (C4) scenarios. Countries and States that have set 100% renewables targets include Scotland for 2020 (Scottish Government 2021), Austria (2030), Denmark (2035) and California (2045) (Figure 4.3).

While 100% renewable electricity generation by 2050 is found to be feasible, it is not without issues. For example, (Jacobson et al. 2017, 2019) find it feasible for 143 countries with only a 9% average increase in economic costs (considering all social costs) if annual electricity demand can be reduced by 57%. Others state that challenges exist with speed of expansion, ensuring sufficient supply at all times or higher costs compared to other alternatives (Clack et al. 2017). In-depth discussion of net zero electricity systems can be found in section 6.6.

START BOX 4.3 HERE

Box 4.3. Examples of high-renewable accelerated mitigation pathways

Many accelerated mitigation pathways include high shares of renewable energy, with national variations. In Europe, some argue that the EU 2050 net zero GHG emissions goal can be met with 100% renewable power generation, including use of renewable electricity to produce hydrogen, biofuels (including imports), and synthetic hydrocarbons, but will require significant increases in transmission capacity (Duscha et al. 2019; Zappa et al. 2019). Capros et al. (2019) explore a 1.5°C compatible pathway that includes 85% renewable generation, with battery, pumped hydro, and chemical storage for variable renewables. High-renewable scenarios also exist for individual Member States. In France, for example, Krakowski et al. (2016) propose a 100% renewable power generation scenario that relies primarily on wind (62%), solar PV (26%) and oceans (12%). To reach this aim, integration into the European grid is of vital importance (Brown et al. 2018). While debated, incremental costs could be limited regardless of specific assumptions of future costs of individual technologies (Shirizadeh et al. 2020). In Germany, similarly, 100% renewable electricity systems are found feasible by numerous studies (Oei et al. 2020; Thomas Klaus et al. 2020; Wuppertal-Institut 2021; Hansen et al. 2019).

In South Africa, it is found that long-term mitigation goals could be achieved with accelerated adoption of solar PV and wind generation, if the electricity sector decarbonises by phasing-out coal entirely by 2050, even if CCS is not feasible before 2025 (Altieri et al. 2015; Beck et al. 2013). Abundant solar PV and wind potential, coupled with land availability suggest that more than 75% of power generation could ultimately originate from solar PV and wind (Oyewo et al. 2019; Wright et al. 2019).

For the US, share of renewables in power generation in 2050 in accelerated mitigation scenarios vary widely, 40% in (Hodson et al. 2018; Jayadev et al. 2020), more than half renewable and nuclear in (Victor et al. 2018) to 100% in (Jacobson et al. 2017, 2019).

Under cost optimisation scenarios for Brazil, electricity generation, which is currently dominated by hydropower, could reach 100% by adding biomass (Köberle et al. 2020). Other studies find that renewable energy, including biomass, could account for more than 30% of total electricity generation (Portugal-Pereira et al. 2016; Nogueira de Oliveira et al. 2016).

In Colombia, where hydropower resources are abundant and potential also exist for solar and wind, a deep decarbonisation pathway would require 57% renewable power generation by 2050 (Arango-Aramburo et al. 2019) while others find 80% would be possible (Delgado et al. 2020).

In Asia, Japan sees could have up to 50% variable renewable electricity supply to reduce CO_2 emissions by 80% by 2050 in some of its deep mitigation scenarios (Shiraki et al. 2021; Ju et al. 2021; Silva Herran and Fujimori 2021; Kato and Kurosawa 2019; Sugiyama et al. 2019). One view of China’s 1.5°C pathway includes 59% renewable power generation by 2050 (Jiang et al. 2018). One view of India’s 1.5°C pathway also includes 52% renewable power generation, and would require storage needs for 35% of generation (Parikh et al. 2018).

END BOX 4.3 HERE

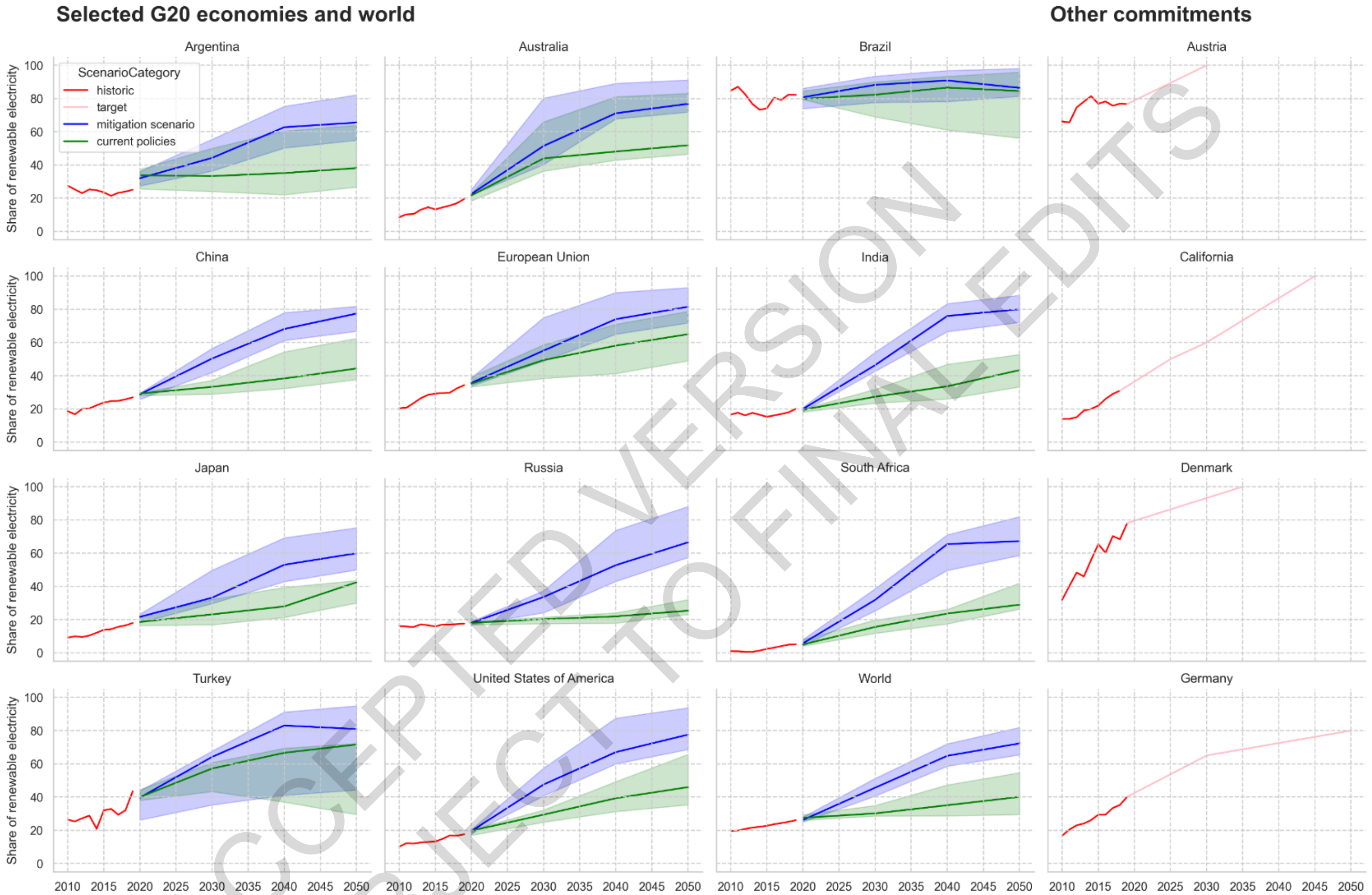

Figure 4.3 Historical and projected levels and targets for the share of renewables in electricity generation

Sources: IEA energy balances for past trends, IPCC AR6 scenario dataset including national model and regional versions in global models (10th to 90th percentile of 1.5 with no overshoot (C0) to below 2°C (C4) scenarios), national / regional sources

4.2.5.3 Bioenergy plays significant role in resource abundant countries in Latin America and parts of Europe

Bioenergy could account for up to 40% of Brazil's total final energy consumption, and a 60% share of fuel for light-duty vehicles by 2030 (Lefèvre et al. 2018), and is considered most cost-effective in transport and industrial applications (Lap et al. 2020). BECCS in the power sector is also considered cost-effective option for supply-side mitigation (Herreras Martínez et al. 2015; Lucena et al. 2016; Borba et al. 2012).

Bioenergy also plays a prominent role in some EU countries' deep decarbonisation strategies. Domestic biomass alone can help Germany meet its 95% CO_2 reduction by 2050 goal, and biomass and CCS together are needed to reduce CO_2 by 80% by 2050 in the Netherlands (Mikova et al. 2019). Studies suggest that mitigation efforts in France include biofuels and significant increases in biomass use, including up to 45% of industry energy by 2050 for its net GHG neutrality goal (Doumax-Tagliavini and Sarasa 2018; Capros et al. 2019). Increased imports may be needed to meet significant increases in EU's bioenergy use, which could affect energy security and the sustainability of bioenergy production outside of the EU (Mandley et al. 2020; Daioglou et al. 2020).

While BECCS is needed in multiple accelerated mitigation pathways, large-scale land-based biological CDR may not prove as effective as expected, and its large-scale deployment may result in ecological and social impacts, suggesting it may not be a viable carbon removal strategy in the next 10-20 years (Vaughan and Gough 2016; Boysen et al. 2017; Dooley and Kartha 2018). The effectiveness of BECCS could depend on local contexts, choice of biomass, fate of initial aboveground biomass and fossil-fuel emissions offsets—carbon removed through BECCS could be offset by losses due to land-use change (Harper et al. 2018; Butnar et al. 2020; Calvin et al. 2021). Large-scale BECCS may push planetary boundaries for freshwater use, exacerbate land-system change, significantly alter biosphere integrity and biogeochemical flows (Heck et al. 2018; Stenzel et al. 2021; Fuhrman et al. 2020; Ai et al. 2021). See 7.4 and 12.5 for further discussions.

4.2.5.4 CCS may be needed to mitigate emissions from the remaining fossil fuels that cannot be decarbonised, but the economic feasibility of deployment is not yet clear

CCS is present in many accelerated mitigation scenarios in the literature. In Brazil, (Nogueira de Oliveira et al. 2016) consider BECCS and CCS in hydrogen generation more feasible than CCS in thermal power plants, with costs ranging from USD70-100/tCO_2. Overall, (van der Zwaan et al. 2016) estimate that 33-50% of total electricity generation in Latin America could be ultimately covered by CCS. In Japan, CCS and increased bioenergy adoption plus waste-to-energy and hydrogen-reforming from fossil fuel are all considered necessary in the power sector in existing studies, with potential up to 200 $MtCO_2$ per year (Ashina et al. 2012; Oshiro et al. 2017a; Kato and Kurosawa 2019; Sugiyama et al. 2021). In parts of the EU, after 2030, CCS could become profitable with rising CO_2 prices (Schiffer 2015). CDR is seen as necessary in some net GHG neutrality pathways (Capros et al. 2019) but evidence on cost-effectiveness is scarce and uncertain (European Commission 2013). For France and Sweden, (Millot et al. 2020) include CCS and BECCS to meet net zero GHG emissions by 2050. For Italy, (Massetti 2012) propose a zero-emission electricity scenario with a combination of renewable and coal, natural gas, and BECCS.

In China, an analysis concluded that CCS is necessary for remaining coal and natural gas generation out to 2050 (Jiang et al. 2018; Energy Transitions Commission and Rocky Mountain Institute 2019). Seven to 10 CCS projects with installed capacity of 15 GW by 2020 and total CCS investment of 105 billion RMB (2010 RMB) are projected to be needed by 2050 under a 2°C compatible pathway according to (Jiang et al. 2016, 2013; Lee et al. 2018). Under 1.5°C pathway, an analysis found China would need full CCS coverage of the remaining 12% of power generation from coal and gas power and

250 GW of BECCS (Jiang et al. 2018). Combined with expanded renewable and nuclear development, total estimated investment in this study is 5% of China's total GDP in 2020, 1.3% in 2030, and 0.6% in 2050 (Jiang et al. 2016).

Views regarding feasibility of CCS can vary greatly for the same country. In the case of India's electricity sector for instance, some studies indicate that CCS would be necessary (Vishwanathan et al. 2018a), while others do not—citing concerns around its feasibility due to limited potential sites and issues related to socio-political acceptance—, and rather point to very ambitious increase in renewable energy, which in turn could pose significant challenges in systematically integrating renewable energy into the current energy systems (Viebahn et al. 2014; Mathur and Shekhar 2020). Some limitations of CCS, including uncertain costs, lifecycle and net emissions, other biophysical resource needs, and social acceptance are acknowledged in existing studies (Sekera and Lichtenberger 2020; Jacobson 2019;Viebahn et al. 2014; Mathur and Shekhar 2020)

While national mitigation portfolios aiming at net zero emissions or lower will need to include some level of CDR, the choice of methods and the scale and timing of their deployment will depend on the ambition for gross emission reductions, how sustainability and feasibility constraints are managed, and how political preferences and social acceptability evolve (Cross-Chapter Box 8). Furthermore, mitigation deterrence may create further uncertainty, as anticipated future CDR could dilute incentives to reduce emissions now (Grant et al. 2021), and the political economy of net negative emissions has implications for equity (Mohan et al. 2021).

4.2.5.5 Nuclear power is considered strategic for some countries, while others plan to reach their mitigation targets without additional nuclear power

Nuclear power generation is developed in many countries, though larger-scale national nuclear generation does not tend to associate with significantly lower carbon emissions (Sovacool et al. 2020). Unlike other energy sources such as wind and PV solar, levelized costs of nuclear power has been rising in the last decades (Portugal-Pereira et al. 2018; Gilbert et al. 2017; Grubler 2010). This is mainly due to overrun of overnight construction costs related to delays in project approvals and construction, and more stringent passive safety measures, which increases the complexity of systems. After the Fukushima Dai-Ichi accident in Japan, nuclear programs in several countries have been phased out or cancelled (Carrara 2020; Huenteler et al. 2012; Kharecha and Sato 2019; Hoffman and Durlak 2018). Also the compatibility of conventional PWR and BWR reactors with large proportion of renewable energy in the grid it is yet to be fully understood.

Accelerated mitigation scenarios offer contrasting views on the share of nuclear in power generation. In the US, (Victor et al. 2018) build a scenario in which nuclear contributes 23% of CO_2 emission reductions needed to reduce GHG emissions by 80% from 2005 levels by 2050. Deep power sector decarbonisation pathways could require a two-folded increase in nuclear capacity according to (Jayadev et al. 2020) for the U.S., and nearly a ten-fold increase for Canada, but may be difficult to implement (Vaillancourt et al. 2017). For China to meet a 1.5°C pathway or achieve carbon neutrality by 2050, nuclear may represent 14%-28% of power generation in 2050 according to (Jiang et al. 2018; China National Renewable Energy Centre 2019; Energy Transitions Commission and Rocky Mountain Institute 2019). For South Korea, (Hong et al. 2014; Hong and Brook 2018) find that increasing nuclear power can help complement renewables in decarbonizing the grid. Similarly, India has put in place a 3-stage nuclear programme which aims to enhance nuclear power capacity from the current level of 6 GW to 63 GW by 2032, if fuel supply is ensured (GoI 2015). Nuclear energy is also considered necessary as part of accelerated mitigation pathways in Brazil, although it is not expected to increase significantly by 2050 even under stringent low carbon scenarios (Lucena et al. 2016). France developed its nuclear strategy in response to energy security concerns after the 1970s Oil Crisis, but has committed to reducing nuclear's share of power generation to 50% by 2035 (Millot et al. 2020). Conversely, some analysis find deep mitigation pathways, including net zero GHG emissions and 80-90% reduction from 2013 levels, feasible without additional nuclear power in EU-28 and Japan respectively, but assuming a combination of bio- and novel fuels and CCS or land-use based carbon sinks (Kato and Kurosawa 2019; Duscha et al. 2019).

Radically more efficient use of energy than today, including electricity, is a complementary set of measures, explored in the following.

4.2.5.6 Efficient cooling, SLCFs and co-benefits

In warmer climate regions undergoing economic transitions, improving the energy efficiency of cooling and refrigeration equipment is often important for managing peak electricity demand and can have co-benefits for climate mitigation as well as SLCF reduction, as expected in India, Africa, and Southeast Asia in the future.

Air conditioner adoption is rising significantly in low- and middle-income countries as incomes rise and average temperatures increase, including in Southeast Asian countries such as Thailand, Indonesia, Vietnam, and the Philippines, as well as Brazil, Pakistan, Bangladesh, and Nigeria (Biardeau et al. 2020). Cooling appliances are expected to increase from 3.6 billion to 9.5 billion by 2050, though up to 14 billion could be required to provide adequate cooling for all (Birmingham Energy Institute 2018). Current technology pathways are not sufficient to deliver universal access to cooling or meet the 2030 targets under the SDGs, but energy efficiency, including in equipment efficiency like air conditioners, can reduce this demand and help limit additional emissions that would further exacerbate climate change (UNEP and IEA 2020; Dreyfus et al. 2020; Biardeau et al. 2020). Some countries (India, South Africa) have started to recognise the need for more efficient equipment in their mitigation strategies (Paladugula et al. 2018; Altieri et al. 2016; Ouedraogo 2017).

One possible synergy between SLCF and climate change mitigation is the simultaneous improvement in energy efficiency in refrigeration and air-conditioning equipment during the hydrofluorocarbon (HFC) phase-down, as recognised in the Kigali Amendment to the Montreal Protocol. The Kigali Amendment and related national and regional regulations are projected to reduce future radiative forcing from HFCs by about half in 2050 compared to a scenario without any HFC controls, and to reduce future global average warming in 2100 from a baseline of 0.3-0.5°C to less than 0.1°C, according to a recent scientific assessment of a wide literature (World Meteorological Organization 2018). If ratified by signatories, the rapid phase-down of HFCs under the Kigali Amendment is possible because of extensive replacement of high-global warming potential (GWP) HFCs with commercially available low-GWP alternatives in refrigeration and air-conditioning equipment. Each country's choices of alternative refrigerants will likely be determined by energy efficiency, costs, and refrigerant toxicity and flammability. National and regional regulations will be needed to drive technological innovation and development (Polonara et al. 2017).

4.2.5.7 Efficient buildings, cooler in summer, warmer in winter, towards net zero energy

Most accelerated mitigation pathway scenarios include significant increase in building energy efficiency. Countries in cold regions, in particular, often focus more on building sector GHG emissions mitigation measures such as improving building envelopes and home appliances, and electrifying space heating and water heating.

For example, scenarios for Japan project continued electrification of residential and commercial buildings to 65% and 79% respectively by 2050 to reach 70-90% CO_2 reduction from 2013 levels (Kato and Kurosawa 2019). Similarly, a mitigation pathway for China compatible with 1.5°C would require 58% to 70% electrification of buildings according to (Jiang et al. 2018; Energy Transitions Commission and Rocky Mountain Institute 2019; China National Renewable Energy Centre 2019). For the EU-28 to reach net carbon neutrality, complete substitution of fossil fuels with electricity (up to 65% share), district heating, and direct use of solar and ambient heat are projected to be needed for buildings, along with increased use of solar thermal and heat pumps for heating (Duscha et al. 2019). In the UK and Canada, improved insulation to reduce energy demand and efficient building appliances and heating systems are important building strategies needed to reduce emissions to zero by 2050 (Roberts et al. 2018a; Vaillancourt et al. 2017; Chilvers et al. 2017). In Ireland, achieving 80%-95% emissions reduction below 1990 levels by 2050 also requires changes in building energy technology and efficiency, including improving building envelopes, fuel switching for residential buildings, and replacing service-sector coal use with gas and renewables according to (Chiodi et al. 2013). In South Africa, improving industry and building energy efficiency is also considered a key part of mitigation strategies (Ouedraogo 2017; Altieri et al. 2016).

In addition, an increasing number of countries have set up Net Zero Energy Building targets (Table 4.8) (Höhne et al. 2020). Twenty seven countries have developed roadmap documents for NZEBs, mostly in developed countries in Europe, North America, and Asia-Pacific, focusing on energy efficiency and improved insulation and design, renewable and smart technologies (Mata et al. 2020). The EU, Japan and the U.S. (the latter for public buildings only) have set targets for shifting new buildings to 100% near-zero energy buildings by 2030, with earlier targets for public buildings. Scotland has a similar target for 2050 (Höhne et al. 2020). Technologies identified as needed for achieving near-zero energy buildings vary by region, but include energy-efficient envelope components, natural ventilation, passive cooling and heating, high performance building systems, air heat recovery, smart and information and communication technologies, and changing future heating and cooling supply fuel mixes towards solar, geothermal, and biomass (Mata et al. 2020). Subnational regions in Spain, U.S., Germany, and Mexico have set local commitments to achieving net zero carbon new buildings by 2050, with California having the most ambitious aspirational target of zero net energy buildings for all new buildings by 2030 (Höhne et al. 2020). The EU is also targeting the retrofitting of 3% of existing public buildings to zero-energy, with emphasis on greater thermal insulation of building envelopes (Mata et al. 2020; Höhne et al. 2020). China's roadmaps have emphasised insulation of building envelope, heat recovery systems in combination with renewable energy, including solar, shallow geothermal, and air source heat pumps (Mata et al. 2020).

Table 4.8 Targets by countries, regions, cities and businesses on decarbonising the building sector

	Countries	Subnational Regions	Cities	Businesses
Shift to 100 per cent (near-) zero energy buildings for new buildings	3	6	>28	>44
Fully decarbonise the building sector	1	6	>28	>44
Phase out fossil fuels (for example, gas) for residential heating	1	-	>3	
Increase the rate of zero-energy renovations	1 (public buildings)			

Source: (Höhne et al. 2020) (supplementary information). See also https://newclimate.org/ambitiousactions

4.2.5.8 Electrifying transport

Electrification of transport in tandem with power sector decarbonisation is expected to be a key strategy for deep CO_2 mitigation in many countries. Passenger transport and light duty freight can already be electrified, but electrifying heavy-duty road transport and fuel switching in aviation and shipping are much more difficult and have not been addressed in most of the recent research.

In Germany, widespread electrification of private vehicles is expected by 2030 (Schmid and Knopf 2012) while for the EU-28, 50% overall transport electrification (excluding feedstock) and 75% electrification of road transport is needed to reach net carbon neutrality according to (Duscha et al. 2019). In addition, novel fuels such as hydrogen, synthetic hydrocarbons and sustainable biogenic fuels are needed to decarbonise aviation and water transport to achieve net carbon neutrality (Duscha et al. 2019).

In India, electrification, hydrogen, and biofuels are key to decarbonising the transport sector (Dhar et al. 2018; Mittal et al. 2018; Vishwanathan et al. 2018b; Mathur and Shekhar 2020). Under a 1.5°C scenario, nearly half of the light-duty passenger vehicle stock needs to be electrified according to (Parikh et al. 2018). In China, a 1.5°C-compatible pathway would requires electrification of 2/5th of transport (Jiang et al. 2018; China National Renewable Energy Centre 2019).

Similarly, in Canada, electrification of 59% of light-duty trucks and 23% of heavy-duty trucks are needed as part of overall strategy to reduce CO_2 emissions by 80% by 2050. In addition, hydrogen is expected to play a major role by accounting for nearly one-third of light-duty trucks, 68% of heavy-duty trucks, and 33% of rail by 2050 according to Hammond et al. (2020).

4.2.5.9 Urban form meets information technology

Beyond technological measures, some densely populated countries including Germany, Japan, and India are exploring using information technology/internet-of-things (IOT) to support mode-shifting and reduce mobility demand through broader behaviour and lifestyle changes (Aggarwal 2017; Ashina et al. 2012; Canzler and Wittowsky 2016; Dhar et al. 2018; Vishwanathan et al. 2018b). In Japan, accelerated mitigation pathways consider the use of information technology and IOT to transform human behaviour and transition to a sharing economy (Ashina et al. 2012; Oshiro et al. 2017a, 2018). In Germany, one study points to including electromobility information and communication technologies in the transport sector as key (Canzler and Wittowsky 2016) while another emphasise shifting from road to rail transport, and reduced distances travelled as other possible transport strategies (Schmid and Knopf 2012). India's transport sector strategies also include use of information technology and the internet, a transition to a sharing economy, and increasing infrastructure investment (Dhar et al. 2018; Vishwanathan et al. 2018b). Behaviour and lifestyle change along with stakeholder integration in decision-making are considered key to implementing new transport policies (Aggarwal 2017; Dhar et al. 2018).

4.2.5.10 Industrial energy efficiency

Industrial energy efficiency improvements are considered in nearly all countries but for countries where industry is expected to continue to be a key sector, new and emerging technologies that require significant R&D investment, such as hydrogen and CCS, make ambitious targets achievable.

In China, for example, non-conventional electrical and renewable technologies, including low-grade renewable heat, biomass use for high-temperature heat in steel and cement sectors, and additional electrification in glass, food and beverage, and paper and pulp industries, are part of scenarios that achieve 60% reduction in national CO_2 emission by 2050 (Khanna et al. 2019; Zhou et al. 2019), in addition to increased recycled steel for electric arc furnaces and direct electrolysis or hydrogen-based direct reduction of iron and CCS utilisation in clinker and steel-making (China National Renewable

Energy Centre 2019; Jiang et al. 2018). Similarly, in India, (Vishwanathan and Garg 2020) point to the need for renewable energy and CCS to decarbonize the industrial sector. In EU-28, net CO_2 neutrality can only be reached with 92% reduction in industrial emissions relative to 1990, through electrification, efficiency improvement and new technologies such as hydrogen-based direct reduction of steel, low carbon cement, recycling (Duscha et al. 2019). Both China and EU see 50% of industry electrification by 2050 as needed to meet 1.5°C and net carbon neutrality pathways (Jiang et al. 2018; Capros et al. 2019).

Aggressive adoption of technology solutions for power sector decarbonisation coupled with end-use efficiency improvements and low-carbon electrification of buildings, industry and transport provides a pathway for accelerated mitigation in many key countries, but will still be insufficient to meet zero emission/1.5°C goals for all countries. Although not included in a majority of the studies related to pathways and national modelling analysis, energy demand reduction through deeper efficiency and other measures such as lifestyle changes and system solutions that go beyond components, as well as the co-benefits of the reduction of short-lived pollutants, needs to be evaluated for inclusion in future zero emission/1.5°C pathways.

4.2.5.11 Lowering demand, downscaling economies

Studies have identified socio-technological pathways to help achieve net zero CO_2 and GHG targets at national scale, that in aggregate are crucial to keeping global temperature below agreed limits. However, most of the literature focuses on supply-side options, including carbon dioxide removal mechanisms (BECCS, afforestation, and others) that are not fully commercialised (Cross-Chapter Box 8). Costs to research, deploy, and scale up these technologies are often high. Recent studies have addressed lowering demand through energy conversion efficiency improvements, but few studies have considered demand reduction through efficiency (Grubler et al. 2018) and the related supply implications and mitigation measures.

Five main drivers of long-term energy demand reduction that can meet the 1.5˚C target include quality of life, urbanisation, novel energy services, diversification of end-user roles, and information innovation (Grubler et al. 2018). A low-energy-demand scenario requires fundamental societal and institutional transformation from current patterns of consumption, including: decentralised services and increased granularity (small-scale, low-cost technologies to provide decentralised services), increased use value from services (multi-use vs. single use), sharing economies, digitalisation, and rapid transformation driven by end-user demand. This approach to transformation differs from the status quo and current climate change policies in emphasising energy end-use and services first, with downstream effects driving intermediate and upstream structural change.

Radical low carbon innovation involves systemic, cultural, and policy changes and acceptance of uncertainty in the beginning stages. However, the current dominant analytical perspectives are grounded in neoclassical economics and social psychology, and focus primarily on marginal changes rather than radical transformations (Geels et al. 2018). Some literature is beginning to focus on mitigation through behaviour and lifestyle changes, but specific policy measures for supporting such changes and their contribution to emission reductions remain unclear (see also Section 4.4.2 and Chapter 5).

4.2.5.12 Ambitious targets to reduce short-lived climate forcers, including methane

Recent research shows that temperature increases are likely to exceed 1.5°C during the 2030s and 2°C by mid-century unless both CO_2 and short-lived climate forcers (SLCFs) are reduced (Shindell et al. 2017; Rogelj et al. 2018a). Because of their short lifetimes (days to a decade and a half), SLCFs can provide fast mitigation, potentially avoiding warming of up to 0.6 ºC at 2050 and up to 1.2 ºC at 2100 (Ramanathan and Xu 2010; Xu and Ramanathan 2017). In Asia especially, co-benefits of drastic CO_2 and air pollution mitigation measures reduce emissions of methane, black carbon, sulphur dioxide, nitrogen oxide, and fine particulate matter by approximately 23%, 63%, 73%, 27%, and 65% respectively in 2050 as compared to 2010 levels. Including the co-benefits of reduction of climate forcing adds significantly to the benefits reducing air pollutants (Hanaoka and Masui 2018).

To achieve net zero GHG emissions implies consideration of targets for non-CO_2 gases. While methane emissions have grown less rapidly than CO_2 and F-gases since 1990 (Chapter 2), the literature urges action to bring methane back to a pathway more in line with the Paris goals (Nisbet et al. 2020). Measures to reduce methane emissions from anthropogenic sources are considered intractable – where they sustain livelihoods – but also becoming more feasible, as studies report the options for mitigation in agriculture without undermining food security (Wollenberg et al. 2016; Frank et al. 2017; Nisbet et al. 2020). The choice of emission metrics has implications for SLCF (Cain et al. 2019)(Cross-Chapter Box 2). Ambitious reductions of methane are complementary to, rather than substitutes for, reductions in CO_2 (Nisbet et al. 2020).

Rapid SLCF reductions, specifically of methane, black carbon, and tropospheric ozone have immediate co-benefits including meeting sustainable development goals for reducing health burdens of household air pollution and reversing health- and crop-damaging tropospheric ozone (Jacobson 2002, 2010). SLCF mitigation measures can have regional impacts, including avoiding premature deaths in Asia and Africa and warming in central and Northern Asia, southern Africa, and the Mediterranean (Shindell et al. 2012). Reducing outdoor air pollution could avoid 2.4 million premature deaths and 52 million tonnes of crop losses for four major staples (Haines et al. 2017). Existing research emphasises climate and agriculture benefits of methane mitigation measures with relatively small human health benefits (Shindell et al. 2012). Research also predicts that black carbon mitigation could substantially benefit global climate and human health, but there is more uncertainty about these outcomes than about some other predictions (Shindell et al. 2012). Other benefits to SLCF reduction include reducing warming in the critical near-term, which will slow amplifying feedbacks, reduce the risk of non-linear changes, and reduce long-term cumulative climate impacts—like sea-level rise—and mitigation costs (Hu et al. 2017; UNEP and WMO 2011; Rogelj et al. 2018a; Xu and Ramanathan 2017; Shindell et al. 2012).

4.2.5.13 System analysis solutions are only beginning to be recognised in current literature on accelerated mitigation pathways, and rarely included in existing national policies or strategies

Most models and studies fail to address system impacts of widespread new technology deployment, for example: 1) material and resources needed for hydrogen production or additional emissions and energy required to transport hydrogen; or 2) materials, resources, grid integration, and generation capacity expansion limits of a largely decarbonised power sector and electrified transport sector. These impacts could limit regional and national scale-ups.

Systemic solutions are also not being sufficiently discussed, such as low-carbon materials; light-weighting of buildings, transport, and industrial equipment; promoting circular economy, recyclability and reusability, and addressing the food-energy-water nexus. These solutions reduce demand in multiple sectors, improve overall supply chain efficiency, and require cross-sector policies. Using fewer building materials could reduce the need for cement, steel, and other materials and thus the need for production and freight transport. Concrete can also be produced from low carbon cement, or designed to absorb CO_2 from the atmosphere. Few regions have developed comprehensive policies or strategies for a circular economy, with the exception of the EU and China, and policies in the EU have only emerged within the last decade. While China's circular economy policies emphasises industrial production, water, pollution and scaling-up in response to rapid economic growth and industrialisation, EU's strategy is focused more narrowly on waste and resources and overall resource efficiency to increase economic competitiveness (McDowall et al. 2017).

Increased bioenergy consumption is considered in many 1.5˚C and 2˚C scenarios. System thinking is needed to evaluate bioenergy's viability because increased demand could affect land and water availability, food prices, and trade (Sharmina et al. 2016). To adequately address the energy-water-food nexus, policies and models must consider interconnections, synergies, and trade-offs among and within sectors, which is currently not the norm (see 12.4).

A systems approach is also needed to support technological innovation. This includes recognising unintended consequences of political support mechanisms for technology adoption and restructuring current incentives to realise multi-sector benefits. It also entails assimilating knowledge from multiple sources as a basis for policy and decision-making (Hoolohan et al. 2019).

Current literature does not explicitly consider systematic, physical drivers of inertia, such as capital and infrastructure needed to support accelerated mitigation (Pfeiffer et al. 2018). This makes it difficult to understand what is needed to successfully shift from current limited mitigation actions to significant transformations needed to rapidly achieve deep mitigation.

4.2.6 Implications of accelerated mitigation for national development objectives

4.2.6.1 Introduction

This section examines how accelerated mitigation may impact the realisation of development objectives in the near- and mid-term. It focuses on three objectives discussed in the literature, sustaining economic growth (4.2.6.2), providing employment (4.2.6.3), and alleviating poverty and ensuring equity (4.2.6.4). It complements similar review performed at global level in section 3.6. For a comprehensive survey of research on the impact of mitigation in other areas (including air quality, health, and biodiversity), see Karlsson et al. (2020).

4.2.6.2 Mitigation and economic growth in the near- and mid-term

A significant part of the literature assesses the impacts of mitigation on GDP, consistent with policymakers' interest in this variable. It must be noted upfront that computable equilibrium models, on which our assessments are mostly based, capture the impact of mitigation on GDP and other core economic variables while typically overlooking other effects that may matter (like improvements in air quality). Second, even though GDP (or better, GDP per capita) is not an indicator of welfare (Fleurbaey and Blanchet 2013), changes in GDP per capita across countries and over time are highly correlated with changes in welfare indicators in the areas of poverty, health, and education (Gable et al. 2015). The mechanisms linking mitigation to GDP outlined below would remain valid even with alternative indicators of well-being (5.2.1). Third, another stream of literature criticises the pursuit of economic growth as a goal, instead advocating a range of alternatives and suggesting modelling of post-growth approaches to achieve rapid mitigation while improving social outcomes (Hickel et al. 2021). In the language of the present chapter, these alternatives constitute alternative development pathways.

Most country-level mitigation modelling studies in which GDP is an endogenous variable report negative impacts of mitigation on GDP in 2030 and 2050, relative to the reference (*robust evidence, high agreement*), for example (Nong et al. 2017) for Australia, (Chen et al. 2013) for Brazil, (Mu et al. 2018a; Cui et al. 2019; Zhao et al. 2018; Li et al. 2017; Dong et al. 2018; Dai et al. 2016) for China, (Álvarez-Espinosa et al. 2018) for Colombia, (Fragkos et al. 2017) for the EU, (Mittal et al. 2018) for India, (Fujimori et al. 2019) for Japan, (Veysey et al. 2014) for Mexico, (Pereira et al. 2016) for Portugal, (Alton et al. 2014; van Heerden et al. 2016) for South Africa, (Chunark et al. 2017) for Thailand, (Acar and Yeldan 2016) for Turkey, (Roberts et al. 2018b) for the UK, (Chen and Hafstead 2019; Zhang et al. 2017) for the USA, (Nong 2018) for Vietnam) (Figure 4.4). The downward relationship between mitigation effort and emissions is strong in studies up to 2030, much weaker for studies looking farther ahead. In all reviewed studies, however, GDP continues to grow even with mitigation. It may be noted that none of the studies assessed above integrates the benefits of mitigation in terms of reduced impacts of climate change or lower adaptation costs. This is not surprising since these studies are at national or regional scale and do not extend beyond 2050, whereas the benefits depend on global emissions and primarily occur after 2050. Discussion on reduced impacts is provided in section 3.6.2 and Cross-Working Group Box 1.

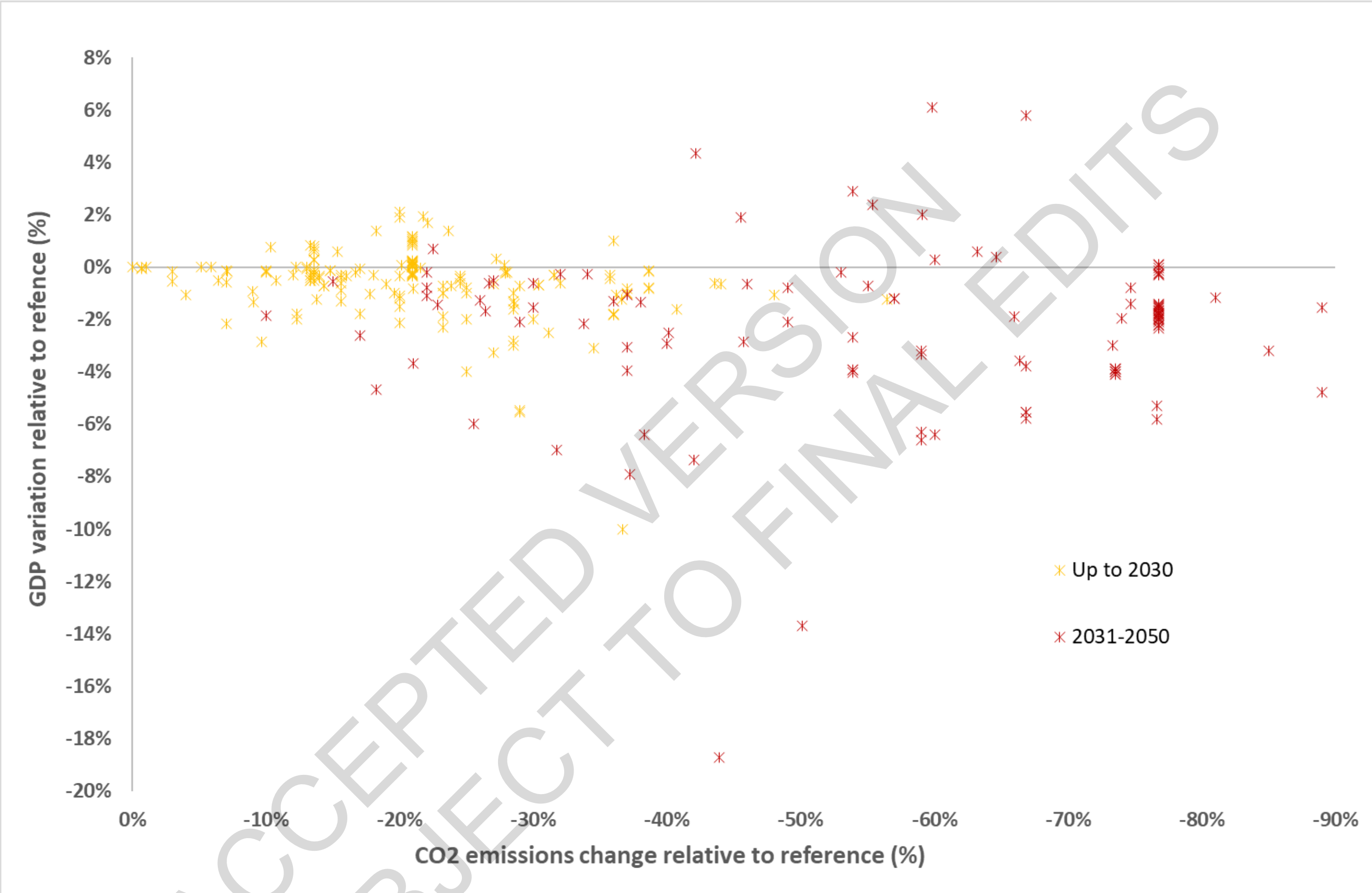

Figure 4.4 GDP against emissions in country-level modelling studies, in variations relative to reference

Two major mechanisms interplay to explain the impact of mitigation on GDP. First, the carbon constraint imposes reduced use of a production factor (fossil energy), thus reducing GDP. In the simulations, the mechanism at work is that firms and households reduce their use of GHG-intensive goods and services in response to higher prices due to reduced fossil energy use. Second, additional investment required for mitigation partially crowds out productive investment elsewhere (Fujimori et al. 2019), except in Keynesian models in which increased public investment actually boosts GDP (Pollitt et al. 2015; Bulavskaya and Reynès 2018; Landa Rivera et al. 2016). Magnitude and duration of GDP loss depend on the stringency of the carbon constraint, the degree of substitutability with less-GHG-intensive goods and services, assumptions about costs of low-carbon technologies and their evolution over time (e.g., (Duan et al. 2018; van Meijl et al. 2018; Cui et al. 2019) and decisions by trading partners, which influence competitiveness impacts for firms (Alton et al. 2014; Fragkos et al. 2017) (*high evidence*, *high agreement*).

In the near-term, presence of long-lived emissions intensive capital stock, and rigidities in the labour market (Devarajan et al. 2011) and other areas may increase impacts of mitigation on GDP. In the mid-term, on the other hand, physical and human capital, technology, institutions, skills or location of households and activities are more flexible. The development of renewable energy may help create more employment and demands for new skills, particularly in the high-skill labour market (Hartley et al. 2019). In addition, cumulative mechanisms such as induced technical change or learning by doing on low-emissions technologies and process may reduce the impacts of mitigation on GDP.

Table 4.9 Examples of country-level modelling studies finding positive short-term outcome of mitigation on GDP relative to baseline

Reference	Country/region	Explanation for positive outcome of mitigation on GDP
(Antimiani et al. 2016)	European Union	GDP increases relative to reference only in the scenario with global cooperation on mitigation
(Willenbockel et al. 2017)	Kenya	The mitigation scenario introduces cheaper (geothermal) power generation units than in BAU (in which thermal increases). Electricity prices actually decrease.
(Siagian et al. 2017)	Indonesia	Coal sector with low productivity is forced into BAU. Mitigation redirects investment towards sectors with higher productivity.
(Blazquez et al. 2017)	Saudi Arabia	Renewable energy penetration assumed to free oil that would have been sold at publicly subsidised price on the domestic market to be sold internationally at market price
(Wei et al. 2019)	China	Analyse impacts of feed-in tariffs to renewables, find positive short-run impacts on GDP; public spending boost activity in the RE sector. New capital being built at faster rate than in reference increases activity more than activity decreases due to lower public spending elsewhere.
(Gupta et al. 2019)	India	Savings adjust to investment and fixed unemployment is considered target of public policy, thereby limiting impact of mitigation on GDP relative to other economic variables (consumption, terms of trade).
(Huang et al. 2019)	China	Power generation plan in the baseline is assumed not cost minimising

Country-level studies find that the negative impacts of mitigation on GDP can be reduced if pre-existing economic or institutional obstacles are removed in complement to the imposition of the carbon constraint (*robust evidence*, *high agreement*). For example, if the carbon constraint takes the form of a carbon tax or of permits that are auctioned, the way the proceeds from the tax (or the revenues from the sales of permits) are used is critical for the overall macroeconomic impacts (Chen et al. 2013). (For a detailed discussion of different carbon pricing instruments, including the auctioning of permits, see Section 13.6.3).

Figure 4.5 shows that depending on the choice of how to implement a carbon constraint, the same level of carbon constraint can yield very different outcomes for GDP. The potential for mitigating GDP implications of mitigation through fiscal reform is discussed in 4.4.1.8.

More generally, mitigation costs can be reduced by proper policy design if the economy initially is not on the efficiency frontier (Grubb 2014), defined as the set of configurations within which the quality of the environment and economic activity cannot be simultaneously improved given current technologies – such improvements in policy design may include reductions in distortionary taxes. Most of the studies which find that GDP increases with mitigation in the near-term precisely assume that the economy is initially not on the frontier. Making the economy more efficient—i.e., lifting the constraints that maintain the economy in an interior position—creates opportunities to simultaneously improve economic activity and reduce emissions. Table 4.9 describes the underlying assumptions in a selection of studies.

Figure 4.5 Illustrative ranges of variations in GDP relative to reference in 2030 associated with introduction of carbon constraint, depending on modality of policy implementation

Based on (Alton et al. 2014; Devarajan et al. 2011; Fernandez and Daigneault 2018; Glomsrød et al. 2016; Nong 2018; Asakawa et al. 2021). Stringency of carbon constraint is not comparable across the studies.

Finally, *marginal* costs of mitigation are not always reported in studies of national mitigation pathways. Comparing numbers across countries is not straightforward due to exchange rate fluctuations, differing assumptions by modellers in individual country studies, etc. The database of national mitigation pathways assembled for this Report—which covers only a fraction of available national mitigation studies in the literature—shows that marginal costs of mitigation are positive, with a median value of 101 USD2010/tCO_2 in 2030, 244 in 2040 and 733 in 2050 for median mitigation efforts of 21%, 46% and 76% relative to business-as-usual respectively. Marginal costs increase over time along accelerated mitigation pathways, as constraints become tighter, with a non-linearity as mitigation reaches 80% of reference emissions or more. Dispersion across and within countries is high, even in the near-term but increases notably in the mid-term (*medium evidence, medium agreement*).

4.2.6.3 Mitigation and employment in the short- and medium-term

Numerous studies have analysed the potential impact of carbon pricing on labour markets. Chateau et al. (2018) and OECD (2017a) find that the implementation of green policies globally (defined broadly as policies that internalise environmental externalities through taxes and other tools, shifting profitability from polluting to green sectors) need not harm total employment, and that the broad skill composition (low-, high- and medium-skilled jobs) of emerging and contracting sectors is very similar, with the largest shares of job creation and destruction at the lowest skill level. To smoothen the labour market transition, they conclude that it may be important to reduce labour taxes, to compensate vulnerable households, and to provide education and training programs, the latter making it easier for labour to move to new jobs. Consistent with this, other studies that simulate the impact of scenarios with more or less ambitious mitigation policies (including 100% reliance on renewable energy by 2050) find relatively small (positive or negative) impacts on aggregate global employment that are more positive if labour taxes are reduced but encompass substantial losses for sectors and regions that today are heavily dependent on fossil fuels (Arndt et al. 2013; Huang et al. 2019; Vandyck et al. 2016; Jacobson et al. 2019). Among worker categories, low-skilled workers tend to suffer wage losses as they are more likely to have to reallocate, something that can come at a cost in the form of a wage cut (assuming that workers who relocate are initially less productive than those who already work in the sector). The results for alternative carbon revenue recycling schemes point to trade-offs: a reduction in labour taxes often leads to the most positive employment outcomes while lump-sum (uniform per-capita) transfers to households irrespective of income yield a more egalitarian outcome.

The results from country-level studies using CGE models tend be similar to those at global level. Aggregate employment impacts are small and may be positive especially if labour taxes are cut, see e.g., (Telaye et al. 2019) for Ethiopia, (Kolsuz and Yeldan 2017) for Turkey, (Fragkos et al. 2017) for the EU, (Mu et al. 2018b) for China. On the other hand, sectoral reallocations away from fossil-dependent sectors may be substantial, see e.g., (Alton et al. 2014) for South Africa or (Huang et al. 2019) for China. Targeting of investment to labour-intensive green sectors may generate the strongest employment gains, see, e.g., (Perrier and Quirion 2018) for France, (van Meijl et al. 2018) for the Netherlands, (Patrizio et al. 2018) for the USA. Changes in skill requirements between emerging and declining sectors appear to be quite similar, involving smaller transitions than during the IT revolution (Bowen et al. 2018).

In sum, the literature suggests that the employment impact of mitigation policies tends to be limited on aggregate, but can be significant at the sectoral level (medium evidence, medium agreement) and that cutting labour taxes may limit adverse effects on employment (limited evidence, medium agreement). Labour market impacts, including job losses in certain sectors, can be mitigated by equipping workers for job changes via education and training, and by reducing labour taxes to boost overall labour demand (Stiglitz et al. 2017) (4.5).

Like most of the literature on climate change, the above studies do not address gender aspects. These may be significant since the employment shares for men and women vary across sectors and countries.

4.2.6.4 Mitigation and equity in the near- and mid-term

Climate mitigation may exacerbate socio-economic pressures on poorer households (Jakob et al. 2014). First, the price increase in energy-intensive goods and services—including food (Hasegawa et al. 2018)—associated with mitigation may affect poorer households disproportionally (Bento 2013), and increase the number of energy-poor (Berry 2019). Second, the mitigation may disproportionally affect low-skilled workers (see previous section). Distributional issues have been identified not only with explicit price measures (carbon tax, emission permits system, subsidy removal), but also with subsidies for renewables (Borenstein and Davis 2016), and efficiency and emissions standards (Davis and Knittel 2019; Bruegge et al. 2019; Levinson 2019; Fullerton and Muehlegger 2019).

Distributional implications, however, are context specific, depending on consumption patterns (initially and ease of adjusting them in response to price changes) and asset ownership (see for example analysis of energy prices in Indonesia by Renner et al. (2019)). In an analysis of the distributional impact of carbon pricing based on household expenditure data for 87 low- and middle-income countries, Dorband et al. (2019) find that, in countries with a per-capita income of up to USD15,000 per capita (PPP adjusted), carbon pricing has a progressive impact on income distribution and that there may be an inversely U-shaped relationship between energy expenditure shares and per-capita income, rendering carbon pricing regressive in high-income countries, i.e., in countries where the capacity to pursue compensatory policies tends to be relatively strong.

The literature finds that the detailed design of mitigation policies is critical for their distributional impacts (*robust evidence, high agreement*). For example, Vogt-Schilb et al. (2019) suggest to turn to cash transfer programs, established as some of the most efficient tools for poverty reduction in developing countries. In an analysis of Latin America and the Caribbean, they find that allocation of 30 percent of carbon revenues would suffice to compensate poor and vulnerable households on average, leaving the rest for other uses. This policy tool is not only available in countries with relatively high per-capita incomes: in Sub-Saharan Africa, where per-capita incomes are relatively low, cash transfer programs have been implemented in almost all countries ((Beegle et al. 2018), p. 57), and are found central to the success of energy subsidy reforms (Rentschler and Bazilian 2017). In the same vein, Böhringer et al. (2021) finds that recycling of revenues from emissions pricing in equal amounts to every household appeals as an attractive strategy to mitigate regressive effects and thereby make stringent climate policy more acceptable on societal fairness grounds. However, distributional gains from such recycling may come at the opportunity cost of not reaping efficiency gains from reductions in the taxes that are most distortionary (Goulder et al. 2019).

Distributional concerns related to climate mitigation are also prevalent in developed countries, as demonstrated, for instance, by France's recent yellow-vest movement, which was ignited by an increase in carbon taxes. It exemplifies the fact that, when analysing the distributional effects of carbon pricing, it is not sufficient to consider vertical redistribution (i.e., redistribution between households at different incomes levels but also horizontal redistribution (i.e., redistribution between households at similar incomes which is due to differences in terms of spending shares and elasticities for fuel consumption). Compared to vertical redistribution, it is more difficult to devise policies that effectively address horizontal redistribution (Douenne 2020; Cronin et al. 2019; Pizer and Sexton 2019). However, it has been shown ex post that transfer schemes considering income levels and location could have protected or even improved the purchasing power of the bottom half of the population (Bureau et al. 2019).

Investments in public transportation may reduce horizontal redistribution if it makes it easier for households to reduce fossil fuel consumption when prices increase (cf. Section 4.4.1.5 and 4.4.1.9). Similarly, in relation to energy use in housing, policies that encourage investments that raise energy efficiency for low-income households may complement or be an alternative to taxes and subsidies as a means of simultaneously mitigating and reducing fuel poverty (Charlier et al. 2019). From a different angle, public acceptance of the French increase in the carbon tax could also have been enhanced via a public information campaign could have raised public acceptance of the carbon tax increase (Douenne and Fabre 2020). (See section 4.4.1.8 for a discussion of this and other factors that influence public support for carbon taxation.).

4.2.7 Obstacles to accelerated mitigation and how overcoming them amounts to shifts in development pathways

As outlined in Sections 4.2.3, 4.2.4, 4.2.5 and 4.2.6 there is improved understanding since AR5 of what accelerated mitigation would entail in the coming decades. A major finding is that accelerated mitigation pathways in the near- to mid-term appear technically and economically feasible in most contexts. Chapter 4, however, cannot stop here. Section 4.2.2 has documented an important policy gap for current climate pledges, and Cross-Chapter Box 4 shows an even larger ambition gap between current pledges and what would be needed in the near- term to be on pathways consistent with below 2°C, let alone 1.5°C. In other words, while the implementation of mitigation policies to achieve updated NDC almost doubles the mitigation efforts, and notwithstanding the widespread availability of the necessary technologies, this doubling of effort merely narrows the gap to pathways consistent with 2°C by at most 20%.

Obstacles to the implementation of accelerated mitigation pathways can be grouped in four main categories (Table 4.10). The first set of arguments can be understood through the lens of cost-benefit analysis of decision-makers, as they revolve around the following question: Are costs too high relative to benefits? More precisely, are the opportunity costs—in economics terms, what is being forfeited by allocating scarce resources to mitigation—justified by the benefits for the decision-maker (whether individual, firm, or nation)? This first set of obstacles is particularly relevant because accelerated mitigation pathways imply significant effort in the short-run, while benefits in terms of limited warming accrue later and almost wholly to other actors. However, as discussed in 3.6 and 4.2.6, mitigation costs for a given mitigation target are not carved in stone. They strongly depend on numerous factors, including the way mitigation policies have been designed, selected, and implemented, the processes through which markets have been shaped by market actors and institutions, and nature of socially- and culturally-determined influences on consumer preferences. Hence, mitigation choices that might be expressed straightforwardly as techno-economic decisions are, at a deeper level, strongly conditioned by underlying structures of society.

Table 4.10 Objections to accelerated mitigation and where they are assessed in the WG3 report

Category	Main dimensions	Location in WGIII report where objection is assessed and solutions are discussed
Costs of mitigation	Marginal, sectoral or macroeconomic costs of mitigation too high; Scarce resources could/should be used for other development priorities; Mitigation	3.6, 4.2.6, 12.2, Chapter 15, Chapter 17

	benefits are not worth the costs (or even non-existent); Lack of financing	
Distributional implications	Risk of job losses; Diminished competitiveness; Inappropriate impact on poor/vulnerable people; negative impact on vested interests	4.5, Chapter 5, Chapter 13, Chapter 14
Lack of technology	Lack of suitable technologies; Lack of technology transfer; unfavourable socio-political environment	4.2.5, Chapter 16
Unsuitable "structures"	Inertia of installed capital stock; Inertia of socio-technical systems; Inertia to behaviour change; Unsuitable institutions	3.5, Chapter 5, Chapter 13

A second set of likely obstacles in the short-term to accelerated mitigation revolves around undesirable distributional consequences, within and across countries. As discussed in 4.2.6.3, the distributional implications of climate policies depend strongly on their design, the way they are implemented, and on the context into which they are inserted. Distributional implications of climate policies have both ethics and equity dimensions, to determine what is desirable/acceptable by a given society in a given context, notably the relative power of different winners and losers to have their interests taken into account, or not, in the relevant decision-making processes. Like costs, distributional implications of accelerated mitigation are rooted in the underlying socio-political-institutional structures of a society.

A third set of obstacles are about technology availability and adoption. Lack of access even to existing cost-effective mitigation technologies remains an important issue, particularly for many developing countries, and even in the short-term. Though it relates most directly to techno-economic costs, technology availability raises broader issues related to the sociotechnical systems within which innovation and adoption are embedded, and issues of technology availability are inherently issues of systemic failure (16.3). The underlying legal, economic and social structures of the economy are central to the different stages of socio-transition processes (Cross-Chapter Box 12).

The last set of obstacles revolves around the unsuitability of existing structures to accelerated mitigation. We include here all forms of established structures, material (e.g., physical capital) or not (institutions, social norms, patterns of individual behaviour), that are potentially long-lived and limit the implementation of accelerated mitigation pathways. Typically, such structures exist for reasons other than climate change and climate mitigation, including the distribution of power among various actors. Modifying them in the name of accelerated climate mitigation thus requires to deal with other non-climate issues as well. For example, resolving the landlord-tenant dilemma, an institutional barrier to the deployment of energy efficiency in building, opens fundamental questions on private property in buildings.

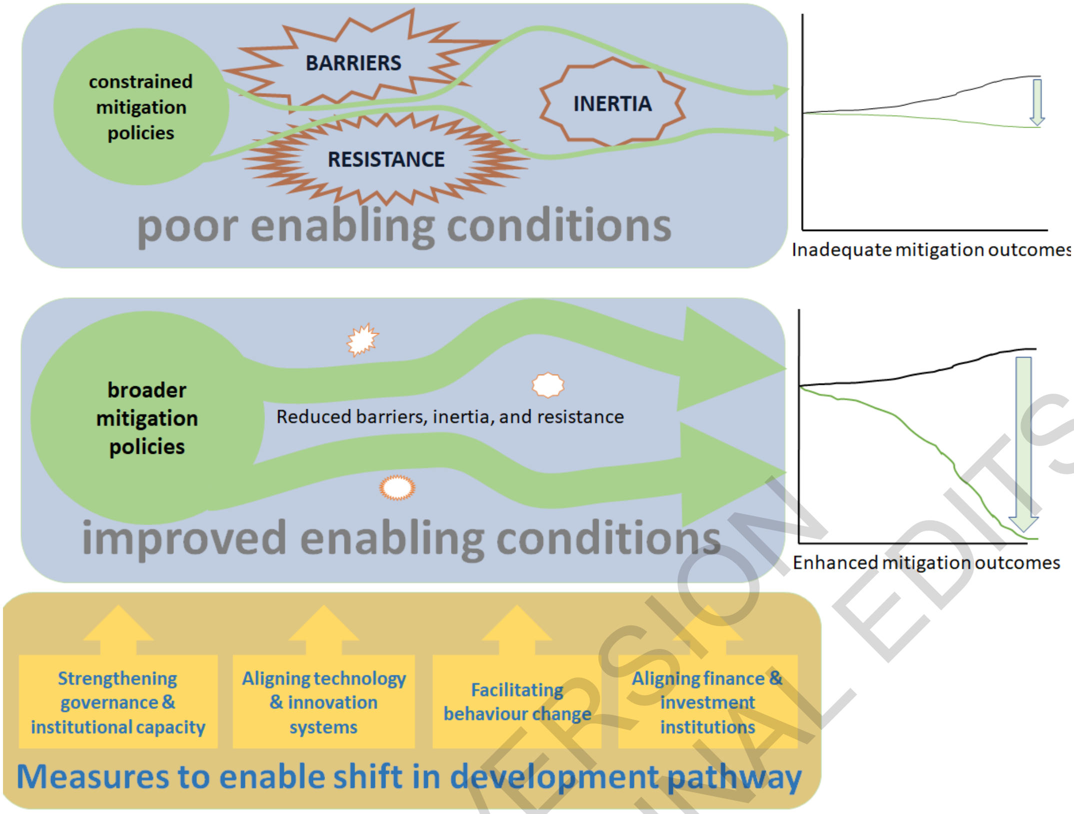

Figure 4.6 Obstacles to mitigation (top panel) and measures to remove these obstacles and enable shift in development pathways (lower panel)

A common thread in the discussion above is that the obstacles to accelerated mitigation are to a large degree rooted in the underlying structural features of societies. As a result, transforming those underlying structures can help to remove those obstacles, and thus facilitate the acceleration of mitigation. This remark is all the more important that accelerated mitigation pathways, while very different across countries, all share three characteristics: speed of implementation, breadth of action across all sectors of the economy, and depth of emission reduction achieving more ambitious targets. Transforming those underlying structures amounts to shifting a society's development pathway (Figure 4.6). In the following Sections 3 and 4, we argue that it is thus necessary to recast accelerated mitigation in the broader context of shifting development pathways, and that doing so opens up additional opportunities to (i) overcome the obstacles outlined above, and also (ii) combine climate mitigation with other development objectives.

4.3 Shifting Development pathways

4.3.1 Framing of development pathways

4.3.1.1 What are development pathways?

The term development pathway is defined in various ways in the literature, and these definitions invariably refer to the evolution over time of a society's defining features. A society's development pathway can be described, analysed, and explained from a variety of perspectives, capturing a range of possible features, trends, processes, and mechanisms. It can be examined in terms of specific quantitative indicators, such as population, urbanisation level, life expectancy, literacy rate, GDP, carbon dioxide emission rate, average surface temperature, etc. Alternately, it can be described with reference to trends and shifts in broad socio-political or cultural features, such as democratisation, liberalisation, colonisation, globalisation, consumerism, etc. Or, it can be described in a way that highlights and details a particular domain of interest; for example, as an "economic pathway", "technological pathway", "demographic pathway", or others. Any such focused description of a pathway is more limited, by definition, than the general and encompassing notion of a development pathway.

Development pathways represent societal evolution over time, and can be assessed retrospectively and interpreted in a historical light, or explored prospectively by anticipating and assessing alternative future pathways. Development pathways, and prospective development pathways in particular, can reflect societal objectives, as in "low-emission development pathways", "climate-resilient development pathways", "sustainable development pathways", "inclusive development pathway", and as such can embed normative assumptions or preferences, or can reflect potential dystopian futures to be avoided. A national development plan (4.3.2) is a representation of a possible development pathway for a given society reflecting its objectives, as refracted through its development planning process.

One approach for exploring shifts in future development pathways is through scenarios. Some examples of scenario exercises in the literature are provided in Table 4.11.

Table 4.11 Prospective development pathways at global, national and local scale

Scale	Process and publication	Description of development pathways
Global	IPCC Special Report on Emission Scenarios (Nakicenovic et al. 2000)	Four different narrative storylines describing relationships between driving forces and the evolution of emission scenarios over the 21st century.
Global	Shared Socioeconomic Pathways (Riahi et al. 2017; O'Neill et al. 2017)	Five narratives describing alternative socio-economic developments, including sustainable development, regional rivalry, inequality, fossil-fuelled development, and middle-of-the-road development, using alternative long-term projections of demographics, human development, economy and lifestyle, policies and institutions, technology, and environment and natural resources.
Global	(Rao et al. 2019)	Alternative development pathways that explore several drivers of rising or falling inequality.
Global	Futures of Work (World Economic Forum 2018)	Eight possible visions of the future of work in the year 2030, based on different combinations of three core variables: the rate of technological change and its impact on business models, the evolution of learning among the current and

		future workforce, and the magnitude of labour mobility across geographies—all of which are likely to strongly influence the nature of work in the future.
National	Mt Fleur Scenarios (Galer 2004)	Four socio-political scenarios intended to explore possible futures of a newly post-apartheid South Africa, which included three dark prophecies and one bright vision which reportedly influenced the new leadership.
National	Mitigation Action Plans and Scenarios (MAPS) (Winkler et al. 2017; Raubenheimer et al. 2015)	Mitigation and development-focused scenarios for Brazil, Chile, Peru, and Colombia, entailing linked sectoral and economy modelling including socio-economic implications, combined with intensive stakeholder engagement.
National	Deep Decarbonisation Pathways (Bataille et al. 2016a; Waisman et al. 2019)	Mitigation-focused scenarios for sixteen countries from each country's perspective, carried out by local institutes using national models. The common method is a tool for decision-makers in each context to debate differing concrete visions for deep decarbonisation, seek consensus on near-term policy packages, with aim to contribute to long-term global decarbonisation.
Local	New Lenses on Future Cities (Shell Global 2014)	Six city archetypes used to create scenarios to help understand how cities could evolve through more sustainable urbanisation processes and become more efficient, while coping with major development challenges in the past.

Different narratives of development pathways can have distinct and even competing focuses such as economic growth, shifts in industrial structure, technological determinism, and can embody alternative framings of development itself (from growth to well-being, see Chapter 5), and of sustainable development in particular (see 1.6 and 17.1). Scenario exercises are structured undertakings to explore alternative future development pathways, often drawing on stakeholder input and accepting the deep and irreducible uncertainty inherent in societal development into the future (Kahane 2019; Schweizer and Kriegler 2012; Raskin and Swart 2020). The results of scenario explorations, including modelling exercises, thus help clarify the characteristics of a particular future pathway, in light of a particular set of assumptions and choice of indicators for assessment. Processes of developing scenarios can inform choices by decision makers of various kinds.

Scenarios are useful to clarify societal objectives, understand constraints, and explore future shifts. Scenario exercises are effective when they enable multi-dimensional assessment, and accommodate divergent normative viewpoints (Kowarsch et al. 2017). Such processes might take into account participants' explicit and implicit priorities, values, disciplinary backgrounds, and world views. The process of defining and describing a society's development pathway contributes to the ongoing process of understanding, explaining and defining the historical and contemporary meaning and significance of a society. The imagination of facilitated stakeholder process combined with the rigour of modelling helps improve understanding of constraints, trade-offs, and choices. "*Scenario analysis offers a structured approach for illuminating the vast range of possibilities. A scenario is a story, told in words and numbers, describing the way events might unfold. If constructed with rigor and imagination, scenarios help us to explore where we might be headed, but more, offering guidance on how to act now to direct the flow of events toward a desirable future*" (Raskin et al. 2002). Scenario processes are valuable for the quantitative and qualitative insights they can provide, and also for the role they can play in providing a forum and process by which diverse institutions and even antagonistic stakeholders can come together, build trust, improve understanding, and ultimately converge in their objectives (Kane and Boulle 2018; Dubash 2021).

4.3.1.2 Shifting development pathways

Development pathways evolve as the result of the countless decisions and actions at all levels of societal structure, as well due to the emergent dynamics within and between institutions, cultural norms, socio-technological systems, and the biogeophysical environment. Society can choose to make decisions and take actions with the shared intention of influencing the future development pathway toward specific agreed objectives.

The SDGs provide a lens on diverse national and local development objectives. Humankind currently faces multiple sustainability challenges that together present global society with the challenge of assessing, deliberating, and attempting to bring about a viable, positive future development pathway. Ecological sustainability challenges include reducing GHG emissions, protecting the ozone, controlling pollutants such as aerosols and persistent organics, managing nitrogen and phosphorous cycles, etc. (Steffen et al. 2015), which are necessary to address the rising risks to biodiversity and ecosystem services on which humanity depends (IPBES 2019a). Socioeconomic sustainability challenges include conflict, persistent poverty and deprivation, various forms of pervasive and systemic discrimination and deprivation, and socially corrosive inequality. The global adoption of the SDGs and their underlying indicators (United Nations 2018) reflect a negotiated prioritisation of these common challenges.

Figure 4.7 illustrates the process of shifting development pathways. The lines illustrate different possible development pathways through time, some of which (shown here toward the top of the figure) remove obstacles to the adoption and effective implementation of sustainable development policies, and thus give access to a rich policy toolbox for accelerating mitigation and achieving SDGs. Other development pathways (shown here toward the bottom of the figure) do not overcome, or even reinforce the obstacles to adopting and effectively implementing sustainable development policies, and thus leave decision-makers with more limited policy toolbox (4.2.7; Figure 4.6). A richer tool box enables faster, deeper and broader mitigation.

The development pathways branch and branch again, signifying how a diversity of decision-makers (policy makers, organizations, investors, voters, consumers, etc.) are continuously making choices that influence which of many potential development pathways society follows. Some of these choices fall clearly within the domain of mitigation policy. For example, what level carbon price, if any, should be imposed? Should fossil fuel subsidies be removed? Most decisions, of course, fall outside the direct domain of mitigation policy. *Shifting development pathways toward sustainability* involves this broader realm of choices beyond mitigation policy *per se*, and requires identifying those choices that are important determinants of the existing obstacles to accelerating mitigation and meeting other SDGs. Addressing these choices coherently shifts the development pathway away from a continuation of existing trends,

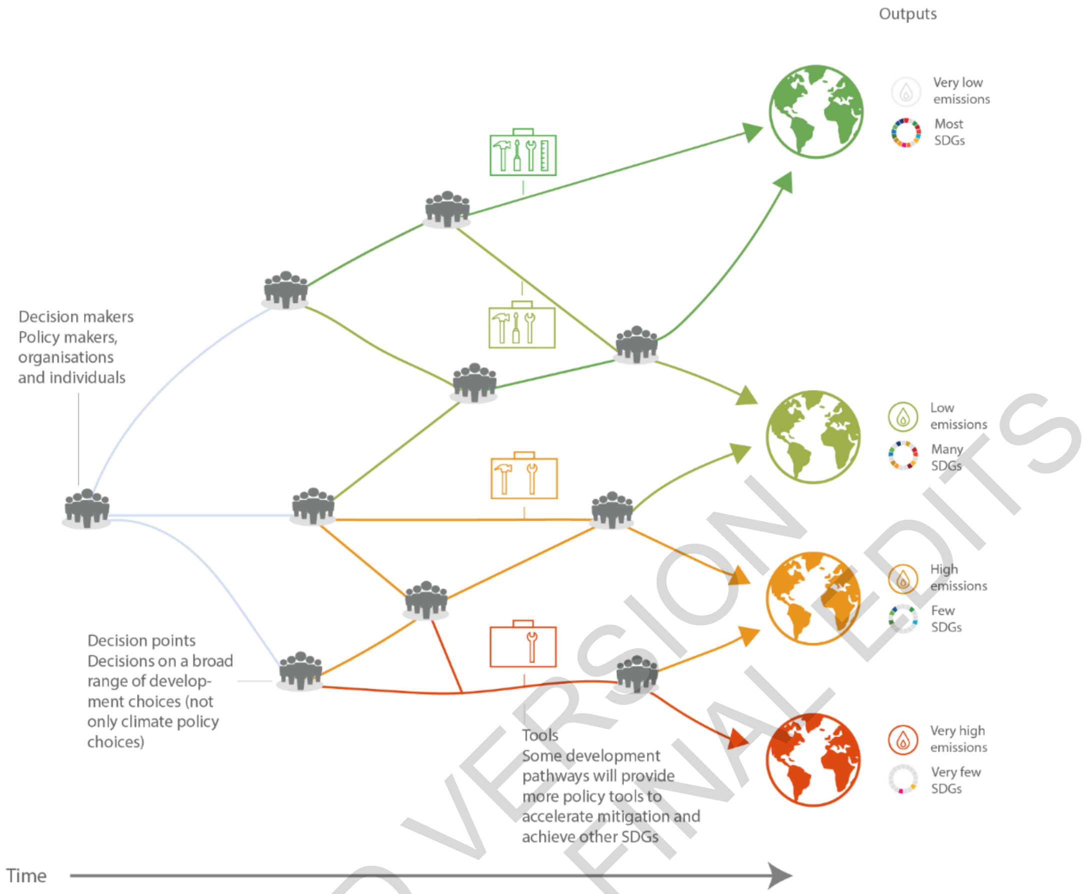

Figure 4.7 Shifting development pathways to increased sustainability: Choices by a wide range of actors at key decision points on development pathways can reduce barriers and provide more tools to accelerate mitigation and achieve other Sustainable Development Goals

4.3.1.3 Expanding the range of policies and other mitigative options

Shifting development pathways aims to influence the ultimate drivers of emissions (and development generally), such as the systemic and cultural determinants of consumption patterns, the political systems and power structures that govern decision making, the institutions and incentives that guide and constrain socio-technical innovation, and the norms and information platforms that shape knowledge and discourse, and culture, values and needs (Raskin et al. 2002). These ultimate drivers determine the mitigative capacity of a society.

Decision-makers might usefully consider a broader palette of policies and measures as part of an overall strategy to meet climate goals and other sustainable development goals (see 4.3.2; Table 4.12). This is consistent with the fact that mitigation is increasingly understood to be inseparable from broader developmental goals, which can be facilitated by policy coherence and integration with broader objectives and policies sectorally and societally. This is supported by other observations that mitigation measures based on conventional climate policy instruments, such as emissions taxes or permits, price incentives such as feed-in tariffs for low-carbon electricity generation, and fuel economy standards, and building codes, which aim to influence the proximate drivers of emissions alone will not achieve the long-term goals of the Paris Agreement (IPCC 2018a; Rogelj et al. 2016; UNEP 2018; Méjean et al.

2015). An approach of shifting development pathways to increased sustainability (SDPS) broadens the scope for mitigation.

4.3.1.4 An approach of SDPS helps manage trade-offs between mitigation and other SDGs.

Beyond removing structural obstacles to accelerated mitigation, broadening the approach to policies that facilitate shifts in development pathways also helps manage the potential tradeoffs between mitigation and other development objectives discussed in section 4.2.7.

Systematic studies of the 17 SDGs have found the interactions among them to be manifold and complex (Pradhan et al. 2017; Nilsson et al. 2016; Weitz et al. 2018; Fuso Nerini et al. 2019). Addressing them calls for interventions affecting fundamental, interconnected, structural features of global society (International Panel on Social Progress 2018; TWI2050 - The World in 2050 2018), such as to our physical infrastructure (e.g., energy, water, industrial, urban infrastructure) (Thacker et al. 2019; Adshead et al. 2019; Waage et al. 2015; Mansell et al. 2019; Chester 2019), our societal institutions (e.g., educational, public health, economic, innovation, and political institutions) (Sachs et al. 2019; Ostrom 2010; Kläy et al. 2015; Messner 2015), and behavioural and cultural tendencies (e.g., consumption patterns, conventional biases, discriminatory interpersonal and intergroup dynamics, and inequitable power structures) (Esquivel 2016; Sachs et al. 2019). These observations imply that attempt to address each SDG in isolation, or as independent technical challenges, would be insufficient, as would incremental, marginal changes. In contrast, effectively addressing the SDGs is likely to mean significant disruption of long-standing trends and transformative progress to shift development pathways to meet all the SDGs, including climate action, beyond incremental changes targeted at addressing mitigation objectives in isolation. In other words, mitigation conceived as incremental change is not enough. Transformational change has implications for equity in its multiple dimensions (Leach et al. 2018; Klinsky et al. 2017a; Steffen and Stafford Smith 2013) including just transitions (4.5).

Working Group II examines *climate resilient development pathways* – continuous processes that imply deep societal changes and/or transformation, so as to strengthen sustainable development, efforts to eradicate poverty and reduce inequalities while promoting fair and cross-scalar capacities for adaptation to global warming and reduction of GHG emissions in the atmosphere. Transformative action in the context of CRD specifically concerns leveraging change in the five dimensions of development (people, prosperity, partnership, peace, planet) (WGII chapter 18).

Section 4.3.2 provides more details on the way development pathways influence emissions and mitigative capacity. Section 4.3.3 provides examples of shifts in development pathways, as well as of policies that might facilitate those. Cross-Chapter Box 5 details the links between SDPS and sustainability.

4.3.2 Implications of development pathways for mitigation and mitigative capacity

4.3.2.1 Countries have different development priorities

At the global level, the SDGs adopted by all the United Nations Member States in 2015 are delineated with a view to end poverty, protect the planet and ensure that all people enjoy peace and prosperity by 2030. The 17 SDGs are integrated and imply that development must balance social, economic and environmental sustainability.

While all countries share the totality of the SDGs, development priorities differ across countries and over time. These priorities are strongly linked to local contexts, and depend on which dimensions of improvements in the well-being of people are considered the most urgent.

Development priorities are reflected in the decisions that actors within societies make, such as policy choices by governments and parliaments at all levels, votes over competing policy platforms by citizens, or selection of issues that non-state actors push for. Multiple objectives range from poverty eradication to providing energy access, addressing concerns of inequality, providing education, improving health, cleaning air and water, improving connectivity, sustaining growth and providing jobs, among others. For example, eradicating poverty and reducing inequality is a key development priority across many countries, such as Brazil (Grottera et al. 2017), Indonesia (Irfany and Klasen 2017), India (GoI, 2015), South Africa (Winkler 2018) and other low- and middle-income countries (Dorband et al. 2019). Reducing inequality relates not only to income, but also to other dimensions such as in access to energy services (Tait 2017), gender, education, racial and ethnic profiles (Andrijevic et al. 2020), and thereby assumes relevance in both developing and developed countries. The development priorities of many poor countries and communities with low capacities to adapt, has been focused more on reducing poverty, providing basic infrastructure, education and improving health, rather than on mitigation (Chimhowu et al. 2019).

4.3.2.2 The nature of national development plans is changing

Governments are increasingly resorting to the development of national plans to build institutions, resources, and risk/shock management capabilities to guide national development. The number of countries with a national development plan has more than doubled, from about 62 in 2006 (World Bank 2007) to 134 plans published between 2012 and 2018 (Chimhowu et al. 2019). The comeback of planning may be linked to increased consideration given to sustainability, which is by construction forward-looking and far ranging, and therefore requires state and civil society to prepare and implement plans at all levels of governance. Governments are increasingly engaging in the development and formulation of national plans in an organised, conscious and continual attempt to select the best available alternatives to achieve specific goals.

A systematic assessment of 107 national development plans and 10 country case studies provides useful insights regarding the type and content of the plans (Chimhowu et al. 2019). development plans are increasingly focusing on mobilising action across multiple actors and multiple dimensions to enhance resilience and improve the ability to undertake stronger mitigation actions. Various initiatives such as the World Summit for Children in 1990; the Heavily Indebted Poor Country initiative that started offering debt relief in exchange for commitments by beneficiary states to invest in health, education, nutrition and poverty reduction in 1996; and push towards Comprehensive Development Frameworks seem to have catalysed the development of national actions plans across countries to estimate, measure and track investments and progress towards SDGs.

The most recent development plans also tend to differ from the earlier ones in terms of their approach. Complexity science has over the years argued for new forms of planning based on contingency, behaviour change, adaptation and constant learning (Colander and Kupers 2016; Ramalingam, 2013), and new plans have increasingly focused on increasing resilience of individuals, organisations and systems (Hummelbrunner and Jones, 2013). Finally, alongside short-term (typically 5 year) plans with operational purpose, countries have also expressed visions of their development pathways over longer time horizons, via, e.g., Voluntary National Reviews submitted in the context of the UN High Level Political Forum on Sustainable Development.

National development plans are also increasingly more holistic in their approach, linking closely with SDGs and incorporating climate action in their agendas. For instance, the Low Carbon Development Initiative (LCDI), launched in 2017 by the Government of Indonesia, seeks to identify the development policies that can help Indonesia achieve multiple (social, economic, and environmental) goals simultaneously along with preserving and improving the country’s natural resources (Bappenas 2019).

Likewise, Nepal's Fifteenth five-year plan recognises the need for climate mitigation and adaptation and corresponding access to international finance and technologies. The plan suggests mobilization of foreign aid in the climate change domain in line with Nepal's priorities and its inclusion in the country's climate-friendly development programs as the key opportunities in this regard (Nepal 2020).

China's development plans have evolved over time from being largely growth oriented, and geared largely towards the objectives of addressing poverty, improving health, education and public well-being to also including modernisation of agriculture, industry and infrastructure, new forms of urbanisation and a clear intent of focusing on innovation and new drivers of development (Central Compilation & Translation Press 2016). China's 14th Five Year Plan not only seeks to promote high quality development in all aspects and focus on strengthening the economy in the global industrial chain, but also includes a vision of an 'ecological civilisation', which had been developed (CPC-CC 2015) and analysed earlier (He 2016; Xiao and Zhao 2017). It seeks to enhance China's climate pledge to peak CO_2 emissions by 2030 and achieve carbon neutrality by 2060 through more vigorous policies and measures. Development plans tie in multiple development priorities that evolve and broaden over time as societies develop, as exemplified inter alia by the history of development plans in India (Box 4.4).

START BOX 4.4 HERE

Box 4.4 India's national development plan

India's initial national development plans focused on improving the living standards of its people, increasing national income and food self-sufficiency. Accordingly, there was a thrust towards enhancing productivity of the agricultural and industrial sectors. While the main focus was on maintaining high economic growth and industrial productivity, poverty eradication, employment and inclusive growth remained important priorities. The National Action Plan on Climate Change with 8 Missions focusing on mitigation as well as adaptation was launched in 2008 integrating climate change considerations in planning and decision making (MoEF 2008). The 12th Five Year Plan (2012-17) also brought in a focus on sustainability and mentioned the need for faster, sustainable and inclusive growth. The National Institution for Transforming India (NITI Aayog) was set up in 2017 replacing the erstwhile Planning Commission, with a renewed focus towards bringing innovation, technology, enterprise and efficient management together at the core of policy formulation and implementation. However, while India has moved away from its Five-Year Plans, decision making is more dynamic, with a number of sector specific initiatives and targets focused on integrating sustainability dimensions through a series of policies and measures supporting resource efficiency, improved energy access, infrastructure development, low carbon options and building resilient communities, among other objectives (MoEFCCC 2021; MoEFCC 2018; GoI 2015). India's overall development pathway currently has a strong focus on achieving robust and inclusive growth to ensure balanced development across all regions and states and across sectors. There is a thrust on embracing new technologies while fostering innovation and upskilling, modernisation of agriculture, improving regional and inter-personal equity, bridging the gap between public and private sector performance, by focusing on efficient delivery of public services, rooting out corruption and black economy, formalising the economy and expanding the tax base, improving the ease of doing business, nursing the stressed commercial banking sector back to a healthy state, and stopping leakages through direct benefit transfers, among other measures (Government of India 2018; MoEFCCC 2021; GoI 2015).

END BOX 4.4 HERE

4.3.2.3 Development pathways shape emissions and capacities to mitigate

Analysis in the mitigation literature often frames mitigation policy as having development co-benefits, the main objective being climate stabilisation. This misses the point that development drives emissions, and not vice versa, and it is the overall development approach and policies that determine mitigation pathways (Munasinghe 2007). A large body of literature supports the fact that development pathways have direct and, just as importantly, indirect implications for GHG emissions (Nakicenovic et al. 2000; Winkler 2017b), through multiple channels, such as the nature of economic activity, spatial patterns of development, degree of inequality, and population growth.

Economic structure: Chapter 2 notes that overall, affluence (GDP per capita), economic growth and population growth have remained the main upward drivers of CO_2 emissions from fossil-fuel combustion in the past decade, with energy efficiency the main countervailing force (2.4) (Wang and Feng 2017; Lin and Liu 2015). A major component of the development pathway of a country is precisely the nature of the economic activities on which the country relies (e.g., agriculture and mining, heavy industry, services, high-tech products, etc.) as well as the way it articulates its economy with the rest of the World (e.g., export-led growth vs. import substitution strategies). Hence, the development pathway ultimately drives the underlying structure of the economy, and to a large degree the relationship between activity and GHG emissions.

At country level, however, the picture is more nuanced. Both India and China show signs of relative decoupling between GDP and emissions because of structural change (Chen et al. 2018a). Sumabat et al. (2016) indicate that economic growth had a negative impact on CO_2 emissions in Philippines. Baek and Gweisah (2013) find that CO_2 emissions tend to drop monotonously as incomes increased. Lantz and Feng (2006) also indicate that per capita GDP is not related to CO_2 emissions in Canada. Other studies point to an emerging consensus that the relationship between CO_2 emissions and economic indicators depends on the level of development of countries (Nguyen and Kakinaka 2019; Sharma 2011). While some literature indicates that absolute decoupling of economic growth and GHG emissions has occurred in some countries (Le Quéré et al. 2019), a larger systematic review found limited evidence of this (Haberl et al. 2020).

Looking ahead, choices about the nature of economic activities are expected to have significant implications for emissions. For example, a development pathway that focuses on enhancing economic growth based on manufacturing is likely to lead to very different challenges for mitigation compared to one that focuses on services-led growth. (Quéré et al. 2018) find that choices about whether or not to export offshore oil in Brazil will have significant implications for the country's GHG emissions. Similarly, in China, transforming industrial structure towards tertiary sectors (Kwok et al. 2018) and restructuring exports towards higher value-added products (Wu et al. 2019) are expected to have significant implications for GHG emissions.

Spatial patterns of development: Chapter 2 notes that rapid urbanisation in developing and transition countries leads to increased CO_2 emissions, the substantial migration of rural populations to urban areas in these countries being the main factor leading to increased levels of income and expenditure of new urban dwellers which in turn leads to increased personal carbon footprints and overall emissions (2.4). Urbanisation, and more broadly spatial patterns of development, are in turned driven to a large part by development choices, such as, inter alia, spatial provision of infrastructure and services, choices regarding the agriculture and forestry sector, land-use policies, support to regional/local development, among others (World Bank, 2009). For example, Dorin (2017) points out that if agriculture sectors in Africa and India follow the same development path that developed countries have followed in the past, namely increased labour productivity through enlargement and robotisation of farms, then unprecedented emigrations of rural workers towards cities or foreign countries will ensue, with large-scale social, economic and environmental consequences. Looking ahead, a development pathway that encourages concentrated influx of people to large urban centres will lead to very different energy and infrastructure consumption patterns than a pathway that prioritises the development of smaller, self-contained towns and cities.

Degree of inequality: Chapter 2 notes that while eradicating extreme poverty and providing universal access to modern energy services to poor populations across the globe has negligible implications for emissions growth, existing studies on the role of poverty and inequality as drivers of GHG emissions provide limited evidence that under certain contexts greater inequality can lead to a deterioration in environmental quality and may be associated with higher GHG emissions (2.4). In fact, factors affecting household consumption based emissions include household size, age, education attainment, employment status, urban vs rural location and housing stock (Druckman and Jackson 2015). There is evidence to indicate that at the household level, the increase in emissions from additional consumption of the lower income households could be larger than the reduction in emissions from the drop in consumption from the high income households (Sager 2019). Accordingly, as countries seek to fulfil the objective of reducing inequality, there are possibilities of higher increase in emissions (Sager 2019).

Since reducing inequality, as noted above, is globally one of the main development priorities, a large body of literature focuses on the compatibility of climate change mitigation and reduction in economic inequality (Berthe and Elie 2015; Grunewald et al. 2017; Hao et al. 2016; Wiedenhofer et al. 2017; Auffhammer and Wolfram 2014; Baek and Gweisah 2013). However, the use of narrow approaches or simple methods of studying the relationships of income inequality and emissions by looking at correlations, may miss important linkages. For example, the influence of inequality on social values such as status and civic mindedness and non-political interests that shape environmental policy can influence overall consumption and its environmental impacts (Berthe and Elie 2015). Moreover, inequalities may also be reflected in gender, education, racial and ethnic profiles and could accordingly be associated with the level of emissions and mitigation prospects (Andrijevic et al. 2020).

The Illustrative Mitigation Pathways (IMP) developed for this Report (Box 3.1 and section 3.2.5) provide another example of how development pathways influence mitigative capacity. Precisely, IMP1.5-SP (Shifting Pathways) and 1.5-Ren (Renewables) lead to the same long-term temperature, but differ in underlying socio-economic conditions. The former is based on Shared Socio-economic Pathway (SSP) 1 (sustainable development), whereas the latter is based on SSP 2 (middle of the road). Comparing 1.5-Ren to 1.5-SP can thus be interpreted as a numerical translation of trying the reach the same long-term temperature goal without and with shifting development pathways towards sustainability. Data shows that the global price of carbon necessary to remain on target is 40%-50% lower in the latter relative to the former, thus indicating that mitigation is cheaper with a shift in development pathway towards sustainability. Other cost indicators (e.g. consumption loss or GDP loss) tell the same story. Since both IMPs were computed using the same underlying model, the comparison is even more robust.

In sum, development pathways can lead to different emission levels and different capacities and opportunities to mitigate (*medium evidence, high agreement*). Thus, focusing on shifting development pathways can lead to larger systemic sustainability benefits.

4.3.2.4 Integrating mitigation considerations requires non-marginal shifts in development pathways

Concerns about mitigation are already being introduced in national development plans, as there is evidence that development strategies and pathways can be carefully designed so as to align towards multiple priorities and achieve greater synergistic benefits. For example, India's solar programme is a key element in its NDC that can in the long run, not only provide energy security and contribute to mitigation, but can simultaneously contribute to economic growth, improved energy access and additional employment opportunities, if appropriate policies and measures are carefully planned and implemented. However, the environmental implications of the transition need to be carefully examined with regard to the socio-economic implications in light of the potential of other alternatives like green hydrogen, nuclear or CCUS. Similarly, South Africa National Development Plan (2011) also integrates transition to low-carbon as part of the country development objectives (Box 4.5).

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Box 4.5 South Africa's National Development Plan

South Africa adopted its first National Development Plan (NDP) in 2011 (NPC 2011), the same year in which the country adopted climate policy (RSA 2011) and hosted COP17 in Durban. Chapter 5 of the NDP addresses environmental sustainability in the context of development planning, and specifically "an equitable transition to a low-carbon economy" (NPC 2011). The chapter refers explicitly to the need for a just transition, protecting the poor from impacts and any transitional costs from emissions-intensive to low-carbon. The plan proposes several mitigation measures, including a carbon budgeting approach, reference to Treasury's carbon tax, use of various low carbon options while maintaining energy security, and the integrated resource plan for electricity. The NDP refers to coal in several chapters, in some places suggesting additional investment (including new rail lines to transport coal and coal to liquids), in others decommissioning coal-fired power "*Procuring at least 20 000MW of renewable electricity by 2030, importing electricity from the region, decommissioning 11 000MW of ageing coal-fired power stations and stepping up investments in energy-efficiency*" (NPC 2011: p.46). Reference to environmental sustainability is not limited to chapter 5 – the introductory vision statement includes acknowledgement "*that each and every one of us is intimately and inextricably of this earth with its beauty and life-giving sources; that our lives on earth are both enriched and complicated by what we have contributed to its condition*" (NPC 2011: p. 21); and the overview of the plan includes a section on climate change, addressing both mitigation and adaptation.

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Looking ahead, given that different development pathways can lead to different levels of GHG emissions and to different capacities and opportunities to mitigate, there is increasing research on how to make development pathways more sustainable. Literature is also focusing on the need for a "new normal" as a system capable of achieving higher quality growth while addressing multiple development objectives by focusing on "innovative development pathways".

Literature suggests that if development pathways are to be changed to address the climate change problem, choices that would need to be made about development pathways would not be marginal (Stern and Professor 2009), and would require a new social contract to address a complex set of inter-linkages across sectors, classes and the whole economy (Winkler 2017b). Shifting development pathways necessitates planning in a holistic manner, rather than thinking about discrete and isolated activities and actions to undertake mitigation. Further, the necessary transformational changes can be positive if they are rooted in the development aspirations of the economy and society in which they take place (Dubash 2012; Jones et al. 2013), but they can also lead to carbon colonialism if the transformations are imposed by Northern donors or perceived as such.

Accordingly, influencing a societies' development pathways draws upon a broader range of policies and other efforts than narrowly influencing mitigation pathways, to be able to achieve the multiple objectives of reducing poverty, inequality and GHG emissions. The implications for employment, education, mobility, housing and many other development aspects must be integrated and new ways of looking at development pathways which are low carbon must be considered (Bataille et al. 2016b; Waisman et al. 2019). For instance, job creation and education are important elements that could play a key role in reducing inequality and poverty in countries like South Africa and India (Rao and Min 2018; Winkler et al. 2015) while these also open up broader opportunities for mitigation.

4.3.2.5 New tools are needed to pave and assess development pathways

Relative to the literature on mitigation pathways described in 4.2.5 and in 4.3.3, the literature on development pathways is limited. The climate research community has developed the Shared Socio-economic pathways (SSPs) that link several socio-economic drivers including equity in relation to welfare, resources, institutions, governance and climate mitigation policies in order to reflect many of the key development directions (O'Neill et al. 2014). In most modelling exercises however, development remains treated as an exogenous input. In addition, models may capture only some dimensions of development that are relevant for mitigation options, thereby not capturing distributional aspects and not allowing consistency checks with broader developmental goals (Valadkhani et al. 2016). Quantitative tools for assessing mitigation pathways could be more helpful if they could provide information on a broader range of development indicators, and could model substantively different alternative development paths, thereby providing information on which levers might shift development in a more sustainable direction.

Doing so requires new ways of thinking with interdisciplinary research and use of alternative frameworks and methods suited to deeper understanding of change agents, determinants of change and adaptive management among other issues (Winkler 2018). This includes, inter alia, being able to examine enabling conditions for shifting development pathways (see 4.4.1); re-evaluating the neo-classical assumptions within most models, both on the functioning of markets and on the behaviour of agents, to better address obstacles on the demand side, obstacles on the supply side and market distortions (Ekholm et al. 2013; Staub-Kaminski et al. 2014; Grubb et al. 2015) improving representation of issues related with uncertainty, innovation, inertia and irreversibility within the larger development contexts, including energy access and security ; improving the representation of social and human capital, and of social, technological and governance innovations (Pedde et al. 2019).

Tools have been developed in that direction, for example in the Mitigation Action Plans and Scenarios (MAPS) community (La Rovere et al. 2014b), but need to be further mainstreamed in the analysis. Back-casting is often a preferred modelling approach for assessment aiming to align national development goals with global climate goals like CO_2 stabilisation. Back-casting is a normative approach where modellers construct desirable futures and specify upfront targets and then find out possible pathways to attain these targets (IPCC et al. 2001). Use of approaches like back-casting are useful not only in incorporating the long term national development objectives in the models, but also evaluating conflicts and synergies more effectively (van der Voorn et al. 2020). In back casting, the long-term national development objectives remain the key benchmarks guiding the model dynamics and the global climate goal is interfaced to realise the co-benefits. The models then delineate the roadmap of national actions such that the national goals are achieved with a comprehensive understanding of the full costs and benefits of low carbon development (often including the costs of adaptation and impacts from residual climate change). Back-casting modelling exercises show that aligning development and climate actions could result in much lower 'social cost of carbon' (Shukla et al. 2008). Back-casting does not aim to produce blueprints. Rather, it indicates the relative feasibility and the social, environmental, and political implications of different development and climate futures on the assumption of a clear relationship between goal setting and policy planning (Dreborg 1996). Accordingly, back-casting exercises are well suited for preparing local specific roadmaps like for cities (Gomi et al. 2011, 2010).

4.3.3 Examples of shifts in development pathways and of supporting policies

As noted in 4.3.1, policy approaches that include a broader range of instruments and initiatives would impact more fundamentally on the actors, institutions and structures of societies and the dynamics among them, aiming to alter the underlying drivers of emissions, opening up a wider range of mitigation opportunities and potential in the process of achieving societal development goals. While the evolution of these drivers is subject to varied influences and complex interactions, there are policy measures by which decision-makers might influence them. Table 4.12 provides some examples of policy measures that can affect key drivers (shown in the row headings).

Table 4.12 Examples of policies that can help shift development pathways

Drivers	**Examples of policy measures**
Behaviour	• Progressive taxation • Ecological tax reform • Regulation of advertisement • Investment in public transit • Eco-labelling
Governance and institutions	• Campaign finance laws • Regulatory transparency • Commitment to multi-lateral environmental governance • Public investment in education and R&D • Public-service information initiatives • Public sector commitment to science-based decision-making • Anti-corruption policies
Innovation	• Investment in public education • Public sector R&D support • Fiscal incentives for private investments in public goods • International technology development and transfer initiatives
Finance and investment	• International investment treaties support common objectives • Litigation and Liability regulations • Reform of subsidies and other incentives not aligned with • Insurance sector and pension regulation • Green quantitative easing • Risk disclosure

Policies such as those listed in Table 4.12 are typically associated with broader objectives than GHG mitigation. They are generally conceived and implemented in the pursuit of overall societal development objectives, such as job creation, macro-economic stability, economic growth, and public health and welfare. However, they can have major influence on mitigative capacity, and hence can be seen as necessary tools if mitigation options are to be significantly broadened and accelerated (*medium evidence, medium agreement*). The example of the UK shows how accelerated mitigation through dietary changes require a wide set of efforts to shift underlying drivers of behaviour. In this case, multiple forces have interacted to lead to reduced meat consumption, including health attitudes, animal welfare concerns, and an increasing focus on climate and other environmental impacts of livestock production, along with corporate investment in market opportunities, and technological developments in meat alternatives (Box 5.5).

Other historic cases that are unrelated to recent mitigation efforts might be more appropriate examples of major socio-technical shifts that were largely driven by intentional, coherent intentional policy initiatives across numerous domains to meet multiple objectives. The modernization of agriculture in various national contexts fits such a mold. In the US, for example, major government investments in agricultural innovation through the creation of agricultural universities and support for research provided advances in the technological basis for modernization. A network of agricultural extension services accelerated the popularization and uptake of modern methods. Infrastructure investments in irrigation and drainage made production more viable, and investment in roadways and rail for transport supported market formation. Agricultural development banks made credit available, and government subsidies improved the profitability for farmers and agricultural corporations. Public campaigns were launched to modify food habits (Ferleger 2000).

Further examples of SDPS across many different systems and sectors are elaborated across this report. Concrete examples assessed in this Chapter include high employment and low emissions structural change, fiscal reforms for mitigation and social contract, combining housing policies to deliver both housing and transport mitigation, and change economic, social and spatial patterns of development of the agriculture sector provide the basis for sustained reductions in emissions from deforestation (4.4.1.7-4.4.1.10). These examples differ by context. Examples in other chapters include transformations in energy, urban, building, industrial, transport, and land-based systems, changes in behaviour and social practices, as well as transformational changes across whole economies and societies (Cross Chapter Box 5, 5.8, Box 6.2, 8.2, 8.3.1, 8.4, 9.8.1, 9.8.2, 10.4.1, Cross-Chapter Box 12}. These examples and others can be understood in the context of an explanation of the concept of SDPS, and how to shifting development pathways (Cross-Chapter Box 5).

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Cross-Chapter Box 5 Shifting development pathways to increase sustainability and broaden mitigation options

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1. What do we mean by development pathways?

In the present report, development pathways refer to patterns of development resulting from multiple decisions and choices made by many actors in the national and global contexts. Each society whether in the Global North or the Global South follows its own pattern of development (Figure 1.6). Development pathways can also be described at smaller scales (e.g., for regions or cities). By extension, the concept can also be applied to sectors and systems (e.g., the development pathway of the agricultural sector or of industrial systems).

2. Why do development pathways matter in a report about mitigation?

2a. Past development pathways determine both today's GHG emissions and the set of opportunities to reduce emissions

Development pathways drive GHG emissions for a large part (2.4, 2.5 and 2.6). For example, different social choices and policy packages with regard to land use and associated rents will result in human settlements with different spatial patterns, different types of housing markets and cultures, and different degrees of inclusiveness, and thus different demand for transport services and associated GHG emissions (8.3.1, 10.2.1).

There is compelling evidence to show that continuing along existing development pathways is unlikely to achieve rapid and deep emission reductions (robust evidence, medium agreement). For example, investments in long-lived infrastructure, including energy supply systems, could lock-in high emissions pathways and risk making deep decarbonisation and sustainable policies more difficult and expensive. Development pathways also determine the set of tools available to mitigate climate change (Figure 4.7). For example, the capacity of households to move closer to their workplace, in response to, e.g., a price signal on carbon and thus on gasoline, depends on rents, which themselves depend on the spatial patterns of development of human settlements (8.3.1). Said differently, mitigation costs depend on past development choices. Similarly, development pathways determine the enablers and levers available for adaptation (WGII, Chapter 18) and for achieving other SDGs.

In the absence of shifts in development pathways, conventional mitigation policy instruments (e.g., carbon tax, emission quotas, technological norms, etc.) may not be able to limit emissions to a degree sufficient for deep decarbonisation or only at very high economic and social costs.

Policies to shift development pathways, on the contrary, make mitigation policies more effective. For example, policies that prioritise non-car transit, or limit rents close to work places would make it easier for households to relocate in response to a price signal on transport, and thus makes the same degree of mitigation achievable at lower economic and social cost.

2b. Shifting development pathways broadens the scope for synergies between development objectives and mitigation

Second, societies pursue a variety of development objectives, of which protecting the Earth's climate is part. The SDGs provide a global mapping of these goals. Absent climate mitigation, our collective ability to achieve the SDGs in 2030 and to sustain them beyond 2030 is likely to be compromised, even if adaptation measures are put in place (WGII).

There are many instances in which reducing GHG emissions and moving towards the achievement of other development objectives can go hand in hand, in the near-, mid- and long-term (3.7, 6.7.7, 7.6.5, 8.2, 9.8, 10.1.1, 11.5.3, 17.3) (Figures 3.40, 12.1). For example, transitions from coal-based power to lower-emissions electricity generation technologies and from Internal Combustion Engine to lower-carbon transport has large mitigation potential and direct benefits for health through reduction in local air pollution (Box 6.2, 10.4.1). Energy efficiency in buildings and energy poverty alleviation through improved access to clean fuels also delivers significant health benefits (9.8.1 and 9.8.2).

Careful design of mitigation policies is critical to achieving these synergies (13.8). Integrated policies can support the creation of synergies between climate change goals and other SDGs. For example, when measures promoting walkable urban areas are combined with electrification and clean renewable energy, there are several co-benefits to be attained (5.2, Figure SPM.8). These include reduced pressures on agricultural land from reduced urban growth, health co-benefits from cleaner air and benefits from enhanced mobility (8.2; 8.4; 4.4.1.9).

Policy design can also manage trade-offs, for example through policy measures as part of just transitions (17.4). However, even with good policy design, decisions about mitigation actions, and the timing and scale thereof, may entail trade-offs with the achievement of other national development objectives in the near-, mid- and long-term. In the near-term, for example, regulations may ban vehicles from city centres to reduce congestion and local air pollution, but reduce mobility and choice. Increasing green spaces within cities without caps on housing prices may involve trade-offs with affordable housing and push low income residents outside the city (8.2.2). In the mid- and long-term, large-scale deployment of biomass energy raises concerns about food security and biodiversity conservation (3.7.1, 3.7.5, 7.4.4, 9.8.1, 12.5.2, 12.5.3). Conflicts between mitigation and other development objectives can act as an impediment to climate action (13.8). Climate change is the result of decades of unsustainable energy production, land-use, production and consumption patterns, as well as governance arrangements and political economic institutions that lock in resource-intensive development patterns (*robust evidence, high agreement*). Reframing development objectives and shifting development pathways towards sustainability can help transform these patterns and practices, allowing space for transitions transforming unsustainable systems (*medium evidence, high agreement*) (Chapter 17 Executive Summary).

Prioritising is one way to manage trade-offs, addressing some national development objectives earlier than others. Another way is to adopt policy packages aimed at shifting development pathways towards sustainability as they expand the range of tools available to simultaneously achieve multiple development objectives, including mitigation. In the city example of section 2a, a carbon tax alone would run counter to other development objectives if it made suburban households locked into high emissions transport modes poorer or if it restricted mobility choices, in particular for low- and middle-income households. Policy packages combining affordable housing and provision of safe low-carbon mobility could both facilitate equitable access to housing (a major development objective in many countries) and make it easier to mitigate by shifting the urban development pathway.

Similarly, a fundamental shift in the service provision that helps reduce energy demand (Chapter 5), driven by targeted policies, investment and enabling socio-cultural and behavioural change, would reduce pressure on supply side mitigation need, hence limiting pressure on water and food and the achievement of associated SDGs. Some studies assume Western European lifestyle as a reference for the global North and an improvement in the living standard for the Global South to reduce energy demand and emissions (e.g., (Grubler et al. 2018)), while others explore a transformative change in the global North to achieve a decent living standard for all (Millward-Hopkins et al. 2020; Bertram et al. 2018) (3.7.8). For example, in the UK, interaction between multiple behavioural, socio-cultural, and corporate drivers including NGO campaigns, social movements and product innovations resulted in an observed decline in meat consumption (5.4, 5.6.4).

3. What does shifting development pathways towards sustainability entail?

Shifting development pathways towards sustainability implies making transformative changes that disrupt existing developmental trends. Such choices would not be marginal (Stern and Professor 2009), but include technology adoption, infrastructure availability and use, and socio-behavioural factors (Chapter 5).

These include creating new infrastructure, sustainable supply chains, institutional capacities for evidence-based and integrated decision-making, financial alignment towards low-carbon socially responsible investments, just transitions and shifts in behaviour and norms to support shifts away from fossil-fuel consumption (Green and Denniss 2018). Adopting multi-level governance modes, tackling corruption where it inhibits shifts to sustainability, and improving social and political trust are also key for aligning and supporting long-term environmentally just policies and processes.

Shifting development pathways entails fundamental changes in energy, urban, building, industrial, transport, and land-based systems. It also requires changes in behaviour and social practices. Overcoming inertia and locked-in practices may face considerable opposition (5.4.5) (Geels et al. 2017). The durability of carbon intensive transport modes and electricity generating infrastructures increase the risk of lock-in to high emissions pathways, as these comprise not just consumer practices, but sunk costs in infrastructure, supporting institutions and rules (Seto et al. 2016; Mattioli et al. 2020). Shifting investments towards low-GHG solutions requires a combination of conducive public policies, attractive investment opportunities, as well as the availability of financing to enable such a transition (15.3).

4. How to shift development pathways?

Shifting development paths is complex. If history is any guide, practices that can easily supplant existing systems and are clearly profitable move fastest (Griliches 1957). Changes that involve 'dissimilar, unfamiliar and more complex science-based components' take more time, acceptance and legitimation and involve complex social learning (Conley and Udry 2010), even when they promise large gains (Pezzoni et al. 2019).

Yet despite the complexities of the interactions that result in patterns of development, history also shows that societies can influence the direction of development pathways based on choices made by decision-makers, citizens, the private sector and social stakeholders. For example, fundamentally different responses to the first oil shock shifted then-comparable economies on to different energy sector development and economic pathways in the 1970s and 80s (Sathaye et al. 2009). More recent examples have shown evidence of voluntary transitions for e.g., advanced lighting in Sweden, improved cook-stoves in China, liquefied petroleum gas stoves in Indonesia or ethanol vehicles in Brazil (Sovacool 2016).

There is no one-size-fits-all recipe for shifting development pathways. However, the following insights can be drawn from past experience and scenarios of possible future development pathways (4.4.1). For example, policies making inner-urban neighbourhoods more accessible and affordable reduce transport costs for low- and middle-income households, and also reduce transport emissions (4.4.1.9). Shifts in development pathways result from both sustained political interventions and bottom-up changes in public opinion. No single sector or policy action is enough to achieve this. Coordinated policy mixes would need to coordinate multiple actors – i.e., individuals, groups and collectives, corporate actors, institutions and infrastructure actors – to deepen decarbonisation and shift pathways towards sustainability (Pettifor 2020). One example was the LPG Subsidy ("Zero Kero") Program in Indonesia which harnessed creative policy design to shift to cleaner energy by overcoming existing private interests. The objective of decreasing fiscal expenditures on domestic kerosene subsidies by replacing it with LPG was achieved by harnessing distribution networks of existing providers supported by government subsidized provision of equipment and subsidized pricing (Cross-Chapter Box 9).

Shifts in one country may spill over to other countries. Collective action by individuals as part of formal social movements or informal lifestyle changes underpins system change (5.2.3, 5.4.1, 5.4.5.3, 13.5).

Sectoral transitions that aspire to shift development pathways often have multiple objectives, and deploy a diverse mix or package of policies and institutional measures (Figure 13.6). Context specific governance conditions can significantly enable or disable sectoral transitions, and play a determinative role in whether a sectoral transition leads to a shift in development pathway. For example, if implemented policies to tackle fuel poverty target the most socially vulnerable households, this can help address barriers poor households face in undertaking building retrofits. In the EU-28, it has been shown that accelerated energy efficiency policies coupled with strong social policies targeting the most vulnerable households, can help reduce the energy demand in residential sector, and deliver additional co-benefits of avoided premature deaths and reduced health impacts (9.8.2).

Literature suggests that through equitable resource distribution, high levels of human development can be provided at moderate energy and carbon levels by changing consumption patterns and redirecting systems in the direction of more sustainable resource use, suggesting that a special effort can be made in the near term for those on higher incomes who account for a disproportionate fraction of global emissions (Millward-Hopkins et al. 2020; Hickel et al. 2021) (5.2.2, Figure 5.14).

The necessary transformational changes are likely to be more acceptable if rooted in the development aspirations of the economy and society within which they take place (Jones et al. 2013; Dubash 2012) and may enable a new social contract to address a complex set of inter-linkages across sectors, classes and the whole economy (Fleurbaey et al. 2018).

Taking advantage of windows of opportunity and disruptions to mindsets and socio-technical systems could advance deeper transformations. These might include the globally declining costs of renewables (Fig.1.7, 2.2.5, Box 16.2), emerging social norms for climate mitigation (Green and Denniss 2018), or the COVID-19 pandemic, all of which might be harnessed to centre political action on protecting human and planetary health (Büchs et al. 2020), but if not handled carefully could also risk to undermine the support for transformation.

5. How can shifts in development pathways be implemented by actors in different contexts?

Shifting development pathways to increased sustainability is a shared aspiration. Yet since countries differ in starting points (e.g., social, economic, cultural, political) and history, they have different urgent needs in terms of facilitating the economic, social, and environmental dimensions of sustainable development and, therefore, give different priorities (4.3.2, 17.4). The appropriate set of policies to shift development pathways thus depends on national circumstances and capacities.

In some developed countries and communities, affluence leads to high levels of consumption and emissions across sectors (Wiedmann et al. 2020; Mazur and Rosa 1974). For some countries, reducing consumption can reduce emissions without compromising on wellbeing. However, some developing countries still face the challenge of escaping “middle-income traps” (Agénor and Canuto 2015), as labour-saving technological change and globalisation have limited options to develop via the manufacturing sector (Altenburg and Rodrik 2017). In least developed countries, infrastructure, industry, and public services are still being established, posing both a challenge to financial support to deploy technologies, and large opportunities to support accelerating low-to-zero carbon options (especially in terms of efficient and sufficient provision, (Millward-Hopkins et al. 2020)). Availability of capital, or lack thereof, is a critical discriminant across countries and requires international cooperation (15.2.2).

Shifting development pathways towards sustainability needs to be supported by global partnerships to strengthen suitable capacity, technological innovation (16.6), and financial flows (14.4.1, 15.2.4). The international community can play a particularly key role by helping ensure the necessary broad participation in climate-mitigation efforts, including by countries at different development levels, through sustained support for policies and partnerships that support shifting development pathways towards sustainability while promoting equity and being mindful of different transition capacities (4.3.2, 16.5, 16.6, 14.4, 17.4).

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In sum, development pathways unfold over time in response to complex dynamics among various drivers and diverse actors with varying interests and motivations (*high agreement, robust evidence*). The way countries develop determines the nature and degree of the obstacles to accelerating mitigation and achieving other sustainable development objectives (*medium-robust evidence, medium agreement*). Meeting ambitious mitigation and development goals cannot be achieved through incremental change (*robust evidence, medium agreement*). Shifting development pathways thus involves designing and implementing policies where possible to intentionally enhance enabling conditions and reduce obstacles to desired outcomes (*medium evidence, medium agreement*).

Section 4.4 elaborates mechanisms through which societies can develop and implement policies to substantially shift development pathways toward securing shared societal objectives. Such policies entail overcoming obstacles (see 4.2.7) by means of favourable enabling conditions: governance and institutions, behaviour, innovation, policy and finance. These enabling conditions are amenable to intentional change – to greater or lesser degrees and over longer or shorter time scales – based on a range of possible measures and processes (see section 4.4).

4.4 How to shift development pathways and accelerate the pace and scale of mitigation

4.4.1 Approaches, enabling conditions and examples

4.4.1.1 Framing the problem

What have we learned so far? As highlighted above, despite 30 years of UNFCCC and growing contributions by non-state actors, the emissions gap keeps growing (4.2.2 and 4.2.3). Mitigation conceived as incremental change is not enough. Meeting ambitious mitigation goals entails rapid, non-marginal changes in production and consumption patterns (4.2.4 and 4.2.5). Taking another approach, we have seen in section 4.3 that shifting development pathways broadens the scope for mitigation (4.3.1, 4.3.2) and offers more opportunities than mitigation alone to combine mitigation with the realisation of other SDGs (4.3.1, Cross-Chapter Box 5).

A practical way forward is to combine shifting development pathways and accelerating mitigation (*medium evidence, high agreement*). This means introducing multi-objective policy packages and sequences with climate and development components that both target mitigation directly and create the conditions for shifts in development pathways that will help accelerate further mitigation down the line, and meet other development objectives. Since development pathways result from a myriad of decisions from multiple actors (4.3.1), coordination across countries and with non-state actors is essential.

The literature does not provide a handbook on how to accomplish the above. However, analysis of past experience as well as understanding of how societies function yield insights that the present section aims at presenting. Human history has seen multiple transformation of economies due to path-breaking innovations (Michaelowa et al. 2018), like the transformation of the energy system from traditional biomass to fossil fuels or from steam to electricity (Fouquet 2010, 2016a; Sovacool 2016). Fouquet (2016b) and Smil (2016) argue that even the most rapid global transformations have taken several decades. Enabling transformational change implies to create now the conditions that lead to that transformation (Díaz et al. 2019). The starting point is that there is no single factor determining such a transformation. Rather a range of enabling conditions can combine in a co-evolutionary process. Amongst the conditions that have been cited in the literature are higher levels of innovation, multilevel governance, transformative policy regimes or profound behavioural transformation (IPCC 2018a; Geels et al. 2018; Kriegler et al. 2018; Rockström et al. 2017). It might be possible to put in place some of the above conditions rapidly, while others may take longer, thereby requiring an early start.

The present chapter uses the set of enabling conditions identified in the IPCC SR1.5 report, namely policy, governance and institutional capacity, finance, behaviour and lifestyles and innovation and technology (de Coninck et al. 2018). As Figure 4.8 illustrates, *public policies* are required to foster both accelerating mitigation and shifting development pathways. They are also vital to guide and provide the other enabling conditions (cf. Table 4.12). Improved governance and enhanced institutional capacity facilitate the adoption of policies that accelerate mitigation and shift development pathways, with the potential to achieve multiple mitigation and development objectives. Finance is required both to accelerate mitigation and to shift development pathways. Chapter 15 argues that near-term actions to shift the financial system over the next decade (2021-2030) are critically important and feasible, and that the immediate post-COVID recovery opens up opportunities to scale up financing from billions to trillions (15.6.7) (Mawdsley 2018). As discussed in section 4.2.5, accelerated mitigation pathways encompass both rapid deployment of new technologies such as CCS or electric vehicles, as well as changes in consumption patterns: rapid deployment of mitigation *technology* and *behaviour change* are thus two enabling conditions to accelerated mitigation. Dynamics of deployment of technologies are relatively well known, pointing to specific, short-term action to accelerate innovation and deployment (Cross-Chapter Box 12), whereas dynamics of collective behaviour change is less well understood. Arguably, the latter also facilitates shifting development pathways.

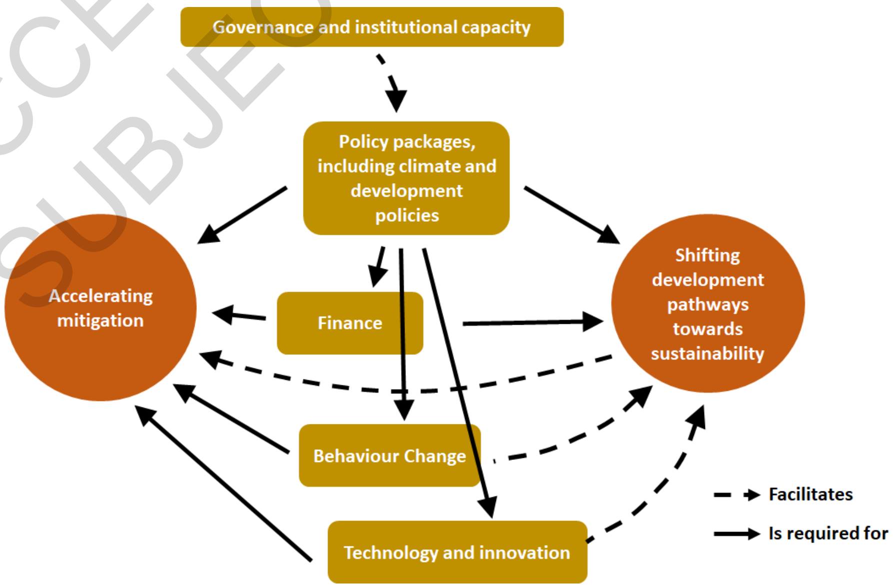

Figure 4.8 Enabling conditions for accelerating mitigation and shifting development pathways towards sustainability

Individual enabling conditions are discussed at length in Chapter 5 (behaviour change), 13 (policies, governance and institutional capacity), 15 (Finance) and 16 (Innovation). The purpose of the discussion below is to draw operational implications from these chapters for action, taking into account the focus of the present Chapter on action at the national level in the near- and mid-term, and its special emphasis on shifting development pathways in addition to accelerated mitigation.

The rest of the section is organised as follows. Policy packages that combine climate and development policies are first discussed (4.4.1.2). The next sections are dedicated to the conditions that facilitate shifts in development pathways and accelerated mitigation: governance and institutions (4.4.1.3), financial resources (4.4.1.4), behaviour change (4.4.1.5) and innovation (4.4.1.6). Four examples of how climate and development policies can be combined to shift pathways and accelerate mitigation are then presented (4.4.1.7, 4.4.1.8, 4.4.1.9 and 4.4.1.10). Section 4.4.2 focuses specifically on how shifts in development pathways can deliver both mitigation and adaptation. Finally, 4.4.3 discusses risks and uncertainties associated with combining shifting development pathways and accelerating mitigation.

4.4.1.2 Policy packages that include climate and development policies

Although many transformations in the past have been driven by the emergence and diffusion of an innovative technology, policy intervention was frequent, especially in the more rapid ones (Grubb et al. 2021; Michaelowa et al. 2018). Likewise, it is not expected that spontaneous behaviour change or market evolution alone yield the type of transformations outlined in the accelerated mitigation pathways described in 4.2.5, or in the shifts in development pathways described in 4.3.3. On the contrary, stringent temperature targets imply bold policies in the short term (Rockström et al. 2017; Kriegler et al. 2018) to enforce effective existing policy instruments and regulations, as well as to reform or remove harmful existing policies and subsidies (Díaz et al. 2019).

Policy integration, addressing multiple objectives, is an essential component of shifting development pathways and accelerating mitigation (*robust evidence, high agreement*). A shift in development pathways that fosters accelerated mitigation may best be achieved through integrated actions that comprise policies in support of the broader SDG agenda, based on country-specific priorities (4.3.2, 13.8, 13.9). These may include for example, fiscal policies, or integrating industrial (Nilsson et al. 2021) and energy policies (Fragkos et al. 2021) with climate policies. Similarly, sectoral transitions that aspire to shifting development pathways towards sustainability often have multiple objectives, and deploy a diverse mix or package of policies and institutional measures (Cross-Chapter Box 5).

Because low-carbon transitions are political processes, analyses are needed *of* policy as well as *for* policy (13.6). Political scientists have developed a number of theoretical models that both *explain* policy-making processes and provide useful insights for *influencing* those processes. Case studies of successes and failures in sustainable development and mitigation offer equally important insights. Both theoretical and empirical analysis reinforce the argument that single policy instruments are not sufficient (*robust evidence, high agreement*). Policymakers might rather mobilise a range of policies, such as financial instruments (taxes, subsidies, grants, loans), regulatory instruments (standards, laws, performance targets) and processual instruments (demonstration projects, network management, public debates, consultations, foresight exercises, roadmaps) (Voß et al. 2007). Policies can be designed to focus on limiting or phasing out high-carbon technology. The appropriate mix is likely to vary between countries and domains, depending on political cultures and stakeholder configurations (Rogge and Reichardt 2016), but is likely to include a combination of: a) standards, nudges and information to encourage low-carbon technology adoption and behavioural change; b) economic incentives to reward low carbon investments; c) supply-side policy instruments including for fossil fuel production (to complement demand-side climate policies) and d) innovation support and strategic investment to encourage systemic change (Grubb 2014). These approaches can be mutually reinforcing. For example, carbon pricing can incentivise low carbon innovation, while targeted support for emerging niche technologies can make them more competitive encourage their diffusion and ultimately facilitate a higher level of carbon pricing. Similarly, the success of feed-in tariffs in Germany only worked as well as it did because it formed part of a broader policy mix including "supply-push" mechanisms such as subsidies for research and "systemic measures" such as collaborative research projects and systems of knowledge exchange (Rogge et al. 2015).

4.4.1.3 Governance and institutional capacity

Governance for climate mitigation and shifting development pathways is enhanced when tailored to national and local contexts. Improved institutions and governance enable ambitious climate action and help bridge implementation gaps (*medium evidence, high agreement*). Improving institutions involve a broad range of stakeholders and multiple regional and temporal scales. It necessitates a credible and trusted process for reconciling perspectives and balancing potential side-effects, managing winners and losers and adopting compensatory measures to ensure an inclusive and just transition (Newell and Mulvaney 2013; Miller and Richter 2014; Diffenbaugh and Burke 2019; Gambhir et al. 2018), managing the risk of inequitable or non-representative power dynamics and avoiding regulatory capture by special interests (Helsinki Design Lab 2014; Kahane 2019; Boulle et al. 2015).

Long experience of political management of change demonstrates that managing such risks is not easy, and requires sufficiently strong and competent institutions (Stiglitz 1998). For example, shift away from fossil fuel-based energy economy could significantly disrupt the status quo, leading to a stranding of financial and capital assets and shifting of political-economic power. Ensuring the decision-making process is not unduly influenced by actors with much to lose is key to managing a transformation. Effective governance, as noted in Chapter 13, requires establishing strategic direction, coordination of policy responses, and mediation among divergent interests. Among varieties of climate governance, which institutions emerge is path-dependent, based on the interplay of national political institutions, international drivers, and bureaucratic structures (Dubash 2021). Focused national climate institutions to address these challenges are more likely to emerge, persist and be effective when they are consistent with a framing of climate change that has broad national political support (*medium evidence, medium agreement*) (4.5, 13.2, 13.5).

Innovative governance approaches can help meet these challenges (Clark et al. 2018; Díaz et al. 2019). *Enabling multilevel governance*—i.e., better alignment across governance scales—and coordination of international organisations and national governments can help accelerate a transition to sustainable development and deep decarbonisation (Tait and Euston-Brown 2017; Michaelowa and Michaelowa 2017; Ringel 2017; Revi 2017; Cheshmehzangi 2016; IPCC 2018a). *Participatory and inclusive governance*—partnerships between state and non-state actors—, and concerted effort across different stakeholders are crucial in supporting acceleration (Roberts 2016; Hering et al. 2014; Figueres et al. 2017; Leal Filho et al. 2018; Burch et al. 2014; Lee et al. 2018; Clark et al. 2018). So do *partnerships through transnational climate governance initiatives*, which coordinate nation-states and non-state actors on an international scale (Hsu et al. 2018). Although they are unlikely to close the gap of the insufficient mitigation effort of national governments (Michaelowa and Michaelowa 2017) (4.2.3), they help building confidence in governments concerning climate policy and push for more ambitious national goals (UNEP 2018b).

Meeting these challenges also requires enhanced institutional capacity and enhanced institutional mechanisms to strengthen the coordination between multiple actors, improve complementarities and synergies between multiple objectives (Rasul 2016; Ringel 2017; Liu et al. 2018) and pursue climate action and other development objectives in an integrated and coherent way (Rogelj et al. 2018b; Von Stechow et al. 2016; Fuso Nerini et al. 2019; Roy et al. 2018; McCollum et al. 2018), particularly in developing countries (Adenle et al. 2017; Rosenbloom 2017). Institutional capacities to be strengthened include vertical collaboration and interaction within Nation-States and horizontal collaboration (e.g., transnational city networks) for the development and implementation of plans, regulations and policies. More specifically capacities include: capacity for knowledge harnessing and integration (from multiple perspectives); for integrated policy design and implementation (Scott 2017); for long-term planning (Lecocq et al. 2021) for monitoring and review process; for coordinating multi-actor processes to create synergies and avoid trade-offs. As a result, institutions that enable and improve human capacities and capabilities are a major driver of transformation. To this extent, promoting education, health care and social safety, also are instrumental to undertake climate change mitigation and cope with environmental problems (Winkler et al. 2007; Sachs et al. 2019). Given that strengthening institutions may be a long term endeavour, it needs attention in the near-term.

4.4.1.4 Channelling financial resources

Accelerated mitigation and shifting development pathways necessitate both re-directing existing financial flows from high- to low-emissions technologies and systems and providing additional resources (*robust evidence, high agreement*). An example is changes in investments from fossil fuels to renewable energy, with pressures to disinvest in the former while increasing levels of 'green finance' (6.7.4, 15.5). While some lower-carbon technologies have become competitive (1.4.3, 2.5), support remains needed for the low-emissions options have higher costs per unit of service provided than high-emission ones. Lack of financial resources is identified as a major barrier to the implementation of accelerated mitigation and of shifts in development pathways. Overcoming this obstacle has two major components. One relates to private capital. The other to public finance.

There is substantial amount of research on the redirection of private financial flows towards low-carbon investment and the role of financial regulators and central banks, as detailed in Chapter 15. Financial systems are an indispensable element of a systemic transition (Fankhauser et al. 2016; Naidoo 2020). Policy frameworks can re-direct financial resources towards low-emission assets and services (UNEP 2015), mainstreaming climate finance within financial and banking system regulation, and reducing transaction costs for bankable mitigation technology projects (Mundaca et al. 2013; Brunner and Enting 2014; Yeo 2019). Shifts in the financial system to finance climate mitigation and other SDGs can be achieved by aligning incentives and investments with multiple objectives (UNEP Inquiry 2016).

Different approaches have been explored to improve such alignment (15.6), from national credit policies to directly green mainstream financial regulations (e.g., through modifications in the Basel rules for banks). For all approaches, an essential precondition is to assess and monitor the contribution of financial flows to climate and sustainability goals, with better metrics that clearly link with financial activity (Chenet et al. 2019). Enabling the alignment of investment decision-making with achieving climate and broader sustainability goals includes acknowledgment and disclosure of climate-change related risk and of risks associated with mitigation in financial portfolios. Current disclosures remain far from the scale the markets need to channel investment to sustainable and resilient solutions (UNEP - Finance Initiative 2020; Clark et al. 2018; Task Force on Climate-Related Financial Disclosures 2019; IPCC 2018b). Disclosure, however, is not enough (Ameli et al. 2020). In addition, climate targets can be translated into investment roadmaps and financing needs for financial institutions, both at national and international level. Financing needs are usable for financial institutions, to inform portfolio allocation decisions and financing priorities (Chenet et al. 2019). At the international level, for example, technology roadmaps for key sectors can be translated into investment roadmaps and financing needs, as shown by existing experiences in energy and industrial sectors (Chenet et al. 2019; WBSCD 2018; International Energy Agency 2015)

The transition from traditional public climate finance interventions to the market-based support of climate mitigation (Bodnar et al. 2018) demands innovative forms of financial cooperation and innovative financing mechanisms to help de-risk low-emission investments and support new business models. These financial innovations may involve sub-national actors like cities and regional governments in raising finance to achieve their commitments (Cartwright 2015; CCFLA 2017). Moreover, public-private partnerships have proved to be an important vehicle for financing investments to meet the SDGs, including economic instruments for financing conservation (Sovacool 2013; Díaz et al. 2019).

Overall, early action is needed to overcome barriers and to adjust the existing i..ncentive system to align national development strategies with climate and sustainable development goals in the medium-term. Steckel et al. (2017) conclude that climate finance could become a central pillar of sustainable development by reconciling the global goal of cost-efficient mitigation with national policy priorities. Without a more rapid, scaled redeployment of financing, in development trajectories that hinder the realisation of the global goals will be locked in (Zadek and Robins 2016). Investment might be designed to avoid trading off the Paris goals against other SDGs, as well as those that simultaneously reduce poverty, inequality, and emissions (Fuso Nerini et al. 2019).

At the national level, it is also essential to create public fiscal space for actions promoting the SDG agenda and thereby broadening the scope of mitigation (*medium evidence, medium agreement*). To do so, pricing carbon—either through tax payments based on the level of emissions or cap-and-trade systems that limit total allowable emissions—is an efficient means of discouraging carbon emissions throughout an economy (both in consumption and production) while simultaneously encouraging a switch to non-carbon energy sources and generating revenues for prioritised actions (13.6.3). Regarding to levels, the High-Level Commission on Carbon Prices concluded that "*carbon-price level consistent with achieving the Paris temperature target is at least USD40–80/tCO_2 by 2020 and USD50–100/tCO_2 by 2030, provided a supportive policy environment is in place*" (CPLC 2017; Wall Street Journal 2019). National level models yield median carbon values of carbon values of 733 USD/tCO_2 in 2050 along accelerated mitigation pathways (4.2.6), while global models find a median value of 578 USD/tCO_2 for pathways that reach net zero CO_2 between 2045 and 2055 [interquartile range 405-708] (3.6.1).

Carbon pricing, however, is designed to reduce its fiscal base. Fiscal space may therefore also need to stem from other sources, although fiscal reforms are complex endeavours (4.4.1.8). For countries at lower income levels, foreign aid can make an important contribution to the same agenda (Kharas and McArthur 2019).It may also be noted that, according to estimates at the global level, military spending amounted to USD1.748 trillion in 2012 (the last year with data), a figure that corresponded to 2.3 percent of GDP, 55 percent of government spending in education, and was 13 times the level of net ODA (World Bank 2020; SIPRI 2020). Given this, moderate reductions in military spending (which may involve conflict resolution and cross-country agreements on arms limitations) could free up considerable resources for the SDG agenda, both in the countries that reduce spending and in the form of ODA. The resolution of conflicts within and between countries before they become violent would also reduce the need for public and private spending repairing human and physical damage. The fact that civil wars are common in the countries that face the severest SDG challenges underscores the importance of this issue (Collier 2007 pp.17-37).

4.4.1.5 Changing behaviour and lifestyles

Changes in behaviour and lifestyles are important to accelerated mitigation. Most global mitigation pathways in line with likely below 2°C and 1.5°C temperature limits assume substantial behavioural and societal change and low-c arbon lifestyles (Luderer et al. 2018a; de Coninck et al. 2018; IPCC 2018a) (See also 3.3, and Table 4.9 and Figure 4.3 in IPCC SR 1.5). Chapter 5 concludes that behavioural changes within transition pathways offer Gigaton-scale CO_2 savings potential at the global level, an often overlooked strategy in traditional mitigation scenarios.

Individual motivation and capacity are impacted by different factors that go beyond traditional social, demographic and economic predictors. However, it is unclear to what extent behavioural factors (i.e., cognitive, motivational and contextual aspects) are taken into account in policy design (Mundaca et al. 2019; Dubois et al. 2019). In fact, while economic policies play a significant role in influencing people's decisions and behaviour, many drivers of human behaviour and values work largely outside the market system (Díaz et al. 2019; Winkler et al. 2015) as actors in society, particularly individuals, do not respond in an economically 'rational' manner based on perfect-information cost-benefit analyses (Shiller 2019; Runge 1984). Rather, compelling narratives can drive individuals to adopt new norms and policies. And norms can be more quickly and more robustly shifted by proposing and framing policies designed with awareness of how framings interact with individual cognitive tendencies (van der Linden et al. 2015). Transformative policies are thus much more likely to be successfully adopted and lead to long-term behavioural change if designed in accordance with principles of cognitive psychology (van der Linden et al. 2015), and with the deep understanding of decision-making offered by behavioural science (UNEP 2017b). Similarly, given that present bias—being motivated by costs and benefits that take effect immediately than those delivered later—significantly shapes behaviour, schemes that bring forward distant costs into the present or that upfront incentives have proved to be more effective (Zauberman et al. 2009; van den Broek et al. 2017; Safarzyńska 2018). Overall, transformational strategies that align mitigation with subjective life satisfaction, and build societal support by positive discourses about economic, social, and cultural benefits of low-carbon innovations, promises far more success than targeting mitigation alone (Asensio and Delmas 2016; WBGU 2011; Geels et al. 2017).

Climate actions are related to knowledge but even strongly to motivational factors (Hornsey et al. 2016; Bolderdijk et al. 2013; Boomsma and Steg 2014), which explains the gap between awareness and action (Ünal et al. 2018). Social influences, particularly from peers, affect people's engagement in climate action (Schelly 2014). Role models appear to have a solid basis in people's everyday preferences (WBGU 2011). Social norms can reinforce individuals' underlying motivations and be effective in encouraging sustainable consumption patterns, as many examples offered by behavioural science illustrate. Social networks also influence and spread behaviours (Service et al. 2014; Clayton et al. 2015; Farrow et al. 2017; Shah et al. 2019). These social influences can be harnessed by climate policy.

Collective action by individuals as part of formal social movements or informal lifestyle movements underpins system change (*robust evidence, high agreement*) (5.4, 5.5). Organisations are comprised of individuals, but also become actors in their own right. Recent literature has considered the role of coalitions and social movements in energy democracy and energy transitions towards sustainability (Hess 2018). Other scholars have examined the role of women in redistributing power, both in the sense of energy transition and in terms of gender relations (Allen et al. 2019; Routledge et al. 2018). Mitigation and broader sustainable development policies that facilitate active participation by stakeholders can build trust, forge new social contracts, and contribute to a positive cycle building climate governance capacity (5.2.3).

However, behavioural change not embedded in structural change will contribute little to climate change mitigation, suggesting that behavioural change is not only a function of individual agency but also depends on other enabling factors, such as the provision of infrastructure and institutions (5.4). Successful shifts towards public transport, for example, involve technologies (buses, trams), infrastructure (light rail, dedicated bus lanes), regulations (operational licenses, performance contracts), institutions (new organisations, responsibilities, oversight), and high-enough density, which in turns depends on such choices as housing or planning policies (4.4.1.9).

4.4.1.6 Fostering Technological Innovation

As outlined in section 4.2.5, rapid, large-scale deployment of improved low-carbon technology is a critical component of accelerated mitigation pathways. As part of its key role in technological change, R&D can make a crucial contribution to accelerated mitigation up to 2030 and beyond, among other things by focusing on closing technology gaps that stand in the way of decarbonising today's high emitting sectors. Such sectors include shipping, trucking, aviation and heavy industries like steel, cement and chemicals. More broadly, it is increasingly clear that digital changes are becoming a key driving force in societal transformation (Tegmark 2017). Digitalisation is not only an "instrument" for resolving sustainability challenges, it is also a fundamental driver of disruptive, multiscalar change (Sachs et al. 2019) that amounts to a shift in development pathway. Information and communication technologies, artificial intelligence, the internet of things, nanotechnologies, biotechnologies, robotics, are not usually categorised as climate technologies, but have a potential impact on GHG emissions (OECD 2017b) (Cross-Chapter Box 11).

The direction of innovation matters (*robust evidence, high agreement*). The research community has called for more "responsible innovation" (Pandza and Ellwood 2013), "open innovation" (Rauter et al. 2019), "mission-oriented" innovation (Mazzucato and Semieniuk 2017), "holistic innovation" (Chen et al. 2018b), "next-generation innovation policy" (Kuhlmann and Rip 2018) or "transformative innovation" (Schot and Steinmueller 2018) so that innovation patterns and processes are commensurate to our growing sustainability challenges. There is a growing recognition that new forms of innovation can be harnessed and coupled to climate objectives (Fagerberg et al. 2016; Wang et al. 2018). As such, innovation and sociotechnical change can be channelled to intensify mitigation via "deliberate acceleration" (Roberts et al. 2018a) and "coalition building" (Hess 2018).

Innovation goes beyond technology. For example, decarbonisation in sectors with long lived capital stock (such as heavy industry, buildings, transport infrastructure) entail technology, policy and financing innovations (Bataille 2020). Similarly, expanding the deployment of photovoltaics can draw upon policies that support specific technical innovations (e.g., to improve photovoltaics efficiency), or innovations in regulatory and market regimes (e.g., net-metering), to innovations in social organisation (e.g., community-ownership). System innovation is a core focus of the transitions literature (Grin et al. 2010; Markard et al. 2012; Geels et al. 2017). Accelerating low carbon transitions not only involves a shift of system elements but also underlying routines and rules, and hence transitions shift the directionality of innovation. They hence concern the development of a new paradigm or regime that is more focused on solving sustainability challenges that cannot be solved within the dominant regime they substitute (Cross-Chapter Box 12).

Several studies have pointed at the important possible contributions of grassroots innovators for the start-up of sustainability transitions (Seyfang and Smith 2007; Smith et al. 2016; Seyfang et al. 2014). In particular, a range of studies have shown that users can play a variety of roles in promoting system innovation: shielding, nurturing (including learning, networking and visioning) and empowering the niches in relation to the dominant system and regime (Schot et al. 2016; Randelli and Rocchi 2017; Meelen et al. 2019). More fundamentally, innovation regimes can be led and guided by markets driven by monetizable profits (as much of private sector led technological innovation of patentable intellectual property), or prioritise social returns (e.g., innovation structures such as innovation prizes, public sector innovation, investments in human capital, and socially-beneficial intellectual property regimes). In both cases, public policies can play a key role by providing resources and favourable incentives (IEA 2020). Chapter 16 provides more details on ways to foster innovation.

4.4.1.7 Example: Structural change provides a way to keep jobs and mitigate

Developing countries have experienced a period of rapid economic growth in the past two decades. Patterns of growth have differed markedly across regions, with newly emerging East Asian economies building on transition to manufacturing—as China has done in the past—while Latin American countries tend to transition directly from primary sector to services (Rodrik 2016), and African countries tend to rely on productivity improvements in the primary sectors (Diao et al. 2019). Yet many countries still face the challenge of getting out of the "middle-income trap" (Agénor and Canuto 2015), as labour-saving technological change and globalisation have limited options to develop via the manufacturing sector (Altenburg and Rodrik 2017).

Looking ahead, several studies have illustrated how structural change towards sustainability could lead to reduced emissions intensity and higher mitigative capacity. In China, for example, the shift away from heavy industry (to light industry and services) has already been identified as the most important force limiting emissions growth (Guan et al. 2018), and as a major factor for future emissions (Kwok et al. 2018).

Overall, Altenburg et al. (2017) argue that reallocation of capital and labour from low- to high-productivity sectors—i.e., structural change—remains a necessity, and that it is possible to combine it with reduced environmental footprint (including, but not limited to, mitigation). They argue that this dual challenge calls for structural transformation policies different from those implemented in the past, most importantly through a "systematic steering of investment behaviour in a socially agreed direction" and encompassing policy coordination (*limited evidence*, *medium agreement*).

In order to permit progress on their SDG agendas, it is essential that countries develop visions of their future decarbonised sectoral production structure, including its ability to generate growth in incomes, employment and foreign exchange earnings. as well as the related spatial distribution of production, employment, and housing. To this extent, governance and institutional capacity matter, such as availability of tools to support long-term planning. A sectoral structure that permits strong growth is essential given strong associations between growth in per-capita incomes and progress on most SDGs (including those related to poverty; health; education; and access to water, sanitation, electricity, and roads; but not income equality), in part due to the fact that higher incomes provide both households and governments with resources that at least in part would be used to promote SDGs (Gable et al. 2015).

The future viability of sectors will depend on the extent to which they can remain profitable while relying on lower-carbon energy. The challenge to identify alternative sectors of growth is particularly acute for countries that today depend on oil and natural gas for most of their foreign exchange and government revenues (Mirzoev et al. 2020). Changes in economic structure will also have gender implications since the roles of men and women vary across sectors. For example, in many developing countries, sectors in which women play a relatively important role, including agriculture and unpaid household services like collection of water and fuel wood, may be negatively affected by climate change (Roy 2018). It may thus be important to take complementary actions to address the gender implications of changes in economic structure.

Given strong complementarities between policies discussed above, an integrated policy approach is crucial. For example, as suggested, the actions that influence the pace at which GHG emissions can be cut with political support may depend on taxation (including carbon taxes), investments in infrastructure, spending on R&D, changes in income distribution (influenced by transfers), and communication. In this light, it is important to consider the demands that alternative policy packages put on government policy-making efficiency and credibility as well as the roles of other enabling conditions. In fact, plans to undertake major reforms may provide governments with impetus to accelerate the enhancement of their capacities as part of the preparations (Karapin 2016; Jakob et al 2019; Withana & Sirini 2016).

4.4.1.8 Example: Embedding carbon finance in broader fiscal reforms offers a way to mitigate and rethink the social contract

In many countries, fiscal systems are currently under stress to provide resources for the implementation of development priorities, such as, for example, providing universal health coverage and other social services (Meheus and McIntyre 2017) or sustainably funding pension systems in the context of aging populations (Asher and Bali 2017; Cruz-Martinez 2018). Overall, Baum et al. (2017) argue that low-income countries are likely not to have the fiscal space to undertake the investment entailed in reaching the SDGs. To create additional fiscal space, major options include improving tax recovery, reducing subsidies and levying additional taxes.

Mitigation offers an opportunity to create additional fiscal space, and thus to serve the objectives outlined above, by creating a new source of revenue for the government via carbon taxation or emissions permit auctioning and by reducing existing expenditures via reduction in subsidies to fossil-fuel. The 1991 tax reform in Sweden is an early example in which environmental taxation (including, but not limited to, fossil fuel taxation) was introduced as part of a package primarily aimed at lowering the marginal tax rates (more than 80% at the time), at reducing other taxes, while keeping most of the welfare state. To do so, the tax base was broadened, including through environmental and carbon taxation (Sterner 2007). Once in place, the carbon tax rate was substantially ramped up over time, and its base broadened (Criqui et al. 2019).

The future potential for using carbon taxation as a way to provide space for fiscal reform has been highlighted in the so-called "green fiscal reform" literature (Vogt-Schilb et al. 2019). The potential is large, since only 13 percent of global GHG emissions were covered by carbon pricing schemes in 2019 (Watts et al. 2019) and since many countries price carbon negatively by subsidising fossil fuel use, thus generating effects that are the opposite of those that positive carbon prices hope to promote. In 2018, the global subsidy value amounted to $427 billion, i.e., some 10 times the payment for carbon use (Watts et al. 2019). However, the size of the potential for creating fiscal space varies strongly across countries given differences in terms of current carbon prices and fuel subsidies.

The limited adoption of and political support for carbon pricing may be explained by the fact that most of the gains occur in the future and depend on actions across the globe, making them seem abstract and unpredictable, whereas the costs in the form of higher carbon prices are immediate (Karapin 2016). Furthermore, the links between carbon pricing and emissions may not be clear to the public who, in addition, may not trust that the government will use budgetary savings according to stated plans. The latter may be due to various factors, including a history of limited government commitment and corruption (Maestre-Andrés et al 2019 ; Withana & Sirini 2016; Chadwick 2017).

The literature reports limited systematic evidence based on *ex post* analysis of the performance of carbon pricing–carbon taxes and greenhouse gas (GHG) emissions trading systems (ETSs) (Haites 2018). Performance assessment is complicated by the effect of other policies and exogenous factors. (Haites 2018) suggests that since 2008, other policies have probably contributed more to emission reductions than carbon taxes, and most tax rates are too low to achieve mitigation objectives. Emissions under ETSs have declined, with the exception of four systems without emissions caps (ibid). Every jurisdiction with an ETS and/or carbon tax also has other policies that affect its GHG emissions.

To help policymakers overcome obstacles, research has reviewed the international experience from carbon pricing reforms. Elimination of fossil fuel subsidies, equivalent to the elimination of negative carbon prices, have been more successful when they have included complementary and transparent measures that enjoy popular support, accompanied by a strong communications component that explains the measures and stresses their benefits (Rentschler and Bazilian 2017; Withana & Sirini 2016; Maestre-Andrés et al 2019).

Part of the losses (and related calls for compensation or exemptions) due to carbon pricing are related to the fact that it hurts the competitiveness of sectors that face imports from countries with lower carbon prices, leading to "carbon leakage" if carbon-intensive production (and related jobs) migrates from countries with relatively high carbon prices. Research confirms that a border carbon tax (or adjustment), set on the basis of the carbon content of the import, including a downward adjustment on the basis of any carbon payments (taxes or other) already made before entry, could reduce carbon leakage while also raising additional revenue and encouraging carbon pricing in the exporting country (Withana & Sirini 2016; Cosbey et al 2019).

The timing of carbon pricing reforms is also important: they are more likely to succeed if they exploit windows of opportunity provided by events that raise awareness of the costs of carbon emissions (like bouts of elevated local air pollution or reports about the role of emissions in causing global warming), as well as momentum from climate actions by other countries and international climate agreements (Karapin 2016; Jakob et al 2019). It is also important to consider the level of international prices of carbon energy: when they are low, consumer resistance would be smaller since prices will remain relatively low, though the tax may become more visible when energy prices increase again. As part of ongoing efforts to accelerate mitigation, such tax hikes may be crucial to avoid a slow-down in the shift to renewable energy sources (Rentschler and Bazilian 2017; Withana & Sirini 2016). In countries that exports carbon energy, carbon taxation may run into additional resistance from producers.

There is also considerable literature providing insights on the political and social acceptability of carbon taxes, suggesting for example that political support may be boosted if the revenue is recycled to the tax payers or earmarked for areas with positive environmental effects (e.g., (Bachus et al. 2019) for Belgium, and (Beiser-McGrath and Bernauer 2019) for Germany and the USA), as well as on the difficulties associated with political vagaries (and economic consequences thereof) associated with the introduction of such instruments (Pereira et al. 2016). Similarly, "best practice" have been drawn from past experience on fossil-fuel subsidy reforms (Sovacool 2017; Rentschler and Bazilian 2017). Specific policies, however, depend on societal objectives, endowments, structure of production, employment, and trade, and institutional structure (including the functioning of markets and government capacity) (Kettner et al. 2019). As noted in Section 4.2.6, macroeconomic analysis finds that the overall economic implications of carbon pricing differ markedly depending on the way the proceeds from carbon pricing are used, and thus on the way the fiscal system is reformed, with potential for double dividend if the proceeds from the tax are used to repeal the most distortive taxes in the economy.

In the context of this section on development pathways, it is worth emphasising that potential revenues drawn from the climate mitigation component of the fiscal reform varies strongly with the context, and may not be sufficient to address the other objectives pursued. Even if the carbon price is high, the revenue it generates may be moderate as a share of GDP and eventually it will be zero if emissions are eliminated. For example, Jakob et al. (2016) find that the carbon pricing revenues that most countries in Sub-Saharan Africa could expect to generate only would meet a small part of their infrastructure spending needs. In Sweden, the country with the highest carbon tax rate in the world, the tax has not been a significant part of total tax revenues. Moreover, emissions from sectors covered by the tax have shrunk and, as a result, the revenues from the tax, as a share of GDP, have also declined, from a peak of 0.93 percent in 2004, when the rate was USD109 per metric ton of CO_2, to 0.48 per cent in 2018, when the rate had reached USD132 (Jonsson et al. 2020; Statistics Sweden 2020). This means that governments that want to avoid a decline in the GDP share for total tax revenues over time would have to raise the intake from other taxes. However, it is here important to note that domestic tax hikes are likely to involve trade-offs since, at the same time as the spending they fund may provide various benefits, they may also reduce the capacity of households and the private sector to consume and invest, something that may reduce growth over time and reduced resources for spending in support of human development (Lofgren et al. 2013). It is also worth emphasising that restructuring of the fiscal system amount to changes in the social contract of the society (Combet and Hourcade 2017, 2014), and thus represents a major economic and social decision.

4.4.1.9 Example: Combining housing policies with carbon taxation can deliver both housing and mitigation in the transport sector

The spatial distribution of households and firms across urban and rural areas is a central characteristic of development pathways. Patterns of urbanisation, territorial development, and regional integration have wide-ranging implications for economic, social and environmental objectives (World Bank 2009). Notably, choices regarding spatial forms of development have large-scale implications for demand for transportation and associated GHG emissions.

Exclusionary mechanisms such as decreasing accessibility and affordability of inner-urban neighbourhoods is a major cause of suburbanisation of low- to middle-income households (e.g., (Hochstenbach and Musterd 2018). Suburbanisation, in turn, is associated with higher transportation demand (Bento et al. 2005) and higher carbon footprints for households (Jones and Kammen 2014). Similarly, other studies find a significant positive link between housing prices and energy demand (Lampin et al. 2013).

Reducing emissions from transport in cities through traditional climate policy instruments (e.g., through a carbon tax) is more difficult when inner-urban neighbourhoods are less accessible and less affordable, because exclusionary mechanisms act as a countervailing force to the rising transportation costs induced by the climate policy, pushing households outwards rather than inwards. Said differently, the costs of mitigating intra-city transportation emissions are higher when inner-urban housing prices are higher (Lampin et al. 2013).

This suggests that policies making inner-urban neighbourhoods more accessible and more affordable can open up broader opportunities for suburban households to relocate in the face of increasing transportation costs. This is particularly important for low- and middle-income households, who spend a greater portion of their income on housing and transportation, and are more likely to be locked into locations that are distant from their jobs. Making inner-urban neighbourhoods more accessible and more affordable has the potential to reduce both the social costs—e.g., households feeling helpless in front of rising fuel prices—and the economic costs of mitigation policies—as a lower price of carbon is likely to achieve the same amount of emission reductions since households have more capacities to adjust.

Making inner-cities neighbourhoods more accessible and more affordable is a complex endeavour (Benner and Karner 2016). At the same time, it is already a policy objective in its own right in many countries, independent of the climate mitigation motivation, for a range of social, health and economic reasons. Revenues derived from climate policies could provide additional resources to support such programs, as some climate policy already have provisions to use their revenues towards low-income groups (Karner and Marcantonio 2018). The mitigation benefits of keeping inner-cities more accessible and affordable for low- and middle-income households often remains out of, or is only emerging in the debates surrounding the planning of fast-developing cities in many developing countries (Grant 2015; IADB 2012; Khosla and Bhardwaj 2019). Finally, from a political economy perspective, it is also interesting to note that (Bergquist et al. 2020) find higher support for climate policy packages in the U.S. when affordable housing programs are included.

In addition, investment in infrastructure is critical to the development of decarbonised economic structures that generate growth, employment, and universal access to a wide range of services that are central to the SDG agenda: transportation, water, sanitation, electricity, flood protection, and irrigation. For low- and middle-income countries, annual costs of reaching these goals by 2030 and putting their economies on a path toward decarbonisation may range between 2 and 8 percent of GDP, with the level depending on spending efficiency. Notably, these costs need not exceed those of more polluting alternatives (Rozenberg and Fay 2019). For transportation, this involves a shift toward more public transportation (rail and bus), and decarbonised electricity for vehicles, combined with land-use policies that densify cities and reduce distances between homes and jobs. By influencing the spatial distribution of households and firms and the organisation of transportation, infrastructure has a strong bearing on GHG emissions and the costs of providing services to different populations. Depending on country context, the private sector may play a particularly important role in the financing of infrastructure (World Bank 2009; Klein 2015).

Many investments in infrastructure and sectoral capital stocks have long lifetimes. Given this, it may be important to make sure that today's investments be fully decarbonised at the start or that they later can be converted to zero carbon. Today's investments in electric vehicles in settings where electricity is produced with fossil fuels is an example of convertible investments—they will be decarbonised once electricity production has switched to renewable energies. For capital stocks that cannot be decarbonised, countries may face costs of decommissioning well before the end of their useful lifetimes, especially when it is needed to respect country commitments to future full decarbonisation.

4.4.1.10 Example: Changing economic, social and spatial patterns of development of the agriculture sector provide the basis for sustained reductions in emissions from deforestation

A growing literature assesses co-benefits of sectoral policies that lead to decarbonisation and simultaneously promote economic development, improve living standards, reduce inequality, and create job opportunities (Bataille et al. 2018; Pye et al. 2016; Maroun and Schaeffer 2012; Richter et al. 2018; Bataille et al. 2016b; La Rovere et al. 2018; Waisman et al. 2019). While this may be particularly challenging in developing countries, given large populations still lacking basic needs, previous development paths show that finding synergies in development and climate objectives in the AFOLU sector is possible. One example is Brazil, which has arguably shifted its development pathway to reduce emissions and make progress towards several SDGs, though progress is not linear. Over the past two decades, Brazil had made remarkable progress in implementing a sequence of policies across multiple sectors. This policy package simultaneously increased minimum wages of low income families, achieved universal energy access, and raised the quality of life and well-being for the large majority of the population (Da Silveira Bezerra et al. 2017; Grottera et al. 2018, 2017; La Rovere et al. 2018). This led to significant social benefits, reduction of income inequality and poverty eradication (Da Silveira Bezerra et al. 2017; Grottera et al. 2017), reflected in a decrease of the Gini coefficient and a rise in the human development index (La Rovere 2017).

Regulatory instruments were used to limit deforestation rates, together with implemented economic instruments that provided benefits to those protecting local ecosystems and enhancing land-based carbon sinks (Soterroni et al. 2019, 2018; Bustamante et al. 2018; Nunes et al. 2017). In parallel, public policies reinforced environmental regulation and command-and-control instruments to limit deforestation rates and implemented market-based mechanisms to provide benefits to those protecting local ecosystems and enhancing land-based carbon sinks (Sunderlin et al. 2014; Hein et al. 2018; Simonet et al. 2019; Nunes et al. 2017). The private sector, aligned with public policies and civil society, implemented the Amazon Soy Moratorium, a voluntary agreement that bans trading of soybeans from cropland associated with cleared Amazon rainforest and blacklists farmers using slave labour. This was achieved without undermining production of soybean commodities (Soterroni et al. 2019). As a result, between 2005 and 2012, the country halved its GHG emissions and reduced the rate of deforestation by 78 per cent (INPE 2019a,b). This example shows that development delivering well-being can be accompanied by significant mitigation. A long-term and strategic vision was important in guiding enabling policies and mechanisms.

In more recent years, some of these shifts in Brazil's development pathways were undone. Political changes have redefined development priorities, with higher priority being given to agricultural development than climate change mitigation. The current administration has reduced the power of environmental agencies and forestry protection laws (including the forest code), while allowing the expansion of cropland to protected Amazon rainforest areas (Ferrante and Fearnside 2019; Rochedo et al. 2018). As a result, in 2020, deforestation exceeded 11,000 km^2, and reached the highest rate in the last 12 years (INPE 2020). The literature cautions that, if current policies and trends continue, the Amazon may reach an irreversible tipping point beyond which it will be impossible to remediate lost ecosystems and restore carbon sinks and indigenous people knowledge (Nobre 2019; Lovejoy and Nobre 2018; INPE 2019a). In addition, fossil fuel subsidies and other fiscal support of increased exploitation of oil resources may create carbon lock-ins that further inhibit low-carbon investments (Lefèvre et al. 2018).

Brazil's progress in mitigation depended significantly on reduced deforestation in the past. If deforestation rates keep on rising, mitigation efforts would need to shift to the energy sector. However, according to Rochedo et al. (2018), mitigation costs in the energy sector in Brazil are three times the costs of reducing deforestation and increasing land-based carbon sinks. Further mitigation strategies may depend on CCS in Brazil as elsewhere (Nogueira de Oliveira et al. 2016; Herreras Martínez et al. 2015), though the economic feasibility of deployment is not yet clear (4.2.5.4).

4.4.2 Adaptation, development pathways and mitigation

Mitigation actions are strongly linked to adaptation. These connections come about because mitigation actions can be adaptive (e.g., some agroforestry projects) but also through policy choices (e.g., climate finance is allocated among adaptation or mitigation projects) and even biophysical links (e.g., climate trajectories, themselves determined by mitigation, can influence the viability of adaptation projects). As development pathways shape the levers and enablers available to a society (4.3.1, Figure 4.7), a broader set of enabling conditions also helps with adaptation (*medium evidence, high agreement*).

Previous assessments have consistently recognised this linkage. The Paris Agreement includes mitigation and adaptation as key areas of action, through NDCs and communicating adaptation actions and plans. The Agreement explicitly recognises that mitigation co-benefits resulting from adaptation can count towards NDC targets. The IPCC Fifth Assessment Report (IPCC 2014) emphasised that sustainable development is helpful in going beyond a narrow focus on separate mitigation and adaptation options and their specific co-benefits. The IPCC Special Report on climate change and land addresses GHG emissions from land-based ecosystems with a focus on the vulnerability of land-based systems to climate change. The report identifies the potential of changes to land use and land management practices to mitigate and adapt to climate change, and to generate co-benefits that help meet other SDGs (Jian et al. 2019).

A substantial literature detailing trade-offs and synergies between mitigation and adaptation exists and is summarised in the IPCC SR15 including energy system transitions; land and ecosystem transitions (including addressing food system efficiency, sustainable agricultural intensification, ecosystem restoration); urban and infrastructure system transitions (including land use planning, transport systems, and improved infrastructure for delivering and using power); industrial system transitions (including energy efficiency, bio-based and circularity, electrification and hydrogen, and industrial Carbon

Capture, Utilisation and Storage (CCUS); and carbon dioxide removal (including bioenergy with CCS, afforestation and reforestation, soil carbon sequestration, and enhanced weathering.) (IPCC 2018: supplementary information Table 4.SM.5.1). Careful design of policies to shift development pathways towards sustainability can increase synergies and manage trade-offs between mitigation and adaptation (*robust evidence*, *medium agreement*).

This section examines how development pathways can build greater adaptive and mitigative capacity, and then turns to several examples of mitigation actions with implications for adaptation where there is a notable link to development pathways and policy choices. These examples are in the areas of agriculture, blue carbon and terrestrial ecosystem restoration.

4.4.2.1 Development pathways can build greater capacity for both adaptation and mitigation

Previous IPCC assessments have reflected on making development more sustainable (Fleurbaey et al. 2014; Sathaye et al. 2007; IPCC et al. 2001). Other assessments have highlighted how ecosystem functions can support sustainable development and are critical to meeting the goals of the Paris Agreement (IPBES 2019b). IPCC SR15 found that sustainable development pathways to 1.5 °C broadly support and often enable transformations and that "sustainable development has the potential to significantly reduce systemic vulnerability, enhance adaptive capacity, and promote livelihood security for poor and disadvantaged populations (*high confidence)*" (IPCC 2018b: 5.3.1). With careful management, shifting development pathways can build greater adaptive and mitigative capacity, as further confirmed in recent literature (Schramski et al. 2018; Harvey et al. 2014; Ebi et al. 2014; Rosenbloom et al. 2018; Antwi-Agyei et al. 2015; Singh 2018; IPBES 2019b). The literature points to the challenge of design of specific policies and shifts in development pathways to achieve both mitigation and adaptation goals.

Governance and Institutional capacity

Governance and institutional capacity necessary for mitigation actions also enables effective adaptation actions. Implementation of mitigation and adaptation actions can, however, encounter different sets of challenges. Mitigation actions requiring a shift away from established sectors and resources (e.g., fossil fuels) entail governance challenges to overcome vested interests (SEI et al. 2020; Piggot et al. 2020). Mitigation-focused initiatives from non-state actors tend to attain greater completion than adaptation-focused initiatives (NewClimate Institute et al. 2019).

Behaviour and lifestyles

On the level of individual entities, adaptation is reactive to current or anticipated environmental changes but mitigation is undertaken deliberately. Chapter 5 considers behavioural change, including the reconsideration of values and what is meant by well-being, and reflecting on a range of actors addressing both adaptation and mitigation. Shifting development pathways may be disruptive (Cross Chapter Box 5), and there may be limits to propensity to change. Some studies report that climate change deniers and sceptics can be induced to undertake pro-environmental action if those actions are framed in terms of societal welfare, not climate change (Bain et al. 2012; Hornsey et al. 2016). Concrete initiatives to change behaviour and lifestyles include the Transition Town movement, which seeks to implement a just transition—both in relation to adaptation and mitigation—in specific localities (Roy et al. 2018).

Finance

Finance and investment of mitigation actions must be examined in conjunction with funding of adaptation actions, due to biophysical linkages and policy trade-offs (Box 15.1). Most climate funding supports mitigation efforts, not adaptation efforts (Buchner et al. 2019) (Halimanjaya and Papyrakis 2012). Mitigation projects are often more attractive to private capital (Abadie et al. 2013; Buchner et al. 2019). Efforts to integrate adaptation and mitigation in climate change finance are limited (Locatelli et al. 2016; Kongsager et al. 2016) There is a perception that integration of mitigation and adaptation projects would lead to competition for limited finance available for adaptation (Locatelli et al. 2016). Long-standing debates (Ayers and Huq 2009; Smith et al. 2011) whether development finance counts as adaptation funding remain unresolved. See chapter 15 for more in-depth discussion relating investment in funding mitigation and adaptation actions.

Innovation and technologies

Systems transitions that address both adaptation and mitigation include the widespread adoption of new and possibly disruptive technologies and practices and enhanced climate-driven innovation (IPCC 2018a). See Chapter 16 for an in-depth discussion of innovation and technology transfer. The literature points to trade-offs that developing countries face in investing limited resources in research and development, though finding synergies in relation to agriculture (Adenle et al. 2015). Other studies point to difference in technology transfers for adaptation and mitigation (Biagini et al. 2014). Adaptation projects tend to use existing technologies whereas mitigation climate actions are more likely to rely on novel technologies. Innovations for mitigation are typically technology transfers from developed to less-developed countries (Biagini et al. 2014), however this so-called North-South technology transfer pathway is not exclusive (Biagini et al. 2014), and is increasingly challenged by China's global role in implementing mitigation actions (Chen 2018; Urban 2018). Indigenous knowledge can be a unique source for techniques for adaptation (Nyong et al. 2007) and may be favoured over externally generated knowledge (Tume et al. 2019).

Policy

Adaptation-focused pathways might reduce inequality, if adequate support is available and well-distributed (Pelling and Garschagen 2019). Some studies suggest that cities might plan for possible synergies in adaptation and mitigation strategies, currently done independently (Grafakos et al. 2019). The literature suggests that cities might identify both mitigation and adaptation as co-benefits of interventions targeted at developmental goals (Dulal 2017).

4.4.2.2 Specific links between mitigation and adaptation

Mitigation actions can be adaptive and vice-versa. In particular, many nature-based solutions (NBS) for climate mitigation are adaptive (*medium evidence, medium agreement*). Multiple NBS are being pursued under current development pathways (see Chapter 7), but shifting to sustainable development pathways may enable a wider set of nature-based mitigation solutions with adaptation benefits. An example of this would be a shift to more sustainable diets through guidelines, carbon taxes, or investment in R&D of animal product substitutes (Figure 13.2) which could reduce pressure on land and allow for implementation of multiple NBS. Many of these solutions are consistent with meeting other societal goals, including biodiversity conservation and other sustainable development goals (Griscom et al. 2017; Tallis et al. 2018; Fargione et al. 2018). However, there can be synergies and trade-offs in meeting a complex set of sustainability goals (e.g., biodiversity, see 7.6.5 and 3.1.5).

Development is a key factor leading to land degradation in many parts of the world (IPBES 2019b). Shifting development pathways to sustainability can include restoration and protection of ecosystems, which can enhance capacity for both mitigation and adaptation actions (IPBES 2019b).

In this section, we explore mitigation actions related to sustainable agriculture, coastal ecosystems ("blue carbon"), and restoration and protection of some terrestrial ecosystems. These mitigation actions are exemplary of trade-offs and synergies with adaptation, sensitivity to biophysical coupling, and linkages to development pathways. Other specific examples can be found in Chapters 6 to 11.

Farming system approaches can benefit mitigation and adaptation

Farming system approaches can be a significant contributor to mitigation pathways. These practices (which are not mutually exclusive) include agroecology, conservation agriculture, integrated production systems and organic farming (Box 7.5). Such methods have potential to sequester significant amounts of soil carbon (7.4.3.1) as well as reduce emissions from on-field practices such as rice cultivation, fertilizer management, and manure management (7.4.3) with total mitigation potential of 3.9±0.2 $GtCO_2$-eq yr^{-1} (Chapter 7). Critically, these approaches may have significant benefits in terms of adaptation and other development goals.

Farming system approaches to agricultural mitigation have a wide variety of co-benefits and tradeoffs. Indeed, there are conceptual formulations for these practices in which the co-benefits are more of a focus, such as climate-smart agriculture (CSA) which ties mitigation to adaptation through its three pillars of increased productivity, mitigation, and adaptation (Lipper et al. 2014). The '4 per 1000' goal to increase soil carbon by 0.4% per year (Soussana et al. 2019) is compatible with the three pillars of CSA. Sustainable intensification, a framework which centers around a need for increased agricultural production within environmental constraints also complements CSA (Campbell et al. 2014). The literature reports examples of mitigation co-benefits of adaptation actions, with evidence from various regions (Chapter 7, Thornton and Herrero (2015), Thornton et al. (2018)).

Conservation agriculture, promoted for improving agricultural soils and crop diversity (Powlson et al. 2016) can help build adaptive capacity (Smith et al. 2017; Pradhan et al. 2018a) and yield mitigation co-benefits through improved fertiliser use or efficient use of machinery and fossil fuels (Cui et al. 2018; Harvey et al. 2014; Pradhan et al. 2018a).

There is a complex set of barriers to implementation of farming-system approaches for climate mitigation (7.6.4), suggesting a need for deliberate shifts in development pathways to achieve significant progress in this sector. The link between NDCs and mitigation in the land use sector can provide impetus for such policies. For example, there are multiple agricultural mitigation options that southeast Asian countries could use to meet NDCs that would have an important adaptive impact (Amjath-Babu et al. 2019).

Some agricultural practices considered sustainable have trade-offs, and their implementation can have negative effects on adaptation or other ecosystem services. Fast-growing tree monocultures or biofuel crops may enhance carbon stocks but reduce downstream water availability and decrease availability of agricultural land (Windham-Myers et al. 2018; Kuwae and Hori 2019). In some dry environments similarly, agroforestry can increase competition with crops and pastures, decreasing productivity, and reduce catchment water yield (Schrobback et al. 2011).

Agricultural practices can adapt to climate change while decreasing CO_2 emissions on the farm field. However, if such a practice leads to lower yields, interconnections of the global agricultural system can lead to land use change elsewhere and a net increase in GHG emissions (Erb et al. 2016). Implementation of sustainable agriculture can increase or decrease yields depending on context (Pretty et al. 2006).

Blue carbon and mitigation co-benefits of adaptation actions

The Paris Agreement recognises that mitigation co-benefits resulting from Parties' adaptation actions and/or economic diversification plans can contribute to mitigation outcomes (UNFCCC 2015: Article 4.7). Blue carbon refers to biologically-driven carbon flux or storage in coastal ecosystems such as seagrasses, salt marshes, and mangroves (Wylie et al. 2016; Fennessy et al. 2019; Fourqurean et al. 2012; Tokoro et al. 2014) (see Cross-Chapter Box 8 on blue carbon as a storage medium and removal process).

Restoring or protecting coastal ecosystems is a mitigation action with synergies with adaptation and development. Such restoration has been described as a 'no regrets' mitigation option in the Special Report on the Ocean and Cryosphere in a Changing Climate (Bindoff et al. 2019) and advocated as a climate solution at national scales (Bindoff et al. 2019; Taillardat et al. 2018; Fargione et al. 2018) and global scales (Howard et al. 2017). On a per-area basis, carbon stocks in coastal ecosystems can be higher than in terrestrial forests (Howard et al. 2017), with below-ground carbon storage up to 1000 tC ha^{-1} (Crooks et al. 2018; McLeod et al. 2011; Bindoff et al. 2019). Overall, coastal vegetated systems have a mitigation potential of around 0.5% of current global emissions, with an upper limit of less than 2% (Bindoff et al. 2019).

Restoration or protection of coastal ecosystems is an important adaptation action with multiple benefits, with bounded global mitigation benefits (Gattuso et al. 2018; Bindoff et al. 2019). Such restoration/preservation reduces coastal erosion and protects from storm surges, and otherwise mitigates impacts of sea level rise and extreme weather along the coast line (Siikamäki et al. 2012; Romañach et al. 2018; Alongi 2008). Restoration of tidal flow to coastal wetlands inhibits methane emissions which occur in fresh and brackish water (Kroeger et al. 2017) (7.4.2.8 describes a more inclusive set of ecosystem services provided by coastal wetlands). Coastal habitat restoration projects can also provide significant social benefits in the form of job creation (through tourism and recreation opportunities), as well as ecological benefits through habitat preservation (Edwards et al. 2013; Sutton-Grier et al. 2015; Sutton-Grier and Moore 2016; Kairo et al. 2018; Wylie et al. 2016; Bindoff et al. 2019).

Coastal ecosystem-based mitigation can be cost-effective, but interventions should be designed with care. One concern is to assure that actions remain effective at higher levels of climate change (Alongi 2015; Bindoff et al. 2019). Also, methane emissions from ecosystems may partially reduce the benefit of the carbon sequestration (Rosentreter et al. 2018) depending on the salinity (Poffenbarger et al. 2011; Kroeger et al. 2017). As the main driver of mangrove forest loss is aquaculture/agriculture (Thomas et al. 2017), there may be entrenched interests opposing restoration and protection actions.

Restoration and protection of terrestrial ecosystems

Restoration of terrestrial landscapes can be a direct outcome of development pathways, and can be critical to achieving a variety of SDGs (especially 1, 2, 6, 8, 13, 15) (Lapola et al. 2018; Vergara et al. 2016) although it also presents risks and can have trade-offs with other SDGs (Cao et al. 2010; Dooley and Kartha 2018). Landscape restoration is nearly always a mitigation action, and can also provide adaptive capacity. While policy in Brazil has tended to focus on the Amazon as a carbon sink, the mitigation co-benefits of ecosystem-based adaptation actions have been highlighted in the literature (Di Gregorio et al. 2016; Locatelli et al. 2011). A study of potential restoration of degraded lands in Latin America (Vergara et al. 2016) indicates that substantial benefits for mitigation, adaptation, and economic development accrue after several years, underscoring a reliance on deliberate development choices. In agricultural contexts, restoration is a development choice that can enhance adaptive and mitigative capacity via impact on farmer livelihoods.

Preventing degradation of landscapes can support both mitigation and adaptation (IPCC 2019). Restoration of ecosystems is associated with improved water filtration, ground water recharge and flood control and multiple other ecosystem services (Ouyang et al. 2016).

Restoration projects must be designed with care. There can be trade-offs in addition to the synergies noted above (7.6.4.3). Restorations may be unsuccessful if not considered in their socio-economic context (Lengefeld et al. 2020; Iftekhar et al. 2017; Jellinek et al. 2019). Restoration projects for mitigation purposes can be more effective if done with adaptation in mind (Gray et al. 2011) as a changing climate may render some mitigation actions biophysically infeasible (Arneth et al. 2021). Landscape restoration projects intended for CDR may underperform due to future release of stored carbon, or deferral of storage until after irreversible climate change effects (e.g. extinctions) (Dooley and Kartha 2018).

Afforestation plans have received substantial attention as a climate mitigation action, with ongoing unresolved debate on the feasibility and tradeoffs of such plans. Such afforestation programs can fail for biophysical reasons (7.4.2.2, Fleischman et al. 2020) but also lack of consideration of socioeconomic and development contexts (Fleischman et al. 2020).

4.4.3 Risks and uncertainties

Shifting development pathways and accelerating mitigation are complex endeavours that carry risks. Some of these risks can be easily captured by quantitative models. Others are better understood via qualitative approaches, such as qualitative narrative storylines (told in words) and methods mixing qualitative and quantitative models (Kemp-Benedict 2012; Hanger-Kopp et al. 2019). The following outline key risks and relevant hedging strategies identified in the literature.

4.4.3.1 Actions by others not consistent with domestic efforts

The international context is a major source of uncertainty for national-level planning, especially for small- or medium-sized open economies, because the outcome of domestic choices may significantly depend on decisions made by other countries and actor, over which national governments have limited or no control (Lachapelle and Paterson 2013). Availability of foreign financial resources in countries with limited domestic savings (Baum et al. 2017) and availability of technology transfers (Glachant and Dechezleprêtre 2017) are some examples. Other external decisions with significant bearing on domestic action include mitigation policies in other countries (Dai et al. 2017), and especially in major trading partners, the lack of which can result in competitive disadvantage for sectors exposed to international competition (Alton et al. 2014). The international prices of the key commodities (notably energy), goods and services are important, notably when shifting development pathway is based on structural change (e.g., Willenbockel et al. (2017) for Ghana and Kenya).

Remedies include first devising policy packages that are, to the extent possible, robust to uncertainty regarding external decisions. For example, mitigation in the building sector is considered less problematic for competitiveness since the construction sector is less exposed to international competition. Remedies also include securing international cooperation to reduce the uncertainty that domestic decision-makers face about the international context. Shifting investments towards low-GHG solutions requires a combination of conducive public policies, attractive investment opportunities and financing of transitions (15.6), which can enable shifting development pathways. Cooperation can generate positive spill overs through technology diffusion (13.6.6). Third, cooperation is not limited to governments. As discussed in section 4.2.3, international cooperative initiatives among non-State actors (cities, economic branches, etc.) can also provide know-how, resources and stable cooperative frameworks that reduce uncertainty for individual actors (14.5.5).

4.4.3.2 Parts of complex policy packages fail

As outlined in the examples in section 4.4.1 above, shifting development pathways and accelerating mitigation are complex endeavours, on which there is limited experience and know-how from the past. An uncertainty is that parts of these policy packages may fail, i.e., under-deliver relative to the amount of mitigation and of transformations initially expected. For example, France has failed to meet its 2015-2018 carbon budget as housing retrofitting programs, in particular, have failed to deliver the expected amount of emission reductions (Haut Conseil pour le Climat 2019). There are two main options to tackle this risk. The first is to build in redundancy. The second is to anticipate that some parts of the policies will inevitably fail, and build-in monitoring and corrective mechanisms in a sequential decision-making process. To this regard, building institutions that can properly monitor, learn from and improve over time is critical (Nair and Howlett 2017).

4.4.3.3 New information becomes available

The science on climate change, its impacts and the opportunities to mitigate is continuously being updated. Even though decisions are no longer made "in a sea of uncertainty" (Lave 1991), we know that new information will come over time, that may have significant bearing on the design and objectives of policies to shift development pathways and accelerate mitigation. New information may come from climate sciences (e.g., updated GWP values or available carbon budgets) (Quéré et al. 2018), impact sciences (e.g., re-evaluation of climate impacts associated with given emission pathways) (Ricke et al. 2018) or mitigation sciences (e.g., on availability of given technologies) (Lenzi et al. 2018; Giannousakis et al. 2020).

At the same time, economic and social systems are characterised by high degree of inertia, via long-lived capital stock or urban forms (Lecocq and Shalizi 2014), or more broadly mutually reinforcing physical, economic, and social constraints (Seto et al. 2016) that may lead to carbon lock-ins (Erickson et al. 2015). Risks associated with long-lasting fossil-fuel power plants have been the object of particular attention. For example, Pfeiffer et al. (2018) estimate that even if the current pipeline of power plants was cancelled, about 20% of the existing capacity might be stranded to remain compatible with 1.5°C or 2°C pathways—implying that additional capital accumulation would lead to higher sunk costs associated with stranded assets (Luderer et al. 2018b; Johnson et al. 2015; Ansar et al. 2013; Kriegler et al. 2018).

In the presence of uncertainty and inertia (or irreversibilities), hedging strategies may be considered, that include selection of risk-hedging strategies and processes to adjust decisions as new information becomes available. The notion of hedging against risks is also prominent in the adaptation literature, as exemplified by the terminology of "climate resilient development" (Fankhauser and McDermott 2016) (WGII, Ch.18). There is also a growing literature on hedging strategies for individual actors (e.g., firms or investors) in the face of the uncertainties associated with mitigation (e.g., policy uncertainty or the associated carbon price uncertainty) (e.g., (Morris et al. 2018) or (Andersson et al. 2016)). On the other hand, there is often limited discussion of uncertainty and of its implication for hedging strategies in the accelerated mitigation pathway literature. Exceptions include (Capros et al. 2019), who elicit "no-regret" and "disruptive" mitigation options for the EU through a detailed sensitivity analysis, and (Watson et al. 2015) who discuss flexible strategies for the U.K. energy sector transition in the face of multiple uncertainties.

4.4.3.4 Black swans (e.g., COVID-19 crisis)

As the current COVID-19 crisis demonstrates, events happen that can derail the best-laid plans. Unexpected events beyond the range of human experience until then are called 'black swans', given the expectation that all swans are white. The only point to note here is that such events may also provide opportunities. In the COVID-19 case, for example, the experience of conducting many activities on-line, which reduces emissions from transport, may leave an imprint on how some of these activities are carried out in the post-COVID-19 world. Similarly, reduced air pollution seen during the pandemics may increase support for mitigation and strengthen the case for climate action. However, the emissions implications of recovery packages depend on choosing policies that support climate action while addressing the socio-economic implications of COVID-19 (Hepburn et al. 2020). Governments may be in a stronger position to do so due to their pivotal role in assuring the survival of many businesses during the pandemics. Given the magnitude of recovery packages and their implications (Pollitt et al. 2021), choosing the direction of recovery packages amounts to choosing a development pathway (Cross-Chapter Box 1).

4.4.3.5 Transformations run into oppositions

As noted above, shifting development pathways and accelerating mitigation involve a broad range of stakeholders and decision-makers, at multiple geographical and temporal scales. They require a credible and trusted process for reconciling perspectives and balancing potential side-effects, managing winners and losers and implementing compensatory measures to ensure an inclusive just transition (Newell and Mulvaney 2013; Miller and Richter 2014; Gambhir et al. 2018; Diffenbaugh and Burke 2019). Such processes are designed to manage the risk of inequitable or non-representative power dynamics (Helsinki Design Lab 2014; Kahane 2019; Boulle et al. 2015). More generally, stakeholder processes can be subject to regulatory capture by special interests, or outright opposition from a variety of stakeholders. Information asymmetry between government and business may shape the results of consultative processes. Long experience of political management of change demonstrates that managing such risks is not easy, and requires sufficiently strong and competent institutions (Stiglitz 1998). The next section on Just Transition (4.5) addresses this issue.

4.5 Equity, including just transitions

Equity is an ethical and at times economic imperative, but it is also instrumentally an enabler of deeper ambition for accelerated mitigation (Hoegh-Guldberg et al. 2019). The literature supports a range of estimates of the net benefits—globally or nationally—of low-carbon transformation, and it identifies a number of difficulties in drawing definitive quantitative conclusions (e.g., comparisons of costs & benefits among different actors, the existence of non-economic impacts, comparison across time, uncertainty in magnitude, 3.6). One of the most important of these dimensions is the distributional consequences of mitigation, as well as a range of equity considerations arising from the uncertainty in net benefits, as well as from the distribution of costs and benefits among winners and losers (Rendall 2019; Caney 2016; Lahn and Bradley 2016; Lenferna 2018a; Kartha et al. 2018b; Robiou Du Pont et al. 2017). Some equity approaches are even just seeking corrective justice including for historical emissions (Adler 2007). For an assessment of literature on fairness in NDCs, see 4.2.2.7.

Equity issues are often discussed in the literature via frameworks that are well-founded in the ethical literature and that have a strong bearing on effort-sharing, but have not yet been quantitatively modelled and expressed in the form of an emissions allocation quantified framework. These include, for example, ethical perspectives based in human rights (Johl and Duyck 2012), human capabilities (Klinsky et al. 2017b), environmental justice (Mohai et al. 2009; Schlosberg 2009), ecological debt (Srinivasana et al. 2008; Warlenius et al. 2015), transitional justice (Klinsky 2017; Klinsky and Brankovic 2018), and planetary boundaries (Häyhä et al. 2016).

While there is extensive literature on equity frameworks for national emissions allocations (CSO Equity Review 2018, 2015, 2017; Kemp-Benedict et al. 2018; Pye et al. 2020; Robiou du Pont and Meinshausen 2018; Fyson et al. 2020; Holz et al. 2018; Pozo et al. 2020), such studies have tended to focus on allocation of a global carbon budget among countries based on quantified equity frameworks. The implicit normative choices made in these analysis have limitations (Kartha et al. 2018a). Moreover, there are many ethical parameters that could be introduced to enrich the existing quantitative frameworks, such as progressivity (Holz et al. 2018), consumption-based accounting (Afionis et al. 2017), prioritarianism (Adler and Treich 2015), and a right to development (Moellendorf 2020). Introducing these ethical frames into conventional quantification approaches generally implies greater allocations for poorer and lower-emitting populations, suggesting that the approaches that are typically highlighted in emissions allocation analyses tends to favour wealthier and higher-emitting countries. Broader, more inclusive sharing of costs and burdens is seen as a way to enhance equity in procedures and outcomes.

Ultimately, equity consequences depend on how costs and benefits are initially incurred and how they are shared as per social contracts (Combet and Hourcade 2017), national policy, and international agreements. The literature suggests a relationship between the effectiveness of cooperative action and the perception of fairness of such arrangements. Winkler et al. (2018) demonstrate that countries have put forward a wide variety of indicators and approaches for explaining the fairness and ambition of their NDCs, reflecting the broader range of perspectives found in the moral philosophical literature cited above. Mbeva and Pauw (2016) further find that adaptation and financing issues take on greater salience in the national perspectives reflected in the NDCs.

Topics of equity and fairness have begun to receive a greater amount of attention within the energy and climate literature, namely through the approaches of gender and race (Pearson et al. 2017; Lennon 2017; Allen et al. 2019), climate justice (Roberts and Parks 2007; Routledge et al. 2018) (Roberts & Parks, 2006; Routledge et al. 2018), and energy justice (Sovacool and Dworkin 2014). While such approaches frequently envision justice and equity as an ethical imperative, justice also possesses the instrumental value of enabling deeper and more socially acceptable mitigation efforts (Klinsky and Winkler 2018).

A concrete focal point on these issues has been that of "just transition". Getting broad consensus for the transformational changes entailed in moving from a high- to a low-carbon economy means 'leaving no one behind', i.e., ensuring (sufficiently) equitable transition for the relevant affected individuals, workers, communities, sectors, regions and countries (Newell & Mulvaney, 2013; Jasanoff 2018). The concept of a "just transition" owes its origin to the US trade union movement of the 1980s. The earliest version of a just transition was called the "Superfund for Workers" modelled on the 1980 Superfund program that designed federal funds for the clean-up of toxic substances from chemicals, mining and energy production (Stevis and Felli 2015). It was further taken up, for example in the collaboration of the International Trade Union Confederation (ITUC), the International Labour Organization (ILO) and the UN Environmental Programme (UNEP) in promoting "green jobs" as integral elements of a just transition (ILO 2015; Rosemberg 2015). In recent years the concept of a "just transition" has gained increased traction, for example incorporated in the outcome of the Rio+20 Earth Summit and more recently recognised in the preamble of the Paris Agreement, which states "the imperative of a just transition of the workforce and the creation of decent work and quality jobs in accordance with nationally defined development priorities" (UNFCCC 2015c). Some heads of state and government signed a *Solidarity and Just Transition Silesia Declaration* first introduced at COP24 in Poland (HoSG 2018).

The literature identifies targeted and proactive measures from governments, agencies, and authorities to ensure that any negative social, environmental or economic impacts of economy-wide transitions are minimised, whilst benefits are maximised for those disproportionally affected (Healy and Barry 2017). While the precise definition varies by source, core elements tend to include: (1) investments in establishing low-emission and labour-intensive technologies and sectors (Mijn Cha et al. 2020); (2) research and early assessment of the social and employment impacts of climate policies (Green and Gambhir 2020; Mogomotsi et al. 2018); (3) social dialogue and democratic consultation of social partners and stakeholders (Smith 2017; Swilling and Annecke 2012); (4) the creation of decent jobs; active labour markets policies; and rights at work (UNFCCC 2016c; ILO 2015); (5) fairness in energy access and use (Carley and Konisky 2020); (6) economic diversification based on low-carbon investments; (7) realistic training/retraining programs that lead to decent work; (8) gender specific politics that promote equitable outcomes (Allwood 2020); (9) the fostering of international cooperation and coordinated multilateral actions (Lenferna 2018b; Newell and Simms 2020); (10) redressing of past harms and perceived injustices (UNHRC 2020; Setzer and Vanhala 2019); and (11) consideration of inter-generational justice concerns, such as the impacts of policy decisions on future generations (Newell & Mulvaney, 2013).

A just transition could therefore entail that the state intervenes more actively in the eradication of poverty, and creates jobs in lower-carbon sectors, in part to compensate for soon-to-be abandoned fossil-fuel-based sectors, and that governments, polluting industries, corporations and those more able to pay higher associated taxes pay for transition costs, provide a welfare safety net and adequate compensation for people, communities, places, and regions that have been impacted by pollution, marginalised or negatively impacted by a transition from a high- to low-carbon economy and society (Muttitt and Kartha 2020; Le Billon and Kristoffersen 2020; Kartha et al. 2018b). Reducing climate impacts is another important dimension of equity, in that the poor who are least responsible for climate change are most vulnerable to its impacts (WGII, Chapter 8). Focusing on financial losses alone however can obscure an important distinction between losses incurred by corporations and states and losses experienced by workers and communities. Processes established in the name of a just transition are also at risk of being co-opted by incumbent interests and powerful/wealthy agents (Green and Gambhir, 2020). Policy interventions associated with good governance, democratic oversight, and legal recourse can help overcome attempted co-optation of just transition, or use of COVID-19 recovery packages for continued carbon lock-in (Hepburn et al. 2020; SEI et al. 2020).

The just transition concept has thus become an international focal point tying together social movements, trade unions, and other key stakeholders to ensure equity is better accounted for in low-carbon transitions and to seek to protect workers and communities. It also forms a central pillar of the growing movement for a 'Green New Deal'—a roadmap for a broad spectrum of policies, programs, and legislation that aims to rapidly decarbonises the economy while significantly reducing economic inequality (Galvin and Healy 2020)(Allam et al. 2021) The US Green New Deal Resolution (Ocasio-Cortez 2019) for example positions structural inequality, poverty mitigation, and a just transition at its centre. The European Green Deal proposed in 2019 (European Commission 2019), including a UDF100 billion "Just Transition Mechanism" to mitigate the social effects of transitioning away from jobs in fossil based industries. National level green new deals with strong just transition components have been proposed in South Korea, Australia, Spain, UK, Puerto Rico, Canada, as well as regional proposals across Latin America and the Caribbean (Pollin 2020). .

START BOX 4.6 HERE

Box 4.6 Selected organisations and movements supporting a just transition

Asian Pacific Forum on Women, Law and Development (Asia Pacific)
Blue Green Alliance (US)
Beyond Coal campaign (US)
Central Única dos Trabalhadores (Brazil)
Climate Action Network (global)
Climate Justice Alliance (US)
Cooperation Jackson (US)
Dejusticia (Colombia)
Deutscher Gewerkschaftsbund (German Trade

Kentuckians for the Commonwealth (US)
Labor Network for Sustainability (US)
Latrobe Valley Authority (Australia)
Movement Generation (US)
NAACP (US)
National Union of Mineworkers of South Africa (South Africa)
Pan African Climate Justice Alliance (Africa)
Post Petroleum Transitions Roundtable (Mesa de Transición Post Petrolera) (Argentina)

Union Confederation) (Germany)
DiEM25 (pan-European)
European Union
European Trade Union Confederation (EU)
Grassroots Global Justice (US)
IndustriALL Global Union (global)
Indigenous Environmental Network (US)
International Labor Organization (global)
International Trade Union Confederation—-affiliated Just Transition Centre (Global) Just Transition Alliance (US)
Just Transition Centre (global)
Just Transition Fund (US)
Powering Past Coal Alliance (global)
Right to the city alliance (US)
Sierra Club (US)
Sunrise Movement (US)
The Leap Manifesto (Canada)
The Trade Unions for Energy Democracy Initiative (Global)
Trade Union Confederation of the Americas (TUCA) ITUC's regional branch (Americas)
Transitions Town Movement (UK)
Women's Environment and Development Organization (Global)
350.org (Global)

END BOX 4.6 HERE

A just transition at national, regional and local scales can help to ensure that workers, communities, frontline communities and the energy-poor are not left behind in the transition. Moreover, a just transition necessitates that rapid decarbonisation does not perpetuate asymmetries between richer and poorer states and people (UNHRC 2020). Alliances around a just transition in countries across the world take many forms (Box 4.6).

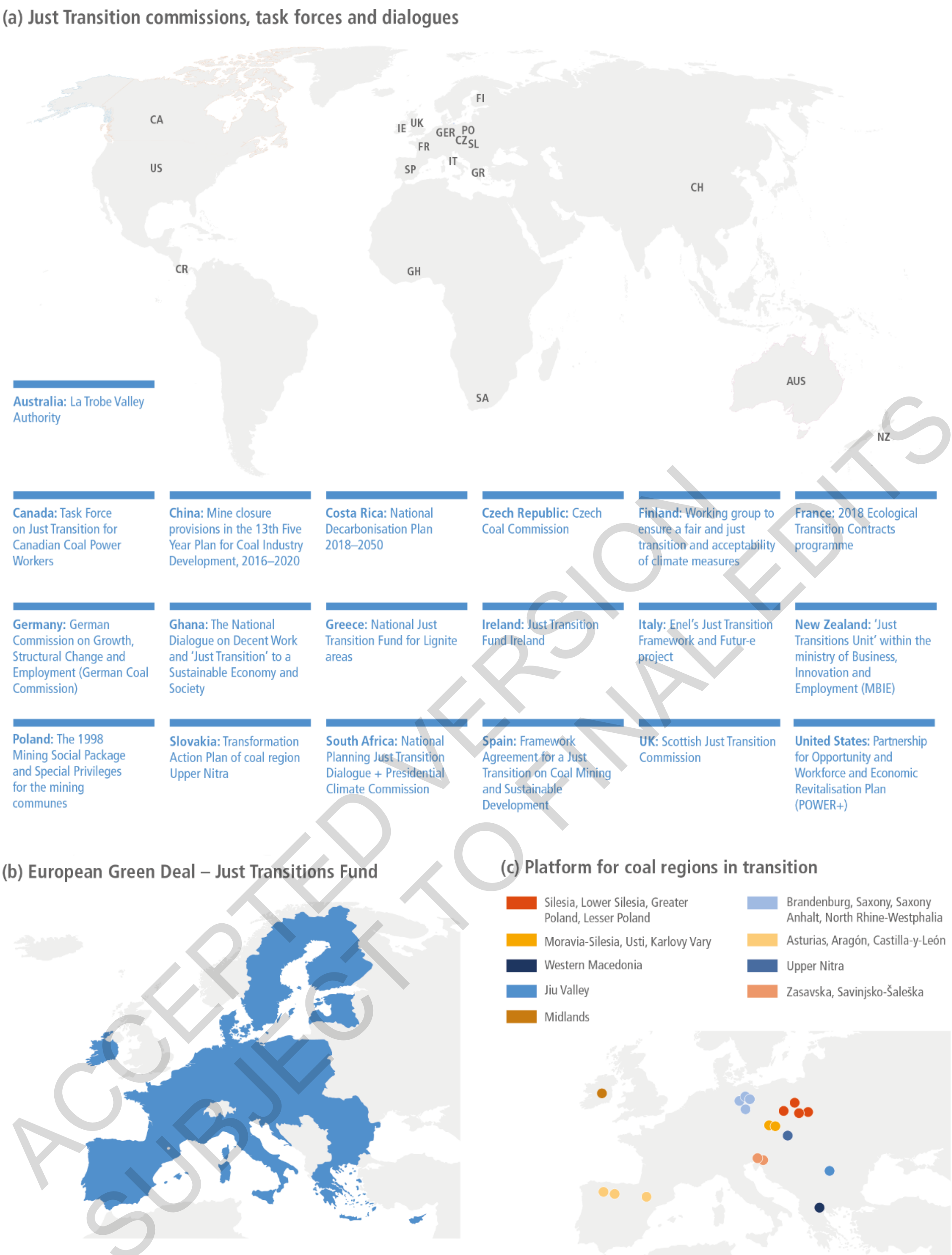

Figure 4.9 Just Transitions around the world, 2020

Panel A shows commissions, task forces, dialogues behind a just transition in many countries ((Snell 2018; Government of Canada 2019; Piggot et al. 2019; Harrison 2013; Government of Costa Rica 2019; Ng et al. 2016; van Asselt and Moerenhout 2018; European Union 2019, 2020; Galgóczi 2019; Finnish Government 2020; Commission on Growth Structural Change and Employment 2019; Ministry of Employment and Labour Relations of Ghana 2018; Popp 2019; Galgóczi 2014; Adeoti et al. 2016; Gass and Echeverria 2017; Ministry of Business Innovation & Employment New Zealand 2019; Mendoza 2014; Szpor, A. and Ziółkowska 2018; Government of Scotland 2020; Bankwatch 2019; NPC (National Planning Commission) 2019; Strambo et al.

2019; Thalmann 2004; White House 2016; Schweitzer, M. and Tonn 2003; International Labor Organization 2018; Mijn Cha et al. 2020); **Panel B shows the funds related to the Just Transition within the European Union Green Deal, and Panel C shows the European Union's Platform for Coal Regions in Transition**.

As Figure 4.9 shows, no fewer than 7 national commissions or task forces on a just transition existed as of 2020 as well as 7 other sets of national policies and a multitude of other actors, networks, and movements. For instance, the German phase-out of coal subsidies involved a savings package for unemployed miners. Subsidy reform packages introduced by Iran, Namibia, the Philippines, Turkey, and the United Kingdom provide similar compensating measures to affected groups (Sovacool 2017). Spain's just transition plan for coal miners includes early retirement, redundancy packages, silicosis compensation, retraining for green jobs, and priority job placement for former miners.

4.6 Knowledge gaps

This section summarises knowledge gaps that require further research:

- Literature on mitigation pathways at the national level remains skewed towards large emitters. Many low-income countries have very few or no studies at all (Lepault and Lecocq 2021) (4.2) (Annex III). Development of new studies and inclusion of associated scenarios in updated mitigation national mitigation pathway database would enhance understanding of mitigation at national level.
- Ex ante and ex post analysis of mitigation action and of mitigation plans by non-state actors, and their relationship with mitigation action and plans by governments is limited (4.2.3).
- System analysis solutions are only beginning to be recognised in current literature on deep mitigation pathways, and rarely included in existing national policies or strategies (4.2.5).
- While the technology elements of accelerated mitigation pathways at national level are generally well documented, studies of the economic and social implications of such pathways remain scarce (4.2.6).
- Literature on the implication of development choices for emissions and for capacity to mitigate is limited (4.3.2). In particular, more contributions from the research community working on development issues would be very useful here.
- Literature describing shifts in development pathways, and the conditions for such shifts (based on past experience or on models) remains scarce (4.3.1, 4.3.3, 4.4.1). Studying shifts in development pathways requires new ways of thinking with interdisciplinary research and use of alternative frameworks and methods suited for understanding of change agents, determinants of change and adaptive management among other issues (Winkler 2018). Research is not only expected to produce knowledge and boost innovation, but also to help identify transformation pathways and to enlighten public debate and public decision making on related political choices.
- Other research gaps concern the open ocean and blue carbon. There is limited knowledge about quantification of the blue carbon stocks. Research is required into what happens if the sequestration capacity of the ocean and marine ecosystems is damaged by climate change to the tipping point until the sink becomes an emitter, and on how to manage blue carbon (4.4.2).
- Knowledge is limited on: i) linking equity frameworks on mitigation with adaptation and most importantly with loss and damage, ii) applying ethical parameters to enrich many of the existing quantitative frameworks, to assess fairness and ambition of NDCs; iii) extending equity

frameworks to quantify equitable international support, as the difference between equity-based national emissions scenarios and national domestic emissions scenarios (4.2.2.7, 4.5).

Frequently asked questions

FAQ 4.1 What is to be done over and above countries existing pledges under the Paris Agreement to keep global warming well below 2°C?

Current pledges and efforts under the PA aimed at keeping global warming below 2°C are not enough, falling short by 14-23 $GtCO_2$-eq (Cross-Chapter Box 4). There is a further shortfall of about 4 to 7 $GtCO_2$-eq in 2030 if the conditions are not fulfilled for those Parties that have made their pledges with conditions for support (4.2.2.3). To cover up for these shortfalls will require taking actions across all sectors that can substantially reduce GHG emissions. Examples of such actions include shifting to low- or zero-emission power generation, such as renewables; changing food systems, such as diet changes away from land-intensive animal products; electrifying transport and developing 'green infrastructure', such as building green roofs, or improving energy efficiency by smart urban planning, which will change the layout of many cities. Because these different actions are connected, it means all relevant companies, industries and stakeholders would need to be involved to increase the support and chance of successful implementation (4.2.5). The deployment of low-emission technology depends upon economic conditions (e.g., employment generation or capacity to mobilize investment), but also on social/cultural conditions (e.g., awareness and acceptability) and institutional conditions (e.g., political support and understanding), and the provision of relevant enabling conditions (4.4.1). Encouraging stronger and more ambitious climate action by non-government and subnational stakeholders, as well as international cooperative initiatives (ICIs) could make significant contributions to emissions reduction (4.2.3).

FAQ 4.2 Option 1: What is to be done in the near-term to accelerate mitigation and shift development pathways?

Increasing speed of implementation, breadth of action across all sectors of the economy, and depth of emission reduction faces important obstacles, that are rooted in the underlying structure of societies (4.2.7). Addressing these obstacles amounts to shifting away from existing developmental trends (i.e., shifting development pathways, Cross-Chapter Box 5). This can be done by strengthening governance and institutional capacity, aligning technology and innovation systems with low-carbon development, facilitating behaviour change and providing adequate finance within the context of multi-objective policy packages and sequences (4.4.1). Shifting development pathways towards sustainability broadens the scope for, and is thus a complement to, accelerated mitigation (4.3).

FAQ 4.3 Is it possible to accelerate mitigation in the near-term while there are so many other development priorities? (education, health, employment, etc.)

It is possible to accelerate mitigation while addressing other developmental priorities by implementing measures that simultaneously address both climate and development goals. Casting mitigation in the broader context of development pathways provides additional opportunities to articulate both (4.3.1.4). Policies such as progressive taxation, investment in public transport, regulatory transparency, commitment to multi-lateral environmental governance, fiscal incentives for private investments, international technology development and transfer initiatives, and risk disclosure and efforts to improve underlying enabling conditions (improving governance and institutional capacity, fostering behavioural change and technological innovation, and provision of finance) address multiple objectives beyond mitigation, such as job creation, macro-economic stability, economic growth, public health and welfare, providing energy access, providing formal housing, and providing mobility. How we manage our land and agriculture, growing cities, transport needs, our industries, and the way people are trained and employed all impact on GHG emissions and the options we have to reduce them. In turn, reducing GHG emissions can also contribute to reducing poverty, preventing hunger, improving health and wellbeing, and providing clean water and clean energy. Implementing right policies and investments can help to address the challenges of how to reduce emissions without constraining development. For example, in land use, widespread planting of a single tree species or crops for bioenergy (organic matter turned into renewable energy) could affect food and water supplies. Therefore, if bioenergy is to be relied upon to offset emissions, the right policies and investments are needed (see also Chapter 17).

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Chapter 5: Demand, services and social aspects of mitigation

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Date of Draft:
28/11/2021

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Executive summary

Assessment of the social science literature and regional case studies reveals how social norms, culture, and individual choices, interact with infrastructure and other structural changes over time. This provides new insight into climate change mitigation strategies, and how economic and social activity might be organised across sectors to support emission reductions. To enhance well-being, people demand services and not primary energy and physical resources per se. Focusing on demand for services and the different social and political roles people play broadens the participation in climate action.

Potential of demand-side actions and service provisioning systems

Demand-side mitigation and new ways of providing services can help *avoid*, *shift*, and *improve* final service demand. Rapid and deep changes in demand make it easier for every sector to reduce GHG emissions in the short and medium term (*high confidence*). {5.2, 5.3}

The indicative potential of demand-side strategies across all sectors to reduce emissions is 40-70% by 2050 (*high confidence*). Technical mitigation potentials compared to the IEA WEO, 2020 STEPS baseline amounts up to 5.7 $GtCO_2eq$ for building use and construction, 8 $GtCO_2eq$ for food demand, 6.5 $GtCO_2eq$ for land transport, and 5.2 $GtCO_2eq$ for industry. Mitigation strategies can be classified as *Avoid*-*Shift*-*Improve* (ASI) options, that reflect opportunities for socio-cultural, infrastructural, and technological change. The greatest *Avoid* potential comes from reducing long-haul aviation and providing short-distance low-carbon urban infrastructures. The greatest *Shift* potential would come from switching to plant-based diets. The greatest *Improve* potential comes from within the building sector, and in particular increased use of energy efficient end-use technologies and passive housing. {5.3.1, 5.3.2, Figure 5.7, Figure 5.8, Table 5.1, Table SM.2}

Socio-cultural and lifestyle changes can accelerate climate change mitigation (*medium confidence*). Among 60 identified actions that could change individual consumption, individual mobility choices have the largest potential to reduce carbon footprints. Prioritizing car-free mobility by walking and cycling and adoption of electric mobility could save 2 $tCO_2eq\ cap^{-1}\ yr^{-1}$. Other options with high mitigation potential include reducing air travel, cooling setpoint adjustments, reduced appliance use, shifts to public transit, and shifting consumption towards plant-based diets. {5.3.1, 5.3.1.2, Figure 5.8}

Leveraging improvements in end-use service delivery through behavioural and technological innovations, and innovations in market organisation, leads to large reductions in upstream resource use (*high confidence*). Analysis of indicative potentials range from a factor 10 to 20 fold improvement in the case of available energy (exergy) analysis, with the highest improvement potentials at the end-user and service-provisioning levels. Realisable service level efficiency improvements could reduce upstream energy demand by 45% in 2050. {5.3.2, Figure 5.10}

Alternative service provision systems, for example those enabled through digitalisation, sharing economy initiatives and circular economy initiatives, have to date made a limited contribution to climate change mitigation (*medium confidence*). While digitalisation through specific new products and applications holds potential for improvement in service-level efficiencies, without public policies and regulations, it also has the potential to increase consumption and energy use. Reducing the energy use of data centres, networks, and connected devices is possible in managing low-carbon digitalisation. Claims on the benefits of the circular economy for sustainability and climate change mitigation have limited evidence. {5.3.4, 5.3.4.1, 5.3.4.2, Figure 5.12, Figure 5.13}

Social aspects of demand-side mitigation actions

***Decent living standards (DLS) and well-being* for all are achievable through the implementation of high-efficiency low demand mitigation pathways (*medium confidence*).** Decent Living Standards (DLS) – a benchmark of material conditions for human well-being – overlaps with many Sustainable Development Goals (SDGs). Minimum requirements of energy use consistent with enabling well-being for all is between 20 and 50 GJ cap^{-1} yr^{-1} depending on the context. {5.2.2.1, 5.2.2.2, Box 5.3}

Providing better services with less energy and resource input has high technical potential and is consistent with providing well-being for all (*medium confidence*). Assessment of 19 demand-side mitigation options and 18 different constituents of well-being show that positive impacts on well-being outweigh negative ones by a factor of 11. {5.2, 5.2.3, Figure 5.6,}

Demand-side mitigation options bring multiple interacting benefits (*high confidence*). Energy services to meet human needs for nutrition, shelter, health, etc. are met in many different ways with different emissions implications that depend on local contexts, cultures, geography, available technologies, social preferences. In the near term, many less-developed countries and poor people everywhere require better access to safe and low-emissions energy sources to ensure decent living standards and increase energy savings from service improvements by about 20-25%. {5.2, 5.4.5, Figure 5.3, Figure 5.4, Figure 5.5, Figure 5.6, Box 5.2, Box 5.3}

Granular technologies and decentralized energy end-use, characterised by modularity, small unit sizes and small unit costs, diffuse faster into markets and are associated with faster technological learning benefits, greater efficiency, more opportunities to escape technological lock-in, and greater employment (*high confidence*). Examples include solar photovoltaic systems, batteries, and thermal heat pumps. {5.3, 5.5, 5.5.3}

Wealthy individuals contribute disproportionately to higher emissions and have a high potential for emissions reductions while maintaining decent living standards and well-being *(high confidence)*. Individuals with high socio-economic status are capable of reducing their GHG emissions by becoming role models of low-carbon lifestyles, investing in low-carbon businesses, and advocating for stringent climate policies. {5.4.1, 5.4.3, 5.4.4, Figure 5.14}

Demand-side solutions require both motivation and capacity for change (*high confidence*). Motivation by individuals or households worldwide to change energy consumption behaviour is generally low. Individual behavioural change is insufficient for climate change mitigation unless embedded in structural and cultural change. Different factors influence individual motivation and capacity for change in different demographics and geographies. These factors go beyond traditional socio-demographic and economic predictors and include psychological variables such as awareness, perceived risk, subjective and social norms, values, and perceived behavioural control. Behavioural nudges promote easy behaviour change, e.g., "*improve*" actions such as making investments in energy efficiency, but fail to motivate harder lifestyle changes. (*high confidence*) {5.4}

Meta-analyses demonstrate that behavioural interventions, including the way choices are presented to consumers[1], work synergistically with price signals, making the combination more effective (*medium confidence*). Behavioural interventions through nudges, and alternative ways of redesigning and motivating decisions, alone provide small to medium contributions to reduce energy

FOOTNOTE [1] The way choices are presented to consumers is known as 'choice architecture' in the field of behavioural economics.

consumption and GHG emissions. Green defaults, such as automatic enrolment in "green energy" provision, are highly effective. Judicious labelling, framing, and communication of social norms can also increase the effect of mandates, subsidies, or taxes. {5.4, 5.4.1, Table 5.3a, Table 5.3b}

Coordinated change in several domains leads to the emergence of new low-carbon configurations with cascading mitigation effects *(high confidence)*. Demand-side transitions involve interacting and sometimes antagonistic processes on the behavioural, socio-cultural, institutional, business, and technological dimensions. Individual or sectoral level change may be stymied by reinforcing social, infrastructural, and cultural lock-ins. Coordinating the way choices are presented to end users and planners, physical infrastructures, new technologies and related business models can rapidly realise system-level change. {5.4.2, 5.4.3, 5.4.4, 5.4.5, 5.5}

Cultural change, in combination with new or adapted infrastructure, is necessary to enable and realise many *Avoid* and *Shift* options (*medium confidence*). By drawing support from diverse actors, narratives of change can enable coalitions to form, providing the basis for social movements to campaign in favour of (or against) societal transformations. People act and contribute to climate change mitigation in their diverse capacities as consumers, citizens, professionals, role models, investors, and policymakers. {5.4, 5.5, 5.6}

Collective action as part of social or lifestyle movements underpins system change (*high confidence*). Collective action and social organising are crucial to shift the possibility space of public policy on climate change mitigation. For example, climate strikes have given voice to youth in more than 180 countries. In other instances, mitigation policies allow the active participation of all stakeholders, resulting in building social trust, new coalitions, legitimising change, and thus initiate a positive cycle in climate governance capacity and policies. {5.4.2, Figure 5.14}

Transition pathways and changes in social norms often start with pilot experiments led by dedicated individuals and niche groups (*high confidence*). Collectively, such initiatives can find entry points to prompt policy, infrastructure, and policy reconfigurations, supporting the further uptake of technological and lifestyle innovations. Individuals' agency is central as social change agents and narrators of meaning. These bottom-up socio-cultural forces catalyse a supportive policy environment, which enables changes. {5.5.2}

The current effects of climate change, as well as some mitigation strategies, are threatening the viability of existing business practices, while some corporate efforts also delay mitigation action (*medium confidence*). Policy packages the include job creation programs help to preserve social trust, livelihoods, respect, and dignity of all workers and employees involved. Business models that protect rent extracting behaviour may sometimes delay political action. Corporate advertisement and brand building strategies may also attempt to deflect corporate responsibility to individuals or aim to appropriate climate care sentiments in their own brand–building. {5.4.3, 5.6.4}

Middle actors -professionals, experts, and regulators- play a crucial albeit underestimated and underutilised role in establishing low-carbon standards and practices (*medium confidence*). Building managers, landlords, energy efficiency advisers, technology installers, and car dealers influence patterns of mobility and energy consumption by acting as middle actors or intermediaries in the provision of building or mobility services and need greater capacity and motivation to play this role. {5.4.3}

Social influencers and thought leaders can increase the adoption of low-carbon technologies, behaviours, and lifestyles (*high confidence*). Preferences are malleable and can align with a cultural shift. The modelling of such shifts by salient and respected community members can help bring about changes in different service provisioning systems. Between 10% and 30% of committed individuals are required to set new social norms. {5.2.1, 5.4}

Preconditions and instruments to enable demand-side transformation

Social equity reinforces capacity and motivation for mitigating climate change (*medium confidence*). Impartial governance such as fair treatment by law and order institutions, fair treatment by gender, and income equity, increases social trust, thus enabling demand-side climate policies. High status (often high carbon) item consumption may be reduced by taxing absolute wealth without compromising well-being. {5.2, 5.4.2, 5.6}

Policies that increase the political access and participation of women, racialized, and marginalised groups, increase the democratic impetus for climate action. (*high confidence*). Including more differently situated knowledge and diverse perspectives makes climate mitigation policies more effective. {5.2, 5.6}

Carbon pricing is most effective if revenues are redistributed or used impartially (*high confidence*). A carbon levy earmarked for green infrastructures or saliently returned to taxpayers corresponding to widely accepted notions of fairness increases the political acceptability of carbon pricing. {5.6, Box 5.11}

Greater contextualisation and granularity in policy approaches better addresses the challenges of rapid transitions towards zero-carbon systems (*high confidence*). Larger systems take more time to evolve, grow, and change compared to smaller ones**.** Creating and scaling up entirely new systems takes longer than replacing existing technologies and practices. Late adopters tend to adopt faster than early pioneers. Obstacles and feasibility barriers are high in the early transition phases. Barriers decrease as a result of technical and social learning processes, network building, scale economies, cultural debates, and institutional adjustments. {5.5, 5.6}

The lockdowns implemented in many countries in response to the COVID-19 pandemic demonstrated that behavioural change at a massive scale and in a short time is possible (*high confidence*). COVID-19 accelerated some specific trends, such as an uptake in urban cycling. However, the acceptability of collective social change over a longer term towards less resource-intensive lifestyles depends on social mandate building through public participation, discussion and debate over information provided by experts, to produce recommendations that inform policy-making. {Box 5.2}

Mitigation policies that integrate and communicate with the values people hold are more successful (*high confidence*). Values differ between cultures. Measures that support autonomy, energy security and safety, equity and environmental protection, and fairness resonate well in many communities and social groups. Changing from a commercialised, individualised, entrepreneurial training model to an education cognizant of planetary health and human well-being can accelerate climate change awareness and action {5.4.1, 5.4.2}

Changes in consumption choices that are supported by structural changes and political action enable the uptake of low-carbon choices (*high confidence*). Policy instruments applied in coordination can help to accelerate change in a consistent desired direction. Targeted technological change, regulation, and public policy can help in steering digitalization, the sharing economy, and circular economy towards climate change mitigation. {5.3, 5.6}

Complementarity in policies helps in the design of an optimal demand-side policy mix (*medium confidence*). In the case of energy efficiency, for example, this may involve CO_2 pricing, standards and norms, and information feedback.{5.3, 5.4, 5.6}

5.1 Introduction

The Sixth Assessment Report of the IPCC (AR6), for the first time, features a chapter on demand, services, and social aspects of mitigation. It builds on the AR4, which linked behaviour and lifestyle change to mitigating climate change (IPCC 2007; Roy and Pal 2009; IPCC 2014a), the Global Energy Assessment (Roy et al. 2012), and the AR5, which identified sectoral demand-side mitigation options across chapters (IPCC 2014b; Creutzig et al. 2016b; IPCC 2014a). The literature on the nature, scale, implementation and implications of demand-side solutions, and associated changes in lifestyles, social norms, and well-being, has been growing rapidly (Creutzig et al. 2021a) (Box 5.2). Demand-side solutions support near-term climate change mitigation (Méjean et al. 2019; Wachsmuth and Duscha 2019) and include consumers' technology choices, behaviours, lifestyle changes, coupled production-consumption infrastructures and systems, service provision strategies, and associated socio-technical transitions. This chapter's assessment of the social sciences (also see Supplementary Materials I Chapter 5) reveals that social dynamics at different levels offer diverse entry points for acting on and mitigating climate change (Jorgenson et al. 2018).

Three entry points are relevant for this chapter. First, well-designed demand for services scenarios are consistent with adequate levels of well-being for everyone (Rao and Baer 2012; Grubler et al. 2018; Mastrucci et al. 2020; Millward-Hopkins et al. 2020), with high and/or improved quality of life (Max-Neef 1995), improved levels of happiness (Easterlin et al. 2010) and sustainable human development (Arrow et al. 2013; Dasgupta and Dasgupta 2017).

Second, demand-side solutions support staying within planetary boundaries (Haberl et al. 2014; Matson et al. 2016; Hillebrand et al. 2018; Andersen and Quinn 2020; UNDESA 2020; Hickel et al. 2021; Keyßer and Lenzen 2021): they entail fewer environmental risks than many supply side technologies (Von Stechow et al. 2016) and make carbon dioxide removal technologies, such as Bio-Energy with Carbon Capture and Storage (BECCS) less relevant (Van Vuuren et al. 2018) or possibly irrelevant in modelling studies (Grubler et al. 2018; Hickel et al. 2021; Keyßer and Lenzen 2021) still requiring ecosystem based carbon dioxide removal. In the IPCC's SR1.5C (IPCC 2018), four stylised scenarios have explored possible pathways towards stabilising global warming at 1.5°C (SPM SR.15 Figure 3a (IPCC 2014a), (Figure 5.1) One of these scenarios, LED-19, investigates the scope of demand-side solutions (Figure 5.1). The comparison of scenarios reveals that such low-energy demand pathways eliminate the need for technologies with high uncertainty, such as BECCS.

Third, interrogating demand for services from the well-being perspective also opens new avenues for assessing mitigation potentials (Brand-Correa and Steinberger 2017; Mastrucci and Rao 2017; Rao and Min 2018a; Mastrucci and Rao 2019; Baltruszewicz et al. 2021). Arguably, demand-side interventions often operate institutionally or in terms of restoring natural functioning and have so far been politically side lined but COVID-19 revealed interesting perspectives (Box 5.2). Such demand-side solutions also support near-term goals towards climate change mitigation and reduce the need for politically challenging high global carbon prices (Méjean et al. 2019) (Box 5.11). The well-being focus emphasises equity and universal need satisfaction, compatible with Sustainable Development Goals (SDGs) progress (Lamb and Steinberger 2017).

The requisites for well-being include collective and social interactions as well as consumption-based material inputs. Moreover, rather than material inputs *per se*, people need and demand services for dignified survival, sustenance, mobility, communication, comfort and material well-being (Nakićenović et al. 1996b; Johansson et al. 2012; Creutzig et al. 2018). These services may be provided in many different context-specific ways using physical resources (biomass, energy, materials, etc.) and available technologies (e.g. cooking tools, appliances). Here we understand demand as demand for services (often requiring material input), with particular focus on services that are required for well-being (such as lighting, accessibility, shelter, etc.), and that are shaped by culturally and geographically differentiated social aspects, choice architectures and the built environment (infrastructures).

Focusing on demand for services broadens the climate solution space beyond technological switches confined to the supply side, to include solutions that maintain or improve well-being related to nutrition, shelter and mobility while (sometimes radically) reducing energy and material input levels (Creutzig et al. 2018; Cervantes Barron 2020; Baltruszewicz et al. 2021; Kikstra et al. 2021b). This also recognises that mitigation policies are politically, economically and socially more feasible, as well as more effective, when there is a two-way alignment between climate action and well-being (OECD 2019a). There is *medium evidence and high agreement* that well-designed demand for services scenarios are consistent with adequate levels of well-being for everyone (Rao and Baer 2012; Grubler et al. 2018; Rao et al. 2019b; Millward-Hopkins et al. 2020; Kikstra et al. 2021b), with high and/or improved quality of life (Max-Neef 1995; Vogel et al. 2021) and improved levels of happiness (Easterlin et al. 2010) and sustainable human development (Gadrey and Jany-Catrice 2006; Arrow et al. 2013; Dasgupta and Dasgupta 2017). While demand for services is high as development levels increase, and related emissions are growing in many countries (Yumashev et al. 2020; Bamisile et al. 2021), there is also evidence that provisioning systems delink services provided from emissions (Conte Grand 2016; Patra et al. 2017; Kavitha et al. 2020). Various mitigation strategies, often classified into Avoid-Shift-Improve (ASI) options, effectively reduce primary energy demand and/or material input (Haas et al. 2015; Haberl et al. 2017; Samadi et al. 2017; Hausknost et al. 2018; Haberl et al. 2019; Van den Berg et al. 2019; Ivanova et al. 2020). Users' participation in decisions about how services are provided, not just their technological feasibility, is an important determinant of their effectiveness and sustainability (Whittle et al. 2019; Vanegas Cantarero 2020).

Sector-specific mitigation approaches (Chapters 6-11) emphasise the potential of mitigation via improvements in energy- and materials- efficient manufacturing (Gutowski et al. 2013; Gramkow and Anger-Kraavi 2019; Olatunji et al. 2019; Wang et al. 2019), new product design (Fischedick et al. 2014), energy-efficient buildings (Lucon et al. 2014), shifts in diet (Bajželj et al. 2014; Smith et al. 2014), and transport infrastructure design shifts (Sims et al. 2014), compact urban forms (Seto et al. 2014). In this chapter, service-related mitigation strategies are categorized as **A**void, **S**hift, or **I**mprove (ASI) options to show how mitigation potentials, and social groups who can deliver them, are much broader than usually considered in traditional sector-specific presentations. ASI originally arose from the need to assess the staging and combinations of interrelated mitigation options in the provision of transportation services (Hidalgo and Huizenga 2013). In the context of transportation services, ASI seeks to mitigate emissions through *avoiding* as much transport service demand as possible (e.g., telework to eliminate commutes, mixed-use urban zoning to shorten commute distances), *shifting* remaining demand to more efficient modes (e.g., bus rapid transit replacing passenger vehicles), and *improving* the carbon intensity of modes utilised (e.g., electric buses powered by renewables) (Creutzig et al. 2016a). This chapter summarises ASI options and potentials across sectors and generalises the definitions. 'Avoid' refers to all mitigation options that reduce unnecessary (in the sense of being not required to deliver the desired service output) energy consumption by redesigning service provisioning systems; 'shift' refers to the switch to already existing competitive efficient technologies and service provisioning systems; and 'improve' refers to improvements in efficiency in existing technologies. The Avoid-Shift-Improve framing operates in three domains: 'Socio-cultural', where social norms, culture, and individual choices play an important role – a category especially but not only relevant for avoid options; 'Infrastructure', which provides the cost and benefit landscape for realising options and is particularly relevant for shift options; and 'Technologies', especially important for the improve options. Avoid, Shift, and Improve choices will be made by individuals and households, instigated by salient and respected role models and novel social norms, but require support by adequate infrastructures designed by urban planners and building and transport professionals, corresponding investments, and a political culture supportive of mitigation action. This is particularly true for many Avoid and Shift decisions that are difficult because they encounter psychological barriers of breaking routines, habits and imagining new lifestyles and the social costs of not conforming to society (Kaiser 2006). Simpler Improve decisions like energy efficiency investments on the other hand can be triggered and sustained by traditional policy instruments complemented by behavioural nudges.

A key concern about climate change mitigation policies is that they may reduce quality of life. Based on growing literature, in this chapter we adopt the concept of Decent Living Standards (DLS, explained further in relation to other individual and collective well-being measures and concepts in the Social Sciences Primer) as a universal set of service requirements essential for achieving basic human well-being. DLS includes the dimensions of nutrition, shelter, living condition, clothing, health care, education, and mobility (Frye et al. 2018; Rao and Min 2018b). DLS provides a fair, direct way to understand the basic low-carbon energy needs of society and specifies the underlying material and energy requirements. This chapter also comprehensively assesses related well-being metrics that result from demand-side action observing overall positive effects (5.3). Similarly, ambitious low-emissions demand-side scenarios suggest that well-being could be maintained or improved while reducing global final energy demand, and some current literature estimates that it is possible to meet Decent Living Standards for all within the 2-degree warming window (Grubler et al. 2018; Burke 2020; Keyßer and Lenzen 2021) (5.4). A key concern here is how to blend new technologies with social change to integrate Improving ways of living, Shifting modalities and Avoiding certain kinds of emissions altogether (5.6). Social practice theory emphasizes that material stocks and social relations are key in forming and maintaining habits (Reckwitz 2002; Haberl et al. 2021) . This chapter reflects these insights by assessing the role of infrastructures and social norms in GHG emission intensive or low-carbon lifestyles (5.4).
A core operational principle for sustainable development is equitable access to services to provide well-being for all, while minimising resource inputs and environmental and social externalities/trade-offs, underpinning the Sustainable Development Goals (SDGs) (Princen 2003; Lamb and Steinberger 2017; Dasgupta and Dasgupta 2017). Sustainable development is not possible without changes in consumption patterns within the widely recognised constraints of planetary boundaries, resource availability, and the need to provide decent living standards for all (Langhelle 2000; Toth and Szigeti 2016; O'Neill et al. 2018). Inversely, reduced poverty and higher social equity offer opportunities for delinking demand for services from emissions, e.g., via more long-term decision making after having escaped poverty traps and by reduced demand for non-well-being enhancing status consumption (Nabi et al. 2020; Ortega-Ruiz et al. 2020; Parker and Bhatti 2020; Teame and Habte 2020) (5.3).

Throughout this chapter we discuss how people can realise various opportunities to reduce GHG emission-intensive consumption (5.2 and 5.3), and act in various roles (5.4), within an enabling environment created by policy instruments and infrastructure that builds on social dynamics (5.6).

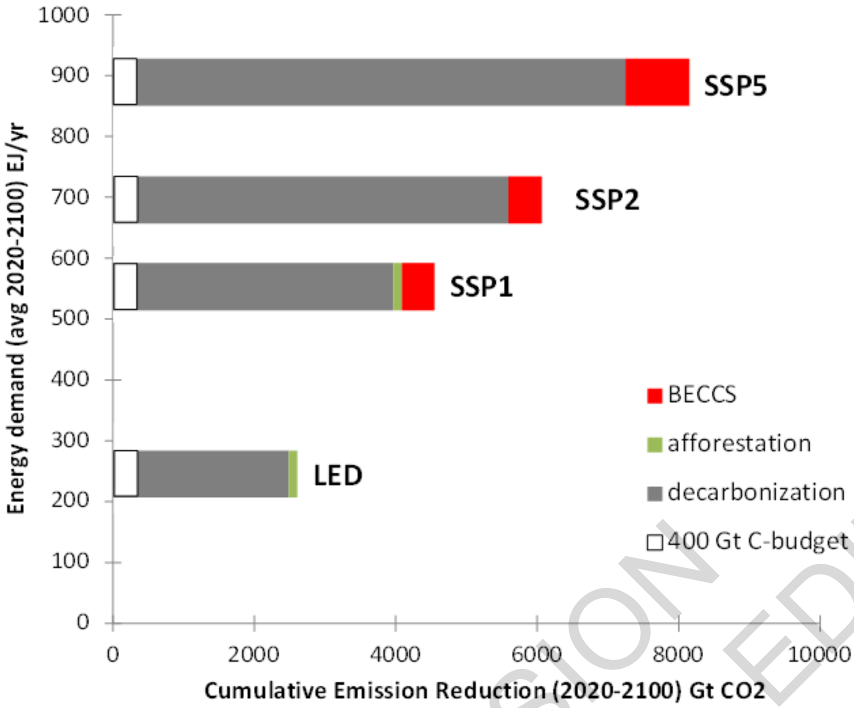


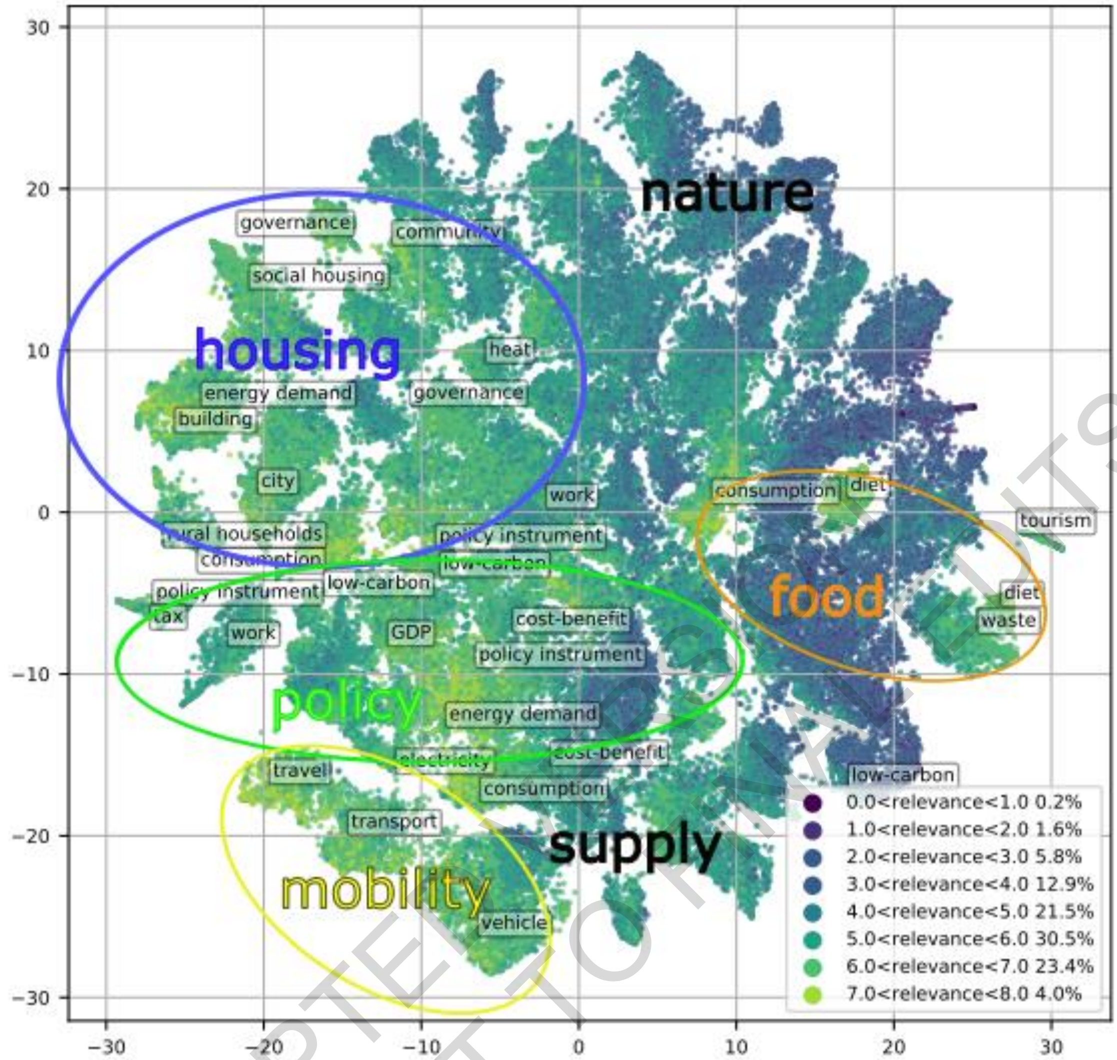
Figure 5.1 Low Energy Demand (LED) Scenario needs no BEECS and needs less decarbonisation efforts. Dependence of the size of the mitigation effort to reach a 1.5°C climate target (cumulative $GtCO_2$ emission reduction 2020-2100 by option) as a function of the level of energy demand (average global final energy demand 2020-2100 in EJ yr^{-1}) in baseline and corresponding 1.5°C scenarios (1.9 W m^{-2} radiative forcing change) based on the IPCC Special Report on 1.5°C global warming (data obtained from the scenario explorer database, LED baseline emission data obtained from authors). In this figure an example of remaining carbon budget of 400 Gt has been taken (from Rogelj, 2019) for illustrative purpose. 400 Gt is also the number given in Table SPM.2 (pg. 29, IPCC 2021) for a probability of 67% to limit global warming to 1.5°C .

START BOX 5.1 HERE

Box 5.1 Bibliometric foundation of demand-side climate change mitigation

A bibliometric overview of the literature found 99,065 academic peer-reviewed papers identified with 34 distinct search queries addressing relevant content of this chapter (Creutzig et al. 2021a). The literature is growing rapidly (15% yr^{-1}) and the literature body assessed in the AR6 period (2014-2020) is twice as large as all literature published before.

A large part of the literature is highly repetitive and/or includes no concepts or little quantitative or qualitative data of relevance to this chapter. For example, a systematic review on economic growth and decoupling identified more than 11,500 papers treating this topic, but only 834 of those, i.e. 7%, included relevant data (Wiedenhofer et al. 2020). In another systematic review, assessing quantitative estimates of consumption-based solutions (Ivanova et al. 2020), only 0.8% of papers were considered after consistency criteria were enforced. Altogether, we relied on systematic reviews wherever possible. Other important papers were not captured by systematic reviews, but included in this chapter through expert judgement. Based on topical modelling and relevance coding of resulting topics, the full literature body can be mapped into two dimensions, where spatial relationships indicate topical distance (Box 5.1, Figure 1). The interpretation of topic demonstrates that the literature organises in four clusters of high relevance for demand-side solutions (housing, mobility, food, and policy), whereas other clusters (nature, energy supply) are relatively less relevant.



Box 5.1, Figure 1 Map of the literature on demand, services and social aspects of climate change mitigation.

Dots show document positions obtained by reducing the 60-dimensional topic scores to two dimensions aiming to preserve similarity in overall topic score. The two axes therefore have no direct interpretation but represent a reduced version of similarities between documents across 60 topics. Documents are coloured by query category. Topic labels of the 24 most relevant topics are placed in the centre of each of the large clusters of documents associated with each topic. % value in caption indicates the proportion of studies in each "relevance" bracket.

Source: (Creutzig et al. 2021a)

END BOX 5.1 HERE

Section 5.2 provides evidence on the links among mitigation and well-being, services, equity, trust, and governance. Section 5.3 quantifies the demand-side opportunity space for mitigation, relying on the Avoid, Shift and Improve framework. Section 5.4 assesses the relevant contribution of different parts of society to climate change mitigation. Section 5.5 evaluates the overall dynamics of social transition processes while Section 5.6 summarises insights on governance and policy packages for demand-side mitigation and well-being. A Social Science Primer defines and discusses key terms and social science concepts used in the context of climate change mitigation.

START BOX 5.2 HERE

Box 5.2 COVID-19, service provisioning and climate change mitigation

There is now *high evidence and high agreement* that the COVID-19 pandemic has increased the political feasibility of large-scale government actions to support the services for provision of public goods, including climate change policies. Many behavioural changes due to COVID-19 reinforce sufficiency and emphasis on solidarity, economies built around care, livelihood protection, collective action, and basic service provision, linked to reduced emissions.

COVID-19 led to direct and indirect health, economic, and confinement-induced hardships and suffering, mostly for the poor, and reset habits and everyday behaviours of the well-off too, enabling a reflection on the basic needs for a good life. Although COVID-19 and climate change pose different kinds of threats and therefore elicit different policies, there are several lessons from COVID-19 for advancing climate change mitigation (Klenert et al. 2020; Manzanedo and Manning 2020; Stark 2020). Both crises are global in scale, requiring holistic societal response; governments can act rapidly, and delay in action is costly (Bouman et al. 2020a; Klenert et al. 2020). The pandemic highlighted the role of individuals in collective action and many people felt morally compelled and responsible to act for others (Budd and Ison, 2020). COVID-19 also taught the effectiveness of rapid collective action (physical distancing, wearing masks, etc.) as contributions to the public good. The messaging about social distancing, wearing masks and handwashing during the pandemic called attention to the importance of effective public information (e.g. also about reducing personal carbon footprints), recognising that rapid pro-social responses are driven by personal and socio-cultural norms (Sovacool et al. 2020a; Bouman et al. 2020a). In contrast, low trust in public authorities impairs the effectiveness of policies and polarizes society (Bavel et al. 2020; Hornsey 2020).

During the shutdown, emissions declined relatively most in aviation, and absolutely most in car transport (Le Quéré et al. 2020, Sarkis et al. 2020), and there were disproportionally strong reductions in GHG emissions from coal (Bertram et al. 2021)(Chapter 2). At their peak, CO_2 emissions in individual countries decreased by 17% in average (Le Quéré et al. 2020). Global energy demand was projected to drop by 5% in 2020, energy-related CO_2 emissions by 7%, and energy investment by 18% (IEA 2020a). Covid-19 shock and recovery scenarios project final energy demand reductions of 1–36 EJ yr−1 by 2025 and cumulative CO2 emission reductions of 14–45 GtCO2 by 2030 (Kikstra et al. 2021a). Plastics use and waste generation increased during the pandemic (Klemeš et al. 2020; Prata et al. 2020). Responses to COVID-19 had important connections with energy demand and GHG emissions due to quarantine and travel restrictions (Sovacool et al. 2020a). Reductions in mobility and economic activity reduced energy use in sectors such as industry and transport, but increased energy use in the residential sector (Diffenbaugh et al. 2020). COVID-19 induced behavioural changes that may translate into new habits, some beneficial and some harmful for climate change mitigation. New digitally enabled service accessibility patterns (videoconferencing, telecommuting) played an important role in sustaining various service needs while avoiding demand for individual mobility. However, public transit lost customers to cars, personalised two wheelers, walking and cycling, while suburban and rural living gained popularity, possibly with long-term consequences. Reduced air travel, pressures for more localised food and manufacturing supply chains (Hobbs 2020; Nandi et al. 2020; Quayson et al. 2020), and governments' revealed willingness to make large-scale interventions in the economy also reflect sudden shifts in service provisions and GHG emissions, some likely to be lasting (Aldaco et al. 2020; Bilal et al. 2020; Boyer 2020; Norouzi et al. 2020; Prideaux et al. 2020; Hepburn et al. 2020; Sovacool et al. 2020a). If changes in some preference behaviours, e.g. for larger homes and work environments to enable home working and online education, lead to sprawling suburbs or gentrification with linked environmental consequences, this could translate into long-term implications for climate change (Beaunoyer et al. 2020; Diffenbaugh et al. 2020). Recovering from the pandemic by adopting low energy demand practices – embedded in new travel, work, consumption and production behaviour and patterns– could reduce carbon prices for a 1.5°C consistent pathway by 19%, reduce energy supply investments until 2030 by 1.8 trillion USD, and lessen pressure on the upscaling of low-carbon energy technologies (Kikstra et al. 2021a).

COVID-19 drove hundreds of millions of people below poverty thresholds, reversing decades of poverty reduction accomplishments (Krieger 2020; Mahler et al. 2020; Patel et al. 2020; Sumner et al. 2020) and raising the spectre of intersecting health and climate crises that are devastating for the most vulnerable (Flyvbjerg 2020; Phillips et al. 2020). Like those of climate change, pandemic impacts fall heavily on disadvantaged groups, exacerbate the uneven distribution of future benefits, amplify existing inequities, and introduce new ones (Devine-Wright et al. 2020; Beaunoyer et al. 2020). Addressing such inequities is a positive step towards the social trust that leads to improved climate policies as well as individual actions. Increased support for care workers and social infrastructures within a solidarity economy is consistent with lower-emission economic transformation (Shelley 2017; Di Chiro 2019; Pichler et al. 2019; Smetschka et al. 2019).

Fiscally, the pandemic may have slowed the transition to a sustainable energy world: governments redistributed public funding to combat the disease, adopted austerity and reduced capacity, i.e. among nearly 300 policies implemented to counteract the pandemic, the vast majority are related to rescue, including worker and business compensation, and only 4% of these focus on green policies with potential to reduce GHG emissions in the long-term; some rescue policies also assist emissions-intensive business (Leach et al. 2021; Hepburn et al. 2020). However, climate investments can double as the basis of the COVID-19 recovery (Stark 2020), with policies focused on both economic multipliers and climate impacts such as clean physical infrastructure, natural capital investment, clean R&D and education and training (Hepburn et al. 2020). This requires attention to investment priorities, including often-underprioritized social investment, given how inequality intersects with and is a recognised core driver of environmental damage and climate change (Millward-Hopkins et al. 2020).

END BOX 5.2 HERE

5.2 Services, well-being and equity in demand-side mitigation

As outlined in section 5.1, mitigation, equity and well-being go hand in hand to motivate actions. Global, regional, and national actions/policies that advance inclusive well-being and build social trust strengthen governance. There is *high evidence and high agreement* that demand-side measures cut across all sectors, and can bring multiple benefits (Mundaca et al. 2019; Wachsmuth and Duscha 2019; Geels 2020; Niamir et al. 2020b; Garvey et al. 2021; Roy et al. 2021). Since effective demand requires affordability, one of the necessary conditions for acceleration of mitigation through demand side measures is wide and equitable participation from all sectors of society. Low-cost low-emissions technologies, supported by institutions and government policies, can help meet service demand and advance both climate and well-being goals (Steffen et al. 2018a; Khosla et al. 2019). This section introduces metrics of well-being and their relationship to GHG emissions, and clarifies the concept of service provisioning.

5.2.1 Metrics of well-being and their relationship to GHG emissions

There is *high evidence and agreement* in the literature that human well-being and related metrics provide a societal perspective which is inclusive, compatible with sustainable development, and generates multiple ways to mitigate emissions. Development targeted to basic needs and well-being for all entails less carbon-intensity than GDP-focused growth (Rao et al. 2014; Lamb and Rao 2015).

Current socioeconomic systems are based on high-carbon economic growth and resource use (Steffen et al. 2018b). Several systematic reviews confirm that economic growth is tightly coupled with increasing CO_2 emissions (Ayres and Warr 2005; Tiba and Omri 2017; Mardani et al. 2019; Wiedenhofer et al. 2020) although the level of emissions depends on inequality (Baležentis et al. 2020; Liu et al. 2020b), and on geographic and infrastructural constraints that force consumers to use fossil fuels (Pottier et al. 2021). Different patterns emerge in the causality of the energy-growth nexus; (i) energy consumption causes economic growth; (ii) growth causes energy consumption; (iii) bidirectional causality; and (iv) no significant causality (Ozturk 2010). In a systematic review, Mardani et al. (Mardani et al. 2019) found that in most cases energy use and economic growth have a bidirectional causal effect, indicating that as economic growth increases, further CO_2 emissions are stimulated at higher levels; in turn, measures designed to lower GHG emissions may reduce economic growth. However, energy substitution and efficiency gains may offer opportunities to break the bidirectional dependency (Komiyama 2014; Brockway et al. 2017; Shuai et al. 2019). Worldwide trends reveal that at best only relative decoupling (resource use grows at a slower pace than GDP) was the norm during the twentieth century (Jackson 2009; Krausmann et al. 2009; Ward et al. 2016; Jackson 2017), while absolute decoupling (when material use declines as GDP grows) is rare, observed only during recessions or periods of low or no economic growth (Heun and Brockway 2019; Hickel and Kallis 2019; Vadén et al. 2020; Wiedenhofer et al. 2020). Recent trends in OECD countries demonstrate the potential for absolute decoupling of economic growth not only from territorial but also from consumption-based emissions (Le Quéré et al. 2019), albeit at scales insufficient for mitigation pathways (Vadén et al. 2020) (Chapter 2).

Energy demand and demand for GHG intensive products increased from 2010 until 2020 across all sectors and categories. 2019 witnessed a reduction in energy demand growth rate to below 1% and 2020 an overall decline in energy demand, with repercussions into energy supply disproportionally affecting coal via merit order effects (Bertram et al. 2021) (Cross-Chapter Box 1 in Chapter 1). There was a slight but significant shift from high carbon beef consumption to medium carbon intensive poultry consumption. Final energy use in buildings grew from 118 EJ in 2010 to around 128 EJ in 2019 (increased about 8%). The highest increase was observed in non-residential buildings, with a 13% increase against 8% in residential energy demand (IEA 2019a). While electricity accounted for one-third of building energy use in 2019, fossil fuel use also increased at a marginal annual average growth rate of 0.7% since 2010 (IEA 2020a). Energy-related CO_2 emissions from buildings have risen in recent years after flattening between 2013 and 2016. Direct and indirect emissions from electricity and commercial heat used in buildings rose to 10 $GtCO_2$ in 2019, the highest level ever recorded. Several factors have contributed to this rise, including growing energy demand for heating and cooling with rising air-conditioner ownership and extreme weather events. A critical issue remains for how comfortable people feel with temperatures they will be exposed to in the future and this depends on factors such as physical, psychological and behavioral (Singh et al. 2018; Jacobs et al. 2019). Literature now shows *high evidence and high agreement* around the observation that policies and infrastructure interventions that lead to change in human preferences are more valuable for climate change mitigation. In economics, welfare evaluations are predominantly based on the preference approach. Preferences are typically assumed to be fixed, so that only changes in relative prices will reduce emissions. However, as decarbonisation is a societal transition, individuals' preferences do shift and this can contribute to climate change mitigation (Gough 2015). Even if preferences are assumed to change in response to policy, it is nevertheless possible to evaluate policy, and demand-side solutions, by approaches to well-being/welfare that are based on deeper concepts of preferences across disciplines (Fleurbaey and Tadenuma 2014; Dietrich and List 2016; Mattauch and Hepburn 2016; Roy and Pal 2009; Komiyama

2014). In cases of past societal transitions, such as smoking reduction, there is evidence that societies guided the processes of shifting preferences, and values changed along with changing relative prices (Nyborg and Rege 2003; Stuber et al. 2008; Brownell and Warner 2009). Further evidence on changing preferences in consumption choices pertinent to decarbonisation includes (Grinblatt et al. 2008; Weinberger and Goetzke 2010) for mobility; (Erb et al. 2016; Muller et al. 2017; Costa and Johnson 2019) for diets; (Baranzini et al. 2017) for solar panel uptake. If individuals' preferences and values change during a transition to the low-carbon economy, then this overturns conclusions on what count as adequate or even optimal policy responses to climate change mitigation in economics (Jacobsen et al. 2012; Schumacher 2015; Dasgupta et al. 2016; Daube and Ulph 2016; Ulph and Ulph 2021). In particular, if policy instruments, such as awareness campaigns, infrastructure development or education, can change people's preferences, then policies or infrastructure provision – socially constrained by deliberative decision making -- which change both relative prices and preferences, are more valuable for mitigation than previously thought (Mattauch et al. 2016, 2018; Creutzig et al. 2016b). The provisioning context of human needs is participatory, so transformative mitigation potential arises from social as well as technological change (Lamb and Steinberger 2017). Many dimensions of well-being and 'basic needs' are social not individual in character (Schneider 2016), so extending well-being and DLS analysis to emissions also involves understanding individual situations in social contexts. This includes building supports for collective strategies to reduce emissions (Chan et al. 2019), going beyond individual consumer choice. Climate policies that affect collective behaviour fairly are the most acceptable policies across political ideologies (Clayton 2018); thus collective preferences for mitigation are synergistic with evolving policies and norms in governance contexts that reduce risk, ensure social justice and build trust (Atkinson et al. 2017; Cramton et al. 2017; Milkoreit 2017; Tvinnereim et al. 2017; Smith and Reid 2018; Carattini et al. 2019).

Because of data limitations, which can make cross-country comparisons difficult, health-based indicators and in particular life expectancy (Lamb et al. 2014) have sometimes been proposed as quick and practical ways to compare local or national situations, climate impacts, and policy effects (Decancq et al. 2009; Sager 2017; Burstein et al. 2019). A number of different well-being metrics are valuable in emphasising the constituents of what is needed for a decent life in different dimensions (Porter et al. 2017; Smith and Reid 2018; Lamb and Steinberger 2017). The SDGs overlap in many ways with such indicators, and the data needed to assess progress in meeting the SDGs is also useful for quantifying well-being (Gough 2017). For the purposes of this chapter, indicators directly relating GHG emissions to well-being for all are particularly relevant.

Well-being can be categorised either as "hedonic" or "eudaimonic". Hedonic well-being is related to a subjective state of human motivation, balancing pleasure over pain, and has gained influence in psychology assessing 'subjective well-being' such as happiness and minimising pain, assuming that the individual is motivated to enhance personal freedom, self-preservation and enhancement (Sirgy 2012; Ganglmair-Wooliscroft and Wooliscroft 2019; Brand-Correa and Steinberger 2017; Lamb and Steinberger 2017). Eudaimonic well-being focuses on the individual in the broader context, associating happiness with virtue (Sirgy 2012) allowing for social institutions and political systems and considering their ability to enable individuals to flourish. Eudaimonic analysis supports numerous development approaches (Fanning and O'Neill 2019) such as the capabilities (Sen 1985), human needs (Doyal and Gough 1991; Max-Neef et al. 1991) and models of psychosocial well-being (Ryan and Deci 2001). Measures of well-being differ somewhat in developed and developing countries (Sulemana et al. 2016; Ng and Diener 2019); for example, food insecurity, associated everywhere with lower subjective well-being, is more strongly associated with poor subjective well-being in more-developed countries (Frongillo et al. 2019); in wealthier countries, the relationship between living in rural areas is less strongly associated with negative well-being than in less-developed countries (Requena 2016); and income inequality is negatively associated with subjective well-being in developed countries, but positively so in less-developed countries (Ngamaba et al. 2018). This chapter connects demand side climate mitigation options to multiple dimensions of well-being going beyond single dimensional metric of GDP which is at the core of IAMs. Many demand side mitigation solutions generate positive and negative impacts on wider dimensions of human well-being which are not always quantifiable (*medium evidence, medium agreement).*

5.2.1.1 Services for well-being

Well-being needs are met through services. Provision of services associated with low-energy demand is a key component of current and future efforts to reduce carbon emissions. Services can be provided in various culturally-appropriate ways, with diverse climate implications. There is *high evidence and high agreement* in the literature that many granular service provision systems can make 'demand' more flexible, provide new options for mitigation, support access to basic needs, and enhance human well-being. Energy services offer an important lens to analyse the relationship between energy systems and human well-being (Jackson and Papathanasopoulou 2008; Druckman and Jackson 2010; Mattioli 2016; Walker et al. 2016; Fell 2017; Brand-Correa et al. 2018; King et al. 2019; Pagliano and Erba 2019; Whiting et al. 2020). Direct and indirect services provided by energy, rather than energy itself, deliver well-being benefits (Kalt et al. 2019). For example, illumination and transport are intermediary services in relation to education, healthcare, meal preparation, sanitation, etc. which are basic human needs. Sustainable consumption and production revolve around 'doing more and better with the same ' and thereby increasing well-being from economic activities 'by reducing resource use, degradation and pollution along the whole lifecycle, while increasing quality of life' (UNEP 2010). Although energy is required for delivering human development by supporting access to basic needs (Lamb and Rao 2015; Lamb and Steinberger 2017), a reduction in primary energy use and/or shift to low-carbon energy, if associated with the maintenance or improvement of services, can not only ensure better environmental quality but also directly enhance well-being (Roy et al. 2012) the correlation between human development and emissions are not necessarily coupled in the long term, which implies prioritize human well-being and the environment over economic growth (Steinberger et al. 2020). At the interpersonal and community level, cultural specificities, infrastructure, norms, and relational behaviours differ. (Box 5.3). For example, demand for space heating and cooling depends on building materials and designs, urban planning, vegetation, clothing and social norms as well as geography, incomes, and outside temperatures (Campbell et al. 2018; Ivanova et al. 2018; IEA 2019b; Dreyfus et al. 2020; Brand-Correa et al. 2018). In personal mobility, different variable needs satisfiers (e.g., street space allocated to cars, bussesor bicycles) can help satisfy human needs, such as accessibility to jobs, health care, and education. Social interactions and normative values play a crucial role in determining energy demand. Hence, demand-side and service-oriented mitigation strategies are most effective if geographically and culturally differentiated (Niamir et al. 2020a).

Decent Living Standards (DLS) serves as a socio-economic benchmark as it views human welfare not in relation to consumption but rather in terms of services which together help meet human needs (e.g. nutrition, shelter, health, etc.), recognising that these service needs may be met in many different ways (with different emissions implications) depending on local contexts, cultures, geography, available technologies, social preferences, and other factors. Therefore, one key way of thinking about providing well-being for all with low carbon emissions centres around prioritising ways of providing services for DLS in a low-carbon way (including choices of needs satisfiers, and how these are provided or made accessible). They may be supplied to individuals or groups / communities, both through formal markets and/or informally, e.g. by collaborative work, in coordinated ways that are locally-appropriate, designed and implemented in accordance with overlapping local needs.

The most pressing DLS service shortfalls, as shown in Figure 5.2, lie in the areas of nutrition, mobility, and communication. Gaps in regions such as Africa and the Middle East are accompanied by current levels of service provision in the highly industrialised countries at much higher than DLS levels for the same three service categories. The lowest population quartile by income worldwide faces glaring shortfalls in housing, mobility, and nutrition. Meeting these service needs using low-emissions energy sources is a top priority. Reducing GHG emissions associated with high levels of consumption and material throughput by those far above DLS levels has potential to address both emissions and inequality in energy and emission footprints (Otto et al. 2019). This, in turn, has further potential benefits; under the conditions of 'fair' income reallocation public services, this can reduce national carbon footprint by up to 30% while allowing the consumption of those at the bottom to increase (Millward-Hopkins and Oswald 2021). The challenge then is to address the upper limits of consumption. When consumption supports the satisfaction of basic needs any decrease causes deficiencies in human-need satisfaction, contrary, in the case of consumption that exceeds the limits of basic needs. A deprivation causes a subjective discomfort (Brand-Correa et al. 2020) therefore, establishing minimum and maximum standards of consumption or sustainable consumption corridors (Wiedmann et al. 2020) has been suggested to collectively not surpassing the environmental limits depending on the context. In some countries, carbon intensive ways of satisfying human needs have been locked-in, e.g. via car-dependent infrastructures (Druckman and Jackson 2010; Jackson and Papathanasopoulou 2008; King et al. 2019; Mattioli 2016), and both infrastructure reconfiguration and adaptation are required to organise need satisfaction in low-carbon ways (see also Section 10.2 in Chapter 10).

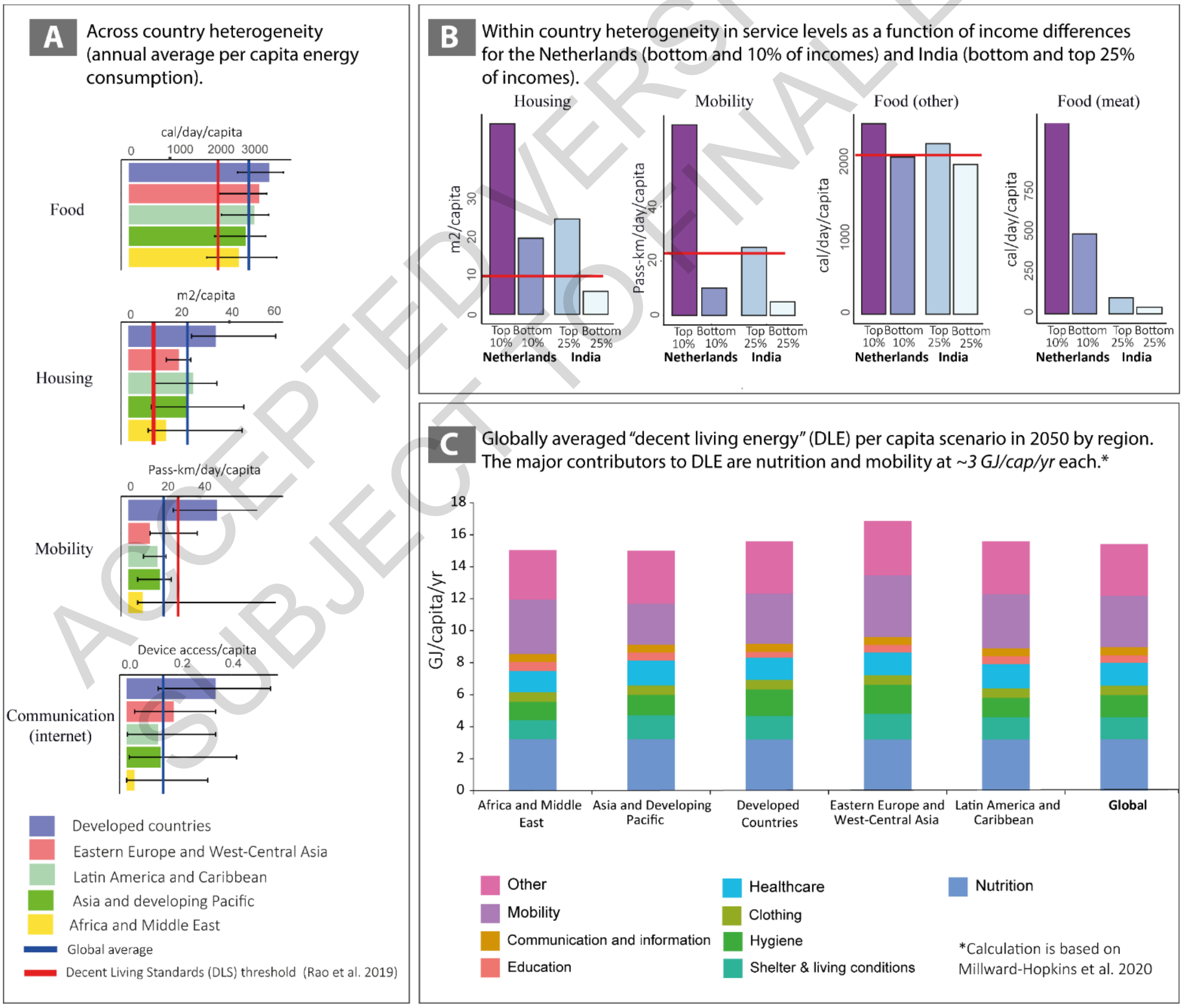


Figure 5.2 [2] Heterogeneity in access to and availability of services for human well-being within and across countries.
Panel A. Across –country differences in panel (a) food-meat, (b)food other, (c) housing, (d) mobility, (e) Communication –mobile phones, and (f) high speed internet access. Variation in service levels across countries within a region are shown as error bars (black). Values proposed as decent standards of living threshold (Rao et al. 2019b) are shown (red dashed lines). Global average values are shown (blue dashed lines). Panel B. Within-country differences in service levels as a function of income differences for the Netherlands (bottom and top 10% of incomes) and India (bottom and top 25% of incomes) (Grubler et al. 2012b) (data update 2016). Panel C. Decent living energy (DLE) scenario using global, regional and DLS dimensions for final energy consumption at 149 EJ (15.3 GJ capita^{-1}yr^{-1}) in 2050 (Millward-Hopkins et al. 2020), requiring advanced technologies in all sectors and radical demand-side changes. Values are shown for 5 world regions based on WG III AR6 Regional breakdown. Here we use passenger km/day/capita as metric for mobility only as a reference, however, transport and social inclusion research suggest the aim is to maximize accessibility and not travel levels or travelled distance.

There is *high evidence and high agreement* in the literature that vital dimensions of human well-being correlate with consumption, but only up to a threshold. High potential for mitigation lies in using low-carbon energy for new basic needs satisfaction while cutting emissions of those whose basic needs are already met (Grubler et al. 2018; Rao and Min 2018b; Millward-Hopkins et al. 2020; Rao et al. 2019b; Keyßer and Lenzen 2021). Decent Living Standards indicators serve as tools to clarify this socio-economic benchmark and identify well-being for all compatible mitigation potential. Energy services provisioning opens up avenues of efficiency and possibilities for decoupling energy services demand from primary energy supply, while needs satisfaction leads to the analysis of the factors influencing the energy demand associated with the achievement of well-being (Brand-Correa and Steinberger 2017; Tanikawa et al. 2021). Vital dimensions of well-being correlate with consumption, but only up to a threshold, decent living energy thresholds range ~13–18.4 GJ^{-1}cap^{-1}yr of final energy consumption but the current consumption ranges from under 5 GJ^{-1}cap^{-1}yr to over 200 GJ^{-1}cap^{-1}yr (Millward-Hopkins et al. 2020), thus a mitigation strategy that protects minimum levels of essential-goods service delivery for DLS, but critically views consumption beyond the point of diminishing returns of needs satisfaction, is able to sustain well-being while generating emissions reductions (Goldemberg et al. 1988; Jackson and Marks 1999; Druckman and Jackson 2010; Girod and De Haan 2010; Vita et al. 2019a; Baltruszewicz et al. 2021). Such relational dynamics are relevant both within and between countries, due to variances in income levels, lifestyle choice (see also 5.4.4), geography, resource assets and local contexts. Provisioning for human needs is recognised as participatory and interrelational; transformative mitigation potential can be found in social as well as technological change (Mazur and Rosa 1974; Goldemberg et al. 1985; Hayward and Roy 2019; Lamb and Steinberger 2017; O'Neill et al. 2018; Vita et al. 2019a). More equitable societies which provide DLS for all can devote attention and resources to mitigation (Dubash 2013; Rafaty 2018; Richards 2003; Oswald et al. 2021). For further exploration of these concepts, see the Chapter 5 Supplementary Material I.

5.2.2 Inequity in access to basic energy use and services

5.2.2.1 Variations in access to needs-satisfiers for Decent Living Standards

There is very *high evidence and very high agreement* that globally, there are differences in the amount of energy that societies require to provide the basic needs for everyone. At present nearly one-third of the world's population are 'energy-poor' facing challenges in both access and affordability, i.e., more than 2.6 billion people have little or no access to energy for clean cooking. About 1.2 billion lack energy for cleaning, sanitation and water supply, lighting, and basic livelihood tasks (Sovacool and Drupady 2016; Rao and Pachauri 2017).The current per capita energy requirement to provide a decent standard

FOOTNOTE [2] The countries and areas classification in this figure deviate from the standard classification scheme adopted by WGIII as set out in Annex II, section 1.

of living range from ~5 to 200 GJ $cap^{-1}yr^{-1}$ (Steckel et al. 2013; Lamb and Steinberger 2017; Rao et al. 2019b; Millward-Hopkins et al. 2020), which shows the level of inequality that exists; this depends on the context such as geography, culture, infrastructure or how services are provided (Brand-Correa et al. 2018) (Box 5.3). However, through efficient technologies and radical demand-side transformations, the final energy requirements for providing DLS by 2050 is estimated at 15.3 GJ $cap^{-1}yr^{-1}$ (Millward-Hopkins et al. 2020). Recent DLS estimates for Brazil, South Africa, and India are in the range between 15 and 25 GJ $cap^{-1}yr^{-1}$ (Rao et al. 2019b).The most gravely energy-poor are often those living in informal settlements, particularly women who live in sub-Saharan Africa and developing Asia, whose socially-determined responsibilities for food, water, and care are highly labour-intensive and made more intense by climate change (Guruswamy 2016; Wester et al. 2019). For example, in Brazil, India and South Africa, where inequality is extreme (Alvaredo et al. 2018) mobility (51-60%), food production and preparation (21-27%) and housing (5-12%) dominate total energy needs (Rao et al. 2019b). Minimum requirements of energy use consistent with enabling well-being for all is between 20 and 50 GJ cap^{-1} yr^{-1} depending on context (Rao et al. 2019b). Inequality in access to and availability of services for human well-being varies in extreme degree across countries and income groups. In developing countries the bottom 50% receive about 10% of the energy used in land transport and less than 5% in air transport, while the top 10% use ~45% of the energy for land transport and around 75% for air transport (Oswald et al. 2020). Within-country analysis shows that particular groups in China— women born in the rural West with disadvantaged family backgrounds— face unequal opportunities for energy consumption (Shi 2019). Figure 5.3 shows the wide variation across world regions in people's access to some of the basic material prerequisites for meeting DLS, and variations in energy consumption, providing a starting point for comparative global analysis.

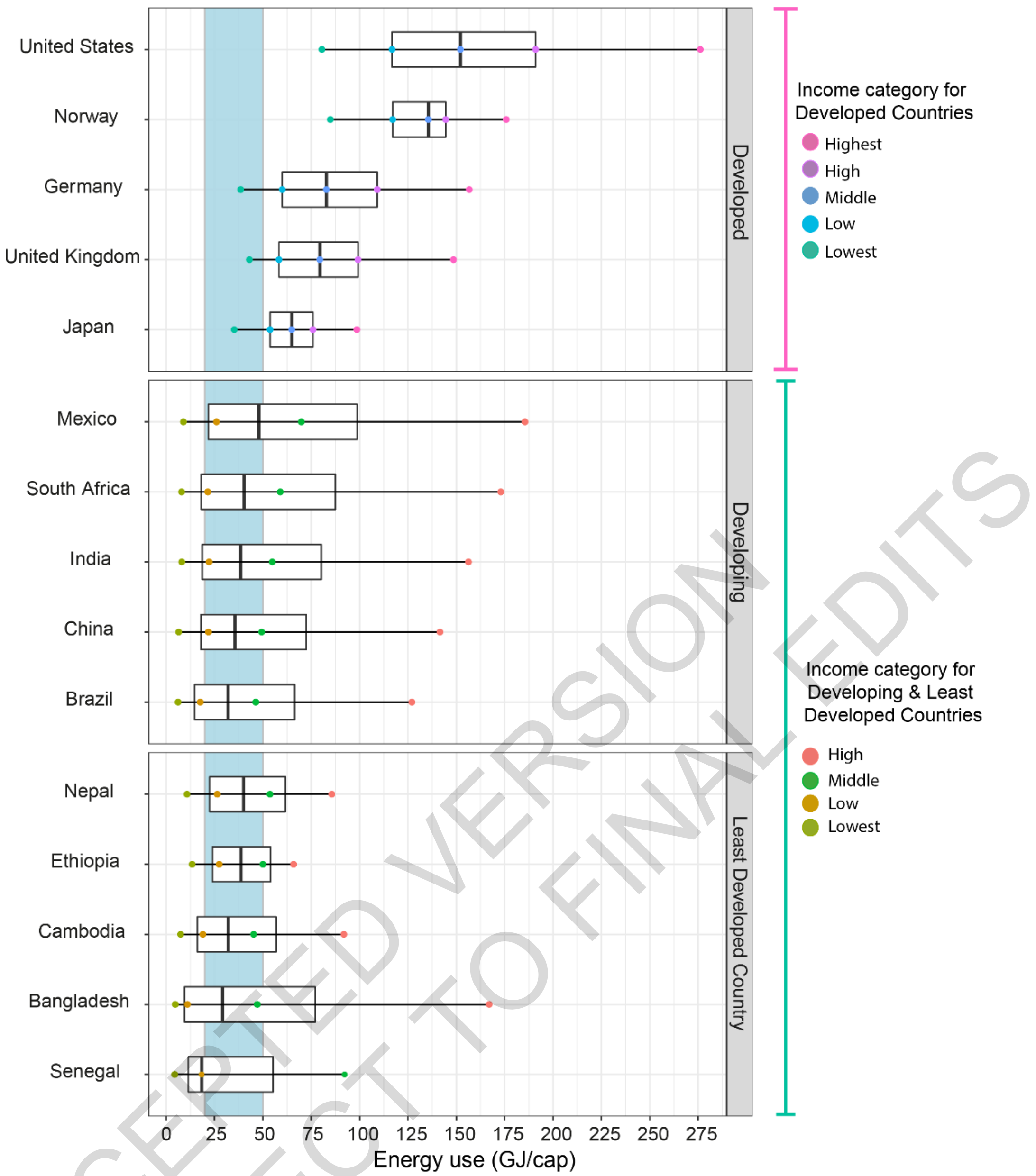


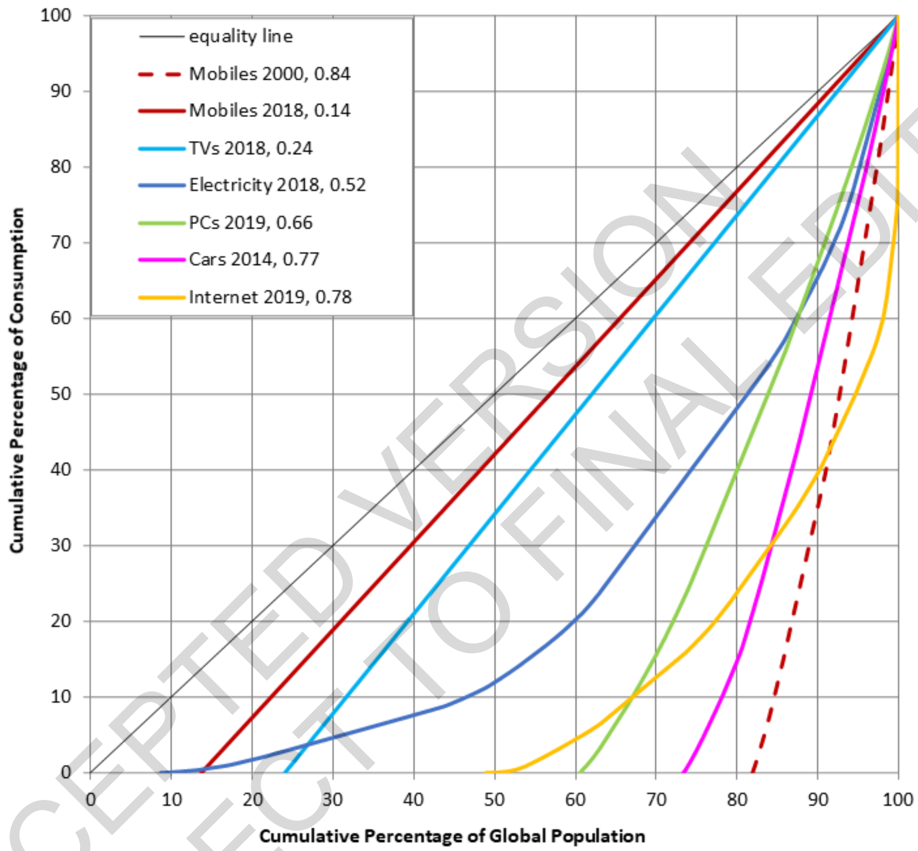
Figure 5.3 Energy use per capita of three groups of countries ranked by socioeconomic development and displayed for each country based on four or five different income groups (according the data availability) as well as geographical representation. The final energy use for decent living standards (20-50 GJ cap^{-1}) is indicated in the blue column (Rao et al. 2019b) as a reference for global range, rather than dependent on each country .

Data based on (Oswald et al. 2020).

START BOX 5.3 HERE

Box 5.3 Inequities in access to and levels of end-use technologies and infrastructure services

Acceleration in mitigation action needs to be understood from societal perspective. Technologies, access and service equity factors sometimes change rapidly. Access to technologies, infrastructures and products, and the services they provide, are essential for raising global living standards and improving human well-being (Alkire and Santos 2014; Rao and Min 2018b). Yet access to and levels of service delivery are distributed extremely inequitably as of now. How fast such inequities can be reduced by granular end-use technologies is illustrated by the cellphone (households with mobiles), comparing the situation between 2014 and 2018. In this eighteen-year period, cellphones changed from a very inequitably-distributed technology to one with almost universal access, bringing accessibility benefits especially to populations with very low disposable income and to those whose physical mobility is limited (Porter 2016). Every human has the right to dignified decent life, to live in good health and to participate in society. This is a daunting challenge, requiring that in the next decade governments build out infrastructure to provide billions of people with access to a number of services and basic amenities in comfortable homes, nutritious food, and transit options (Rao and Min 2018b). For long, this challenge was thought to also be an impediment to developing countries' participation in global climate mitigation efforts. However, recent research shows that this need not be the case (Millward-Hopkins et al. 2020; Rao et al. 2019b).



Technology/Infrastructure	Gini	Year	Population without access bn	%	Coverage world population %	included countries number	Source
Mobiles*	0.84	2000	4.0	81.9	80.4	43	ITU+/WBWDI/WPDS+
Mobiles*	0.14	2018	0.8	13.7	78.3	43	ITU+/WBWDI/WPDS+
TVs*	0.24	2018	1.6	24.1	89.8	86	ITU+/WBWDI/WPDS+
Electricity (kWh)	0.52	2018	0.6	8.7	95.9	142	WB WDI/IEA
PCs	0.66	2019	4.6	60.5	98.0	183	ITU/WBWDI/WPDS+
Cars*	0.77	2014	4.2	73.3	78.9	44	PEW/WBWDI
International bandwidth (bits/sec)	0.78	2019	3.7	48.8	99.3	197	ITU/WBWDI

Box 5.3, Figure 1 International inequality in access and use of goods and services. Upper panel: International Lorenz curves and Gini coefficients accounting for the share of population living in households without access (origin of the curves on the y-axis), multiple ownership not considered. Lower panel: Gini, number of people without access, access rates and coverage in terms of share of global population and number of countries included. *Reduced samples lead to underestimation of inequality. A sample, for example, of around 80% of world population (taking the same 43 countries as

for mobiles and cars) led to a lower Gini of around 0.48 (-0.04) for electricity. The reduced sample was kept for mobiles in 2018 to allow for comparability with 2000.

Source: (Zimm 2019)

Several of the United Nations Sustainable Development Goals (SDGs) (UN 2015) deal with providing access to technologies and service infrastructures to the share of population so far excluded, showing that the UN 2030 Agenda has adopted a multidimensional perspective on poverty. Multidimensional poverty indices, such as the Social Progress Indicator (SPI) and the Individual Deprivation Measure, go beyond income and focus on tracking the delivery of access to basic services by the poorest population groups, both in developing countries (Fulton et al. 2009; Alkire and Robles 2017; Alkire and Santos 2014; Rao and Min 2018b), and in developed countries (Townsend 1979; Aaberge and Brandolini 2015; Eurostat 2018). At the same time, the SDGs, primarily SDG 10 on reducing inequalities within and among countries, promote a more equitable world, both in terms of inter- as well as intra-national equality.

Access to various end-use technologies and infrastructure services features directly in the SDG targets and among the indicators used to track their progress (UNESC 2017; UN 2015): Basic services in households (SDG 1.4.1), Improved water source (SDG 6.1.1); Improved sanitation (SDG 6.1.2); Electricity (SDG 7.1.1); Internet - fixed broadband subscriptions (SDG 17.6.2); Internet - proportion of population (SDG 17.8.1). Transport (public transit, cars, mopeds or bicycles) and media technologies (mobile phones, TVs, radios, PCs, Internet) can be seen as proxies for access to mobility and communication, crucial for participation in society and the economy (Smith et al. 2015). In addition, SDG 10 is a more conventional income-based inequality goal, referring to income inequality (SDG 10.1), social, economic and political inclusion of all (SDG 10.2.), and equal opportunities and reduced inequalities of outcome (SDG 10.3).

END BOX 5.3 HERE

5.2.2.2 Variations in energy use

There is *high evidence and high agreement* in the literature that through equitable distribution, well-being for all can be assured at the lowest-possible energy consumption levels (Steinberger and Roberts 2010; Oswald et al. 2020) by reducing emissions related to consumption as much as possible, while assuring DLS for everyone (Annecke 2002; de Zoysa 2011; Ehrlich and Ehrlich 2013; Spangenberg 2014; Toroitich and Kerber 2014; Dario Kenner 2015; Smil 2017; Toth and Szigeti 2016; Otto et al. 2019; Baltruszewicz et al. 2021). For example, at similar levels of human development, per capita energy demand in the US was 63% higher than in Germany (Arto et al. 2016); those patterns are explained by context in terms of various climate, cultural and historical factors influencing consumption Context matter even in within country analysis ,e.g. electricity consumption in US show that efficiency innovations do exert positive influence on savings of residential energy consumption, but the relationship is mixed; on the contrary, affluence (household income and home size) and context (geographical location) drives significantly resource utilization (Adua and Clark 2019), affluence is central to any future prospect in terms of environmental conditions (Wiedmann et al. 2020). In China, inequality of energy consumption and expenditure varies highly depending on the energy type, end-use demand and climatic region (Wu et al. 2017).

Consumption is energy and materials-intensive and expands along with income. About half of the energy used in the world is consumed by the richest 10% of people, most of whom live in developed countries, especially when one includes the energy embodied in the goods they purchase from other countries and the structure of consumption as a function of income level (Wolfram et al. 2016; Arto et al. 2016; Santillán Vera et al. 2021). International trade plays a central tole being responsible for shifting burdens in most cases from low-income developing countries producers to high income developed countries as consumers (Wiedmann et al. 2020). China is the largest importing market for EU and United States, which accounts for near half and 40% of their imports in energy use respectively (Wu et al. 2019). Wealthy countries have exported or outsourced their climate and energy crisis to low and middle-income countries (Baker 2018) exacerbated by intensive international trade (Steinberger et al. 2012; Scherer et al. 2018). Therefore, issues of total energy consumption are inseparably related to the energy inequity among the countries and regions of the world.

Within the energy use induced by global consumer products, household consumption is the biggest contributor, contributing to around three quarters of the global total (Wu et al. 2019). A more granular analysis of household energy consumption reveals that the lowest two quintiles in countries with average annual income below 15,000 USD cap^{-1} consume less energy than the international energy requirements for DLS (20-50 GJ cap^{-1}); 77% of people consume less than 30 GJ $cap^{-1}yr^{-1}$ and 38% consume less than 10 GJ $cap^{-1}yr^{-1}$ (Oswald et al. 2020). Many energy-intensive goods have high price elasticity (>1.0), implying that growing incomes lead to over-proportional growth of energy footprints in these consumption categories. Highly unequally distributed energy consumption is concentrated in the transport sector, ranging from vehicle purchase to fuels, and most unequally in package holidays and aviation (Gössling 2019; Oswald et al. 2020).

Socio-economic dynamics and outcomes affect whether provisioning of goods and services is achieved at low energy demand levels (Figure 5.4). Specifically, multivariate regression shows that public service quality, income equality, democracy, and electricity access enable higher need satisfaction at lower energy demand, whereas extractivism and economic growth beyond moderate levels of affluence are reduce need satisfaction at higher energy demand (Vogel et al. 2021). Altogether this demonstrates that at a given level of energy provided, there is large scope to improve service levels for well-being by modifying social economic context without increasing energy supply (Figure 5.4).

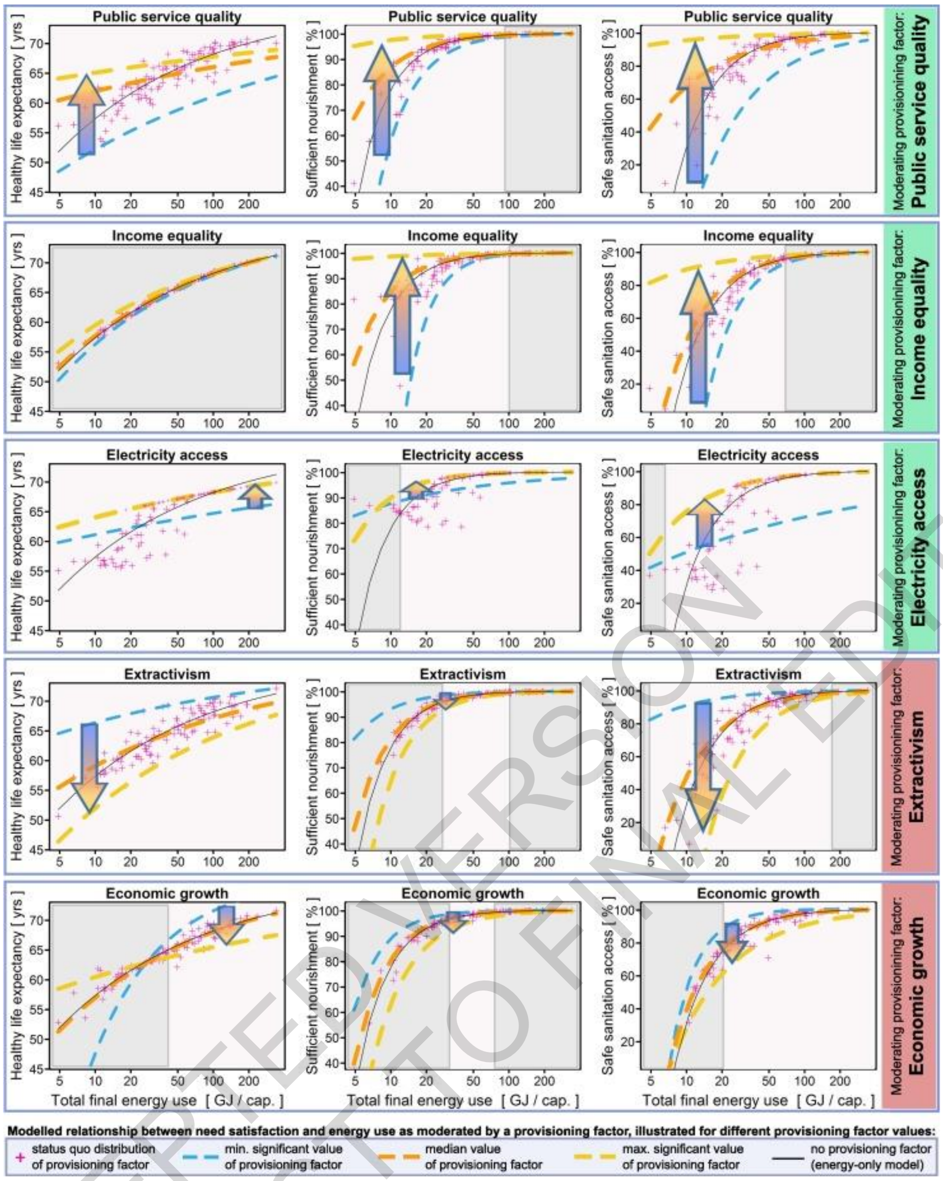


Figure 5.4 Improving services for well-being is possible, often at huge margin, at a given (relatively low) level of energy use

Source:(Vogel et al. 2021)

5.2.2.3 Variations in consumption-based emissions

The carbon footprint of a nation is equal to the direct emissions occurring due to households' transport, heating and cooking, as well as the impact embodied in the production of all consumed goods and services (Wiedmann and Minx 2008; Davis and Caldeira 2010; Hübler 2017; Vita et al. 2019a). There are large differences in carbon footprints between the poor and the rich. As a result of energy use inequality, the lowest global emitters (the poorest 10% in developing countries) in 2013 emitted about 0.1t CO_2 cap^{-1}, whereas the highest global emitters (the top 1% in the richest countries) emitted about 200-300 tCO_2 cap^{-1} (World Bank 2019), . The poorest 50% of the world's population are responsible for only about 10% of total lifetime consumption emissions, in contrast about ~50% of the world's GHG emissions can be attributed to consumption by the world's richest 10%, with the average carbon footprint of the richest being 175 times higher than that of the poorest 10% (Chancel and Piketty 2015) consuming the global carbon budget by nearly 30% during the period 1990-2015 (Kartha et al. 2020; Gore 2020). While the mitigation efforts often focus on the poorest, the lifestyle and consumption patterns of the affluent people often influence the growing middle class (Otto et al. 2019), e.g. Across

EU countries, only 5% of households are living within the 1.5% climate limits and the top 1% emit more than 22 times the target on average, being the transport in both land and air a characteristic of the highest emitters (Ivanova and Wood 2020).

In low-income nations-which can exhibit per-capita carbon footprints 30 times lower than wealthy nations (Hertwich and Peters 2009) emissions are predominantly domestic and driven by provision of essential services (shelter, low-meat diets, clothing). Per capita carbon footprints average 1.6 tonnes per year for the lowest income category, then quickly increase to 4.9 and 9.8 tonne for the two middle-income categories and finally to an average of 17.9 tonnes for the highest income category. Global CO_2 emissions remain concentrated: the top 10% of emitters contribute about 35-45% of the total, while the bottom 50% contribute just 13-15% of global emissions (Hubacek et al. 2017; Chancel and Piketty 2015). In wealthy nations, services such as private road transport, frequent air travel, private jet ownership, meat-intensive diets, entertainment and leisure add significant emissions, while a considerable fraction of the carbon footprint is imported from abroad, embedded in goods and services (Hubacek et al. 2017).

High income households consume and demand energy at an order of magnitude greater than what is necessary for DLS (Oswald et al. 2020). Energy-intensive goods, such as package holidays, have a higher income elasticity of demand than less energy-intensive goods like food, water supply and housing maintenance, which results in high-income individuals having much higher energy footprints (Oswald et al. 2020). Evidence highlights highly unequal GHG emission in aviation: only 2-4% of global population flew internationally in 2018, with 1% of world population emitting 50% of CO_2 from commercial aviation (Gössling and Humpe 2020). Some individuals may add more than 1,600 t CO_2 yr^{-1} individually by air travel (Gössling 2019).

The food sector dominates in all income groups, comprising 28% of households' carbon footprint, with cattle and rice the major contributors (Scherer et al. 2018), food also accounts for 48% and 70% of household impacts on land and water resources, being the meat, dairy, and processed food rising fast together with income (Ivanova et al. 2016). Roughly 20-40% of food produced worldwide is lost to waste before it reaches the market, or is wasted by households, the energy embodied in wasted food was estimated at ~36 $EJyr^{-1}$, and during the period 2010-2016 global food loss and waste equalled 8-10% of total GHG emissions (Godfray and Garnett 2014; Springmann et al. 2018; Mbow et al. 2019). Global agri-food supply chains are crucial in the variation of per capita food consumption-related-GHG footprints, mainly in the case of red meat and dairy (Kim et al. 2020) since highest per capita food-consumption-related GHG emissions do not correlate perfectly with the income status of countries. Thus, it is also crucial to focus on high-emitting individuals and groups within countries, rather than only those who live in high-emitting countries, since the top 10% of emitters live on all continents and one third of them are from the developing world (Chakravarty et al. 2009; Pan et al. 2019).

The environmental impact of increasing equity across income groups can be either positive or negative (Hubacek et al. 2017; Scherer et al. 2018; Rao and Min 2018a; Millward-Hopkins et al. 2020). Projections for achieving equitable levels of service provision globally predict large increases in global GHG emissions and demand for key resources (Blomsma and Brennan 2017), especially in passenger transport, which is predicted to increase nearly three-fold between 2015 and 2050, from 44 trillion to 122 trillion passenger-kilometres (OECD 2019a), and associated infrastructure needs, increasing freight (Murray et al. 2017), increasing demand for cooling (IEA 2018), and shifts to carbon-intensive high-meat diets (FAO 2018).

Increasing incomes for all to attain DLS raises emissions and energy footprints, but only slightly (Jorgenson et al. 2016; Chakravarty et al. 2009; Scherer et al. 2018; Millward-Hopkins et al. 2020;

Oswald et al. 2020, 2021). The amount of energy needed for a high global level of human development is dropping (Steinberger and Roberts 2010) and could by 2050 be reduced to 1950 levels (Millward-Hopkins et al. 2020) requiring a massive deployment of technologies across the different sectors as well as demand-side reduction consumption. The consumption share of the bottom half of the world's population represents less than 20% of all energy footprints, which is less than what the top 5% of people consume (Oswald et al. 2020).

Income inequality itself also raises carbon emissions (Hao et al. 2016; Sinha 2016; Uzar and Eyuboglu 2019; Baloch et al. 2020; Wiedmann et al. 2020; Oswald et al. 2020; Vogel et al. 2021). Wide inequality can increase status-based consumption patterns, where individuals spend more to emulate the standards of the high-income group (the Veblenian effect); inequality also diminishes environmental efforts by reducing social cohesion and cooperation (Jorgenson et al. 2017) and finally, inequality also operates by inducing an increase in working hours that leads to higher economic growth and, consequently, higher emissions and ecological footprint, so working time reduction is key for policy to both reduce emissions and protect employment (Fitzgerald et al. 2015, 2018).

5.2.3 Equity, trust, and participation in demand-side mitigation

There is *high evidence and high agreement* in literature that socio-economic equity builds not only well-being for all, but also trust and effective participatory governance, which in turn strengthen demand-side climate mitigation. Equity, participation, social trust, well-being, governance and mitigation are parts of a continuous interactive and self-reinforcing process (Figure 5.5). Section SM5.1 in the Supplemental Material for this chapter contains more detail on these links, drawing from social science literature.

Economic growth in equitable societies is associated with lower emissions than in inequitable societies (McGee and Greiner 2018), and income inequality is associated with higher global emissions (Ravallion et al. 1997; Rao and Min 2018c; Diffenbaugh and Burke 2019; Fremstad and Paul 2019; Liu and Hao 2020; McGee and Greiner 2018). Relatively slight increases in energy consumption and carbon emissions produce great increases in human development and well-being in less-developed countries, and the amount of energy needed for a high global level of human development is dropping (Steinberger and Roberts 2010). Equitable & democratic societies which provide high quality public services to their population have high well-being outcomes at lower energy use than those which do not, whereas those which prioritize economic growth beyond moderate incomes and extractive sectors display a reversed effect (Vogel et al. 2021).

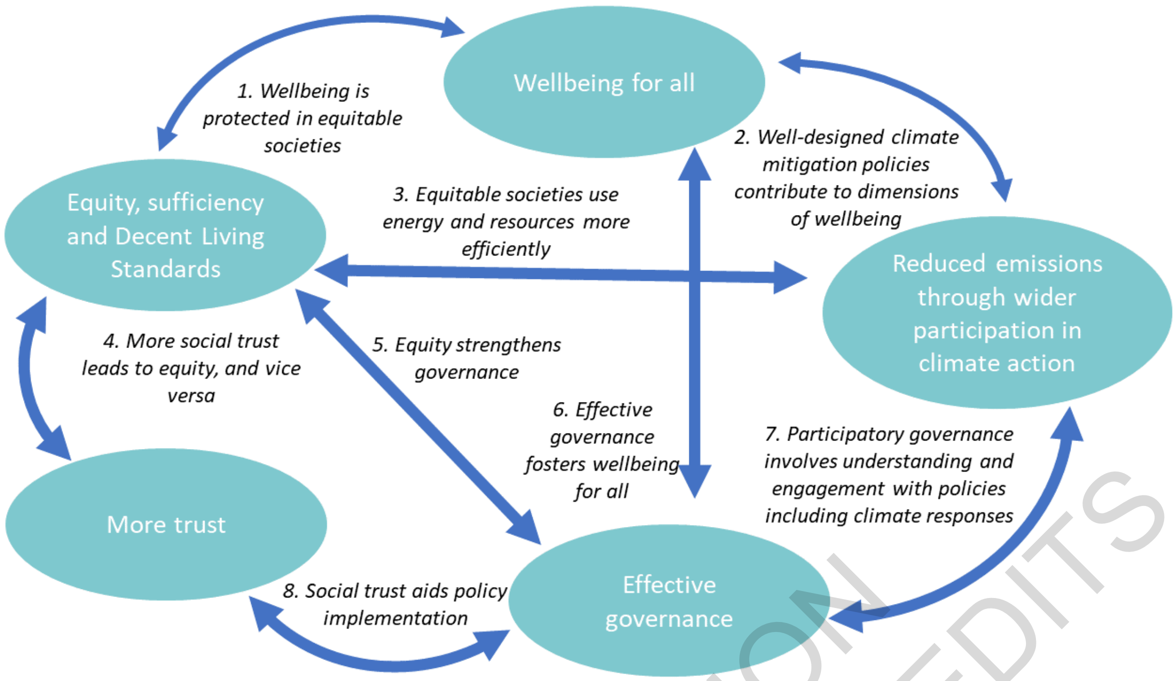


Figure 5.5 Well-being, equity, trust, governance and climate mitigation: positive feedbacks. Well-being for all, increasingly seen as the main goal of sustainable economies, reinforces emissions reductions through a network of positive feedbacks linking effective governance, social trust, equity, participation and sufficiency. This diagram depicts relationships noted in this chapter text and explained further in the Social Science Primer (supplementary material I in this Chapter). The width of the arrows corresponds to the level of confidence and degree of evidence from recent social sciences literature.

Well-designed climate mitigation policies ameliorate constituents of well-being (Creutzig et al. 2021b). The study shows that among all demand-side option effects on well-being 79% are positive, 18% are neutral (or not relevant/specify), and only 3% are negative (*high confidence*) (Creutzig et al. 2021b) (Figure 5.6). Figure 5.6 illustrates active mobility (cycling and walking), efficient buildings and prosumer choices of renewable technologies have the most encompassing beneficial effects on wellbeing with no negative outcome detected. Urban and industry strategies are highly positive overall for wellbeing, but they will also reshape supply-side businesses with transient intermediate negative effects. Shared mobility, like all others, has overall highly beneficial effects on wellbeing, but also displays a few negative consequences, depending on implementation, such as a minor decrease in personal security for patrons of ridesourcing.

Well-being improvements are most notable in health quality, air, and energy (*high confidence*). These categories are also most substantiated in the literature, often under the framing of co-benefits. In many cases, co-benefits outweigh the mitigation benefits of specific GHG emission reduction strategies. Food (*medium confidence*), mobility (*high confidence*), and water (*medium confidence*) are further categories where wellbeing is improved. Mobility has entries with highest well-being rankings for teleworking, compact cities, and urban system approaches. Effects on well-being in water and sanitation mostly comes from buildings and urban solutions. Social dimensions, such as personal security, social cohesion, and especially political stability are less predominantly represented. An exception is economic stability, suggesting that demand-side options generate stable opportunities to participate in economic activities (*high confidence*). Although the relation between demand-side mitigation strategies and the social aspects of human wellbeing is important, this has been less reflected in the literature so far, and hence the assessment finds more neutral/unknown interactions (Figure 5.6).

Policies designed to foster higher well-being for all via climate mitigation include reducing emissions through wider participation in climate action, building more effective governance for improved mitigation, and including social trust, greater equity, and informal-sector support as integral parts of climate policies. Public participation facilitates social learning and people's support of and engagement with climate change priorities; improved governance is closely tied to effective climate policies (Phuong et al. 2017). Better education, health care, valuing of social diversity, and reduced poverty – characteristics of more equal societies–all lead to resilience, innovation, and readiness to adopt progressive and locally-appropriate mitigation policies, whether high-tech or low-tech, centralised or decentralised (Tanner et al. 2009; Lorenz 2013; Chu 2015; Cloutier et al. 2015; Mitchell 2015; Martin and Shaheen 2016; Vandeweerdt et al. 2016; Turnheim et al. 2018). Morover, these factors are the ones identified as enablers of high need satisfaction at lower energy use (Vogel et al. 2021).

There is less policy lock-in in more equitable societies (Seto et al. 2016). International communication, networking, and global connections among citizens are more prevalent in more equitable societies, and these help spread promising mitigation approaches (Scheffran et al. 2012). Climate-related injustices are addressed where equity is prioritised (Klinsky and Winkler 2014). Thus, there is high confidence in the literature that addressing inequities in income, wealth, and DLS not only raises overall well-being and furthers the SDGs but also improves the effectiveness of climate change mitigation policies. For example, job creation, retraining for new jobs, local production of livelihood necessities, social provisioning, and other positive steps toward climate mitigation and adaptation are all associated with more equitable and resilient societies (Okvat and Zautra 2011; Bentley 2014; Klinsky et al. 2016; Roy et al. 2018a). At all scales of governance, the popularity and sustainability of climate policies requires attention to the fairness of their health and economic implications for all, and participatory engagement across social groups – a responsible development framing (Cazorla and Toman 2001; Dulal et al. 2009; Chuku 2010; Shonkoff et al. 2011; Navroz 2019; Hofstad and Vedeld 2020; Muttitt and Kartha 2020; Waller et al. 2020; Roy and Schaffartzik 2020; Temper et al. 2020). Far from being secondary or even a distraction from climate mitigation priorities, an equity focus is intertwined with mitigation goals (Klinsky et al. 2016). Demand-side climate mitigation options have pervasive ancillary, equity-enhancing benefits, e.g. for health, local livelihoods, and community forest resources (Figure 5.6) (Chhatre and Agrawal 2009; Garg 2011; Shaw et al. 2014; Serrao-Neumann et al. 2015; Klausbruckner et al. 2016; Salas and Jha 2019). Limiting climate change risks is fundamental to collective well-being (Max-Neef et al. 1989; Yamin et al. 2005; Nelson et al. 2013; Pecl et al. 2017; Tschakert et al. 2017; Gough 2015, 2017). Section 5.6 discusses well-designed climate policies more fully, with examples. Rapid changes in social norms which are underway and which underlie socially-acceptable climate policy initiatives are discussed in section 5.4.

The distinction between necessities and luxuries helps to frame a growing stream of social sciences literature with climate policy relevance (Arrow et al. 2004; Ramakrishnan and Creutzig 2021). Given growing public support worldwide for strong sustainability, sufficiency, and sustainable consumption, changing demand patterns and reduced demand are accompanying environmental and social benefits (Jackson 2008; Fedrigo et al. 2010; Schroeder 2013; Figge et al. 2014; Spangenberg and Germany 2016; Spengler 2016; Mont et al. 2020; Burke 2020). Beyond a threshold, increased material consumption is not closely correlated with improvements in human progress (Kahneman and Deaton 2010; Vita et al. 2019b, 2020; Frank 1999; Steinberger and Roberts 2010; Oishi et al. 2018; Xie et al. 2018; Wang et al. 2019; Roy et al. 2012). Policies focusing on the "super-rich," also called the "polluter elite," are gaining attention for moral or norms-based as well as emissions-control reasons (Kenner 2019; Pascale et al. 2020; Stratford 2020; Otto et al. 2019) (see Section 5.2.2.3). Conspicuous consumption by the wealthy is the cause of a large proportion of emissions in all countries, related to expenditures on such things as air travel, tourism, large private vehicles and large homes (Brand and Boardman 2008; Brand and

Preston 2010; Gore 2015; Sahakian 2018; Osuoka and Haruna 2019; Lynch et al. 2019; Roy and Pal 2009; Hubacek et al. 2017; Jorgenson et al. 2017; Gössling 2019; Kenner 2019; Roy et al. 2012). Since no country now meets its citizens' basic needs at a level of resource use that is globally sustainable, while high levels of life satisfaction for those just escaping extreme poverty require even more resources, the need for transformative shifts in governance and policies is large (O'Neill et al. 2018; Vogel et al. 2021).

Sectors	SDGs	2	6	7,11	3	6	7	11	11	4		1,2,8,10	5,10,16	5,16	10,16	11,16	8	9,12
	Mitigation strategies / Wellbeing dimensions	Food	Water	Air	Health	Sanitation	Energy	Shelter	Mobility	Education	Communication	Social protection	Participation	Personal Security	Social cohesion	Political stability	Economic stability	Material provision
Building	Sufficiency (adequate floor space, etc.)	[+1] ★★★	[+2] ★★★★	[+2] ★★★★★	[+3] ★★★★★	[+1] ★	[+3] ★★★★	[+1] ★	[+1] ★★	[+1] ★★	[+2] ★★★	[+1] ★★	[+1] ★★		[+2] ★★★★★		[+2] ★★★★	[+2] ★★★★
	Efficiency	[+2] ★	[+2] ★★★★	[+3/-1] ★★★★	[+3/-1] ★★★★★	[+1] ★	[+3] ★★★★	[+2] ★★★★		[+1] ★★★	[+1] ★★★		[+1] ★★★★	[+1] ★★★	[+2/-1] ★★★★		[+2] ★★★★★	[+2/-1] ★★★★
	Lower carbon and renewable energy	[+2/-1] ★★★	[+2/-1] ★★★★	[+3] ★★★★★	[+3] ★★★★★		[+3] ★★★★	[+1] ★★★	[+1] ★★★	[+1] ★★★	[+2] ★★★		[+1] ★★★	[+1] ★★★	[+2/-1] ★★★★		[+2/-1] ★★★★★	[+2] ★★★★
Food	Food waste	[+1] ★★★	[+2] ★★★★	[+2] ★★★★	[+2] ★★★	[+1] ★★	[+1] ★★★★				[+1] ★★	[-1/+1] ★★★	[+1] ★★★			[+1] ★	[+1] ★★	
	Over-consumption	[+1] ★	[+1/-1] ★	[+1/-1] ★	[+3] ★★★★		[+1/-1] ★						[+2] ★★★★			[+1] ★		
	Plant based diets	[+2] ★★★	[+2] ★★★★	[+3] ★★★★★	[+3] ★★★						[-1] ★★★	[+3] ★★★★★	[+1] ★★★★		[-1] ★	[+2] ★		
Transport	Teleworking and online education system	[+1] ★★		[+3] ★★★★	[+2] ★★★★		[+2] ★★★★	[+1] ★★	[+2] ★★★★	[-1] ★★★	[+2] ★★★★	[+1] ★★★★	[+2] ★★★★	[+1/-1] ★★★★	[+2] ★★★★	[+2] ★★★	[+2] ★★★	
	Non-motorized transport	[+2] ★★	[+1] ★★	[+1] ★★★★★	[+3] ★★★★★		[+2] ★★★★		[+3] ★★★★★	[+1] ★★★★	[+3] ★★★	[+1] ★★★	[+1] ★★	[+2] ★★★★	[+2] ★★★	[+2] ★★	[+2] ★★★	
	Shared mobility	[+1] ★★		[+3] ★★★	[+2] ★★★★		[+1] ★★★		[+2] ★★★★		[+1] ★★★	[+2] ★★★	[+1] ★★★	[+1/-1] ★★★	[+1/-1] ★★★★	[-1] ★★★★	[+2] ★★★★	[+2] ★★★★
	Evs	[+1] ★★★		[+2] ★★★★	[+1] ★★★★	[+1] ★★★★	[+3 ★★★★		[+2] ★★★★			[+3] ★★★★★	[+2] ★★★				[+2] ★★★★	[-1] ★★
Urabn	Compact city	[+2/-1] ★★★	[+1] ★★	[+2/-1] ★★★	[+3/-1] ★★★★	[+1] ★★	[+3/-1] ★★★★★	[-1] ★★★★★	[+3] ★★★★★	[+1] ★★★★★	[+1/-1] ★★★	[+2] ★★	[+1] ★★	[+1] ★★★★	[+1/-1] ★★★★★		[+1] ★★★★	[+1] ★★
	Circular and shared economy	[+2] ★★★★	[+1] ★★★	[+2] ★★★	[+2] ★★★		[+3] ★★★	[+2/-1] ★★★	[+3] ★★★★★	[+1] ★★★★	[+1] ★★★★	[+1] ★★★	[+1] ★★★	[+2] ★★★★	[+1] ★★	[+1] ★★	[+2] ★★	[+3] ★★★
	Systems approach in urban policy and practice	[+1] ★★★	[+2] ★★★	[+2] ★★★	[+3] ★★★	[+1] ★★★	[+3] ★★★	[+2] ★★★	[+3] ★★★		[+1] ★★	[-1] ★★	[+1] ★★★	[+2] ★	[+1] ★★		[+1] ★★	[+3] ★★★★★
	Nature based solutions	[+2] ★★★	[+1/-1] ★★★★★	[+3/-1] ★★★★	[+3] ★★★★★	[+1] ★★★	[+3] ★★★	[+1/-1] ★★★	[+1] ★★★	[+2] ★★★★		[+2] ★★	[+3] ★★	[+1] ★★★	[+2/-2] ★★★		[+3] ★★★★	[+1] ★★
Industry	Using less material by design	[+2] ★★	[+2] ★★★	[+3] ★★★	[+2] ★★	[+2] ★★★	[+3] ★★★★	[+2] ★★★★	[+2] ★★★★	[+1] ★★	[+2] ★★★	[+1] ★★	[+1] ★★★	[+1] ★★	[+1] ★★	[+1] ★★	[+2] ★★★	[+3] ★★
	Product life extension	[+2] ★★	[+2] ★★★	[+3] ★★★	[+2] ★★	[+2] ★★★	[+3] ★★★★	[+2] ★★★★	[+2] ★★★★	[+1] ★★	[+2] ★★★	[+1] ★★	[-1] ★★★★	[+1] ★★	[+1] ★★	[+1] ★★	[+2] ★★★	[+3] ★★
	Energy Efficiency	[+2] ★★	[+2] ★★★	[+3] ★★★	[+1] ★★	[+2] ★★★	[+3] ★★★★	[+2] ★★★★	[+2] ★★★★	[+1] ★★	[+2] ★★★	[+2] ★★★★	[+2] ★★★	[+1] ★★		[+1] ★★	[+2] ★★★	[+2] ★★
	Circular economy	[+2] ★★★	[+2] ★★★	[+3] ★★★	[+1] ★★	[+2] ★★★	[+3] ★★★★	[+2] ★★★★	[+2] ★★★★	[+1] ★★	[+2] ★★★	[+1] ★★	[+1] ★★★	[+2] ★★	[+1] ★★		[+2] ★★★	[+3] ★★

Legend
- High positive impact [+3]
- Medium positive impact [+2]
- Low positive impact [+1]
- Overall Neutral
- No impact
- Low negative impact [-1]
- Medium negative impact [-2]
- ★ Confidence level

Figure 5.6 Two-way link between demand-side climate mitigation strategies and multiple dimensions of human well-being and SDGs. All demand-side mitigation strategies improve well-being in sum, though not necessarily in each individual dimension. Incumbent business (in contrast to overall economic performance) may be challenged.

Source: Creutzig et al. 2021b

Inequitable societies use energy and resources less efficiently. Higher income inequality is associated with higher carbon emissions, at least in developed countries (Grunewald et al. 2011; Golley and Meng 2012; Chancel et al. 2015; Grunewald et al. 2017; Jorgenson et al. 2017; Sager 2017; Klasen 2018; Liu et al. 2019); reducing inequality in high-income countries helps to reduce emissions (Klasen 2018). There is high agreement in the literature that alienation or distrust weakens collective governance and fragments political approaches towards climate action (Smit and Pilifosova 2001; Adger et al. 2003; Hammar and Jagers 2007; Van Vossole 2012; Bulkeley and Newell 2015; Smith and Howe 2015; ISSC et al. 2016; Smith and Mayer 2018; Fairbrother et al. 2019; Kulin and Johansson Sevä 2019; Liao et al. 2019; Alvaredo et al. 2018; Hayward and Roy 2019).

Populism and politics of fear are less prevalent under conditions of more income equality (Chevigny 2003; Bryson and Rauwolf 2016; O'Connor 2017; Fraune and Knodt 2018; Myrick and Evans Comfort 2019). Ideology and other social factors also play a role in populist climate scepticism, but many of these also relate to resentment of elites and desire for engagement (Swyngedouw 2011; Lockwood 2018; Huber et al. 2020). "Climate populism" movements are driven by an impetus for justice (Beeson 2019; Hilson 2019). When people feel powerless and/or that climate change is too big a problem to solve because others are not acting, they may take less action themselves (Williams and Jaftha 2020). However, systems for benefit-sharing can build trust and address large-scale "commons dilemmas", in the context of strong civil society (Barnett 2003; Mearns and Norton 2009; Inderberg et al. 2015; Sovacool et al. 2015; Hunsberger et al. 2017; Soliev and Theesfeld 2020). Leadership is also important in fostering environmentally-responsible group behaviours (Liu and Hao 2020).
In some less-developed countries, higher income inequality may in fact be associated with lower per capita emissions, but this is because people who are excluded by poverty from access to fossil fuels must rely on biomass (Klasen 2018). Such energy poverty – the fact that millions of people do not have access to energy sources to help meet human needs – implies the opposite of development (Guruswamy 2010, 2020). In developing countries, livelihood improvements do not necessarily cause increases in emissions (Peters et al. 2012; Reusser et al. 2013; Creutzig et al. 2015a; Chhatre and Agrawal 2009; Baltruszewicz et al. 2021) and poverty alleviation causes negligible emissions (Chakravarty et al. 2009). Greater equity is an important step towards sustainable service provisioning (Godfray et al. 2018; Dorling 2019; Timko 2019).

As discussed in Section 5.6, policies to assist the low-carbon energy transition can be designed to include additional benefits for income equality, besides contributing to greater energy access for the poor (Burke and Stephens 2017; Frank 2017; Healy and Barry 2017; Sen 2017; Chapman et al. 2018; La Viña et al. 2018; Chapman and Fraser 2019; Piggot et al. 2019; Sunderland et al. 2020). Global and intergenerational climate inequities impact people's well-being, which affects their consumption patterns and political actions (Gori-Maia 2013; Clayton et al. 2015; Pizzigati 2018; Albrecht et al. 2007; Fritze et al. 2008) (see Box 5.4).

Consumption reductions, both voluntary and policy-induced, can have positive and double-dividend effects on efficiency as well as reductions in energy and materials use (Mulder et al. 2006; Harriss and Shui 2010; Grinde et al. 2018; Spangenberg and Lorek 2019; Figge et al. 2014; Vita et al. 2020). Less waste, better emissions control and more effective carbon policies lead to better governance and stronger democracies. Systems-dynamics models linking strong emissions-reducing policies and strong social equity policies show that a low-carbon transition in conjunction with social sustainability is possible, even without economic growth (Kallis et al. 2012; Jackson and Victor 2016; Stuart et al. 2017; S. D'alessandro et al. 2019; Huang et al. 2019; Victor 2019; Chapman and Fraser 2019; Gabriel and Bond 2019). Such degrowth pathways may be crucial in combining technical feasibility of mitigation with social development goals (Hickel et al. 2021; Keyßer and Lenzen 2021).

Multi-level or polycentric governance can enhance well-being and improve climate governance and social resilience, due to varying adaptive, flexible policy interventions at different times and scales (Kern and Bulkeley 2009; Lidskog and Elander 2009; Amundsen et al. 2010; Keskitalo 2010; Lee and Koski 2015; Jokinen et al. 2016; Lepeley 2017; Marquardt 2017; Di Gregorio et al. 2019). Institutional transformation may also result from socio-ecological stresses that accompany climate change, leading to more effective governance structures (David Tàbara et al. 2018; Patterson and Huitema 2019; Barnes et al. 2020). An appropriate, context-specific mix of options facilitated by policies can deliver both higher well-being and reduced disparity in access to basic needs for services concurrently with climate mitigation (Thomas and Twyman 2005; Klinsky and Winkler 2014; Lamb et al. 2014; Mearns and Norton 2009; Lamb and Steinberger 2017). Hence, nurturing equitable human well-being through provision of decent living standards for all goes hand in hand with climate change mitigation (ISSC et al. 2016; OECD 2019a). There is *high confidence* in the literature that addressing inequities in income, wealth, and DLS not only raises overall well-being and furthers the SDGs but also improves the effectiveness of climate change mitigation policies.

Participatory governance involves understanding and engagement with policies, including climate policies. Greater public participation in climate policy processes and governance, by increasing the diversity of ideas and stakeholders, builds resilience and allows broader societal transformation towards systemic change even in complex, dynamic and contested contexts (Dombrowski 2010; Wise et al. 2014; Haque et al. 2015; Jodoin et al. 2015; Mitchell 2015; Kaiser 2020; Alegria 2021). This sometimes involves complex policy discussions that can lead to governance innovations, also influencing social norms (Martinez 2020). A specific example are citizen assemblies, deliberating public policy challenges, such as climate change (Devaney et al. 2020). Activist climate movements are changing policies as well as normative values (see Section 5.4 and the Social Science Primer). Environmental justice and climate justice activists worldwide have called attention to the links between economic and environmental inequities, collected and publicised data about them, and demanded stronger mitigation (Goodman 2009; Schlosberg and Collins 2014; Jafry et al. 2019; Cheon 2020). Youth climate activists, and Indigenous leaders, are also exerting growing political influence towards mitigation (Helferty and Clarke 2009; White 2011; Powless 2012; Petheram et al. 2015; Curnow and Gross 2016; Grady-Benson and Sarathy 2016; Claeys and Delgado Pugley 2017; UN 2015; O'Brien et al. 2018; Rowlands and Gomez Peña 2019; Bergmann and Ossewaarde 2020; Han and Ahn 2020; Nkrumah 2021). Indigenous resurgence (activism fuelled by ongoing colonial social / environmental injustices, land claims, and deep spiritual/cultural commitment to environmental protection) not only strengthens climate leadership in many countries, but also changes broad social norms by raising knowledge of Indigenous governance systems which supported sustainable lifeways over thousands of years (Wildcat 2014; Chanza and De Wit 2016; Whyte 2018, 2017; Temper et al. 2020). Related trends include recognition of the value of traditional ecological knowledge, Indigenous governance principles, decentralisation, and appropriate technologies (Lange et al. 2007; Goldthau 2014; Whyte 2017).

Social trust aids policy implementation. More equal societies display higher trust, which is a key requirement for successful implementation of climate policies (Rothstein and Teorell 2008; Carattini et al. 2015; Klenert et al. 2018; Patterson et al. 2018). Inter-personal trust among citizens often promotes pro-environment behaviour by influencing perceptions (Harring and Jagers 2013), enhancing cooperation, and reducing free-riding and opportunistic behaviour (Gür 2020). Individual support for carbon taxes and energy innovations falls when collective community support is lacking (Bolsen et al. 2014; Simon 2020; Smith and Mayer 2018). Social trust has a positive influence on civic engagement among local communities, NGOs, and self-help groups for local clean cooking fuel installation (Nayak et al. 2015).

Section 5.6 includes examples of climate mitigation policies and policy packages which address the interrelationships shown in Figure 5.5. Improving well-being for all through climate mitigation includes emissions-reduction goals in policy packages that ensure equitable outcomes, prioritize social trust-building, support wide public participation in climate action including within the informal sector, and facilitate institutional change for effective multi-level governance, as integral components of climate strategies. This strategic approach, and its feasibility of success, rely on complex contextual factors that may differ widely, especially between Global North and Global South (Atteridge et al. 2012; Patterson et al. 2018; Jewell and Cherp 2020; Singh et al. 2020, 2021).

START BOX 5.4 HERE

Box 5.4 Gender, race, intersectionality and climate mitigation

There is *high evidence* and *high agreement* that empowering women benefits both mitigation and adaptation, because women prioritise climate change in their voting, purchasing, community leadership, and work both professionally and at home (*high evidence, high agreement*). Increasing voice and agency for those marginalised in intersectional ways by Indigeneity, race, ethnicity, dis/ability, and other factors has positive effects for climate policy (*high evidence, high agreement*).

Climate change affects people differently along all measures of difference and identity, which have intersectional impacts linked to economic vulnerability and marginalisation (Morello Frosch et al. 2009; Dankelman 2010; Habtezion 2013; Godfrey and Torres 2016; Walsh 2016; Flatø et al. 2017; Goodrich et al. 2019; Perkins 2019; Gür 2020). Worldwide, racialized and Indigenous people bear the brunt of environmental and climate injustices through geographic location in extraction and energy "sacrifice zones", areas most impacted by extreme weather events, and/or through inequitable energy access (Aubrey 2019; Gonzalez 2020; Lacey-Barnacle et al. 2020; Porter et al. 2020; Temper et al. 2020; Jafry et al. 2019) Disparities in climate change vulnerability not only reflect pre-existing inequalities, they also reinforce them. For example, inequities in income and in the ownership and control of household assets, familial responsibilities due to male out-migration, declining food and water access, and increased disaster exposure can undermine women's ability to achieve economic independence, enhance human capital, and maintain physical and mental health and well-being (Chandra et al. 2017; Eastin 2018; Das et al. 2019). Studies during the COVID crisis have found that, in general, women's economic and productive lives have been affected disproportionately to men's (Alon et al. 2020; ILO 2020). Women have less access to social protections and their capacity to absorb economic shocks is very low, so they face a "triple burden" during crises -- including those resulting from climate change -- and this is heightened for women in the less-developed countries and for those who are intersectionally vulnerable (Coates et al. 2020; McLaren et al. 2020; Wenham et al. 2020; Azong and Kelso 2021; Erwin et al. 2021; Maobe and Atela 2021; Nicoson 2021; Sultana 2021; Versey 2021). Because men currently hold the majority of energy-sector jobs, energy transition will impact them economically and psychologically; benefits, burdens and opportunities on both the demand and supply sides of the mitigation transition have a range of equity implications (Pearl-Martinez and Stephens 2017; Standal et al. 2020; Mang-Benza 2021). Mitigating gendered climate impacts requires addressing inequitable power relations throughout society(Wester and Lama 2019).

Women's well-being and gender-responsive climate policy have been emphasized in international agreements including the Paris accord (UNFCCC 2015), CEDAW General Recommendation 37 (Vijeyarasa 2021), and the 2016 Decision 21/CP.22 on Gender and Climate Change (UNFCCC 2016; Larson et al. 2018). Increasing the participation of women and marginalised social groups, and addressing their special needs, helps to meet a range of SDGs, improve disaster and crisis response, increase social trust, and improve climate mitigation policy development and implementation (Alber

2009; Whyte 2014; Elnakat and Gomez 2015; Salehi et al. 2015; Buckingham and Kulcur 2017; Cohen 2017; Kronsell 2017; Lee and Zusman 2019).

Women have a key role in the changing energy economy due to their demand and end use of energy resources in socially-gendered productive roles in food production and processing, health, care, education, clothing purchases and maintenance, commerce, and other work both within and beyond the home (Räty and Carlsson-Kanyama 2009; Oparaocha and Dutta 2011; Bob and Babugura 2014; Macgregor 2014; Perez et al. 2015; Bradshaw 2018; Clancy and Feenstra 2019; Clancy et al. 2019; Fortnam et al. 2019; Rao et al. 2019a; Quandt 2019; Horen Greenford et al. 2020; Johnson 2020). Women's work and decision-making are central in the food chain and agricultural output in most developing countries, and in household management everywhere. Emissions from cooking fuels can cause serious health damages, and unsustainable extraction of biofuels can also hurt mitigation (Bailis et al. 2015), so considering health, biodiversity and climate tr adeoffs and co-benefits is important (Rosenthal et al. 2018; Aberilla et al. 2020; Mazorra et al. 2020) . Policies on energy use and consumption are often focused on technical issues related to energy supply, thereby overlooking 'demand-side' factors such as household decision-making, unpaid work, livelihoods and care (Himmelweit 2002; Perch 2011; Fumo 2014; Hans et al. 2019; Huyer and Partey 2020). Such gender-blindness represents the manifestation of wider issues related to political ideology, culture and tradition (Carr and Thompson 2014; Thoyre 2020; Perez et al. 2015; Fortnam et al. 2019).

Women, and all those who are economically and/or politically marginalised, often have less access to energy and use less, not just because they may be poorer but case studies show because their consumption choices are more ecologically-inclined and their energy use is more efficient (Lee et al. 2013; Permana et al. 2015; Li et al. 2019). Women's carbon footprints are about 6-28% lower than men's (with high variation across countries), mostly based on their lower meat consumption and lower vehicle use (Isenhour and Ardenfors 2009; Räty and Carlsson-Kanyama 2010; Barnett et al. 2012; Medina and Toledo-Bruno 2016; Ahmad et al. 2017; Fernström Nåtby and Rönnerfalk 2018; Räty and Carlsson-Kanyama 2009; Li et al. 2019). Gender-based income redistribution in the form of pay equity for women could reduce emissions if the redistribution is revenue-neutral (Terry 2009; Dengler and Strunk 2018). Also, advances in female education and reproductive health, especially voluntary family planning, can contribute greatly to reducing world population growth (Abel et al. 2016; Dodson et al. 2020).

Carbon emissions are lower per capita in countries where women have more political 'voice', controlling for GDP per capita and a range of other factors (Ergas and York 2012). While most people recognize that climate change is happening (Lewis et al. 2018; Ballew et al. 2019), climate denialism is more prevalent among men (McCright and Dunlap 2011; Anshelm and Hultman 2014; Jylhä et al. 2016; Nagel 2015), while women are more likely to be environmental activists, and to support stronger environmental and climate policies (Stein 2004; McCright and Xiao 2014, Whyte 2014). Racialised groups are more likely to be concerned about climate change and to take political action to support climate mitigation policies (Leiserowitz and Akerlof 2010; Schuldt and Pearson 2016; Pearson et al. 2017; Ballew et al. 2020; Godfrey and Torres 2016; Johnson 2020). This underscores the important synergies between equity and mitigation. The contributions of women, racialised people, and Indigenous people who are socially positioned as those first and most affected by climate change – and therefore experts on appropriate climate responses – are substantial (Dankelman and Jansen 2010; Wickramasinghe 2015; Black 2016; Vinyeta et al. 2016; Pearse 2017). Equitable power, participation, and agency in climate policy-making is hence an effective contribution for improving governance and decision making on climate change mitigation (Reckien et al. 2017; Collins 2019). Indigenous knowledge is an important source of guidance for biodiversity conservation, impact assessment, governance, disaster preparedness and resilience (Salick and Ross 2009; Green and Raygorodetsky

2010; Speranza et al. 2010; Mekuriaw Bizuneh 2013; Mekuriaw 2017), and women are often the local educators, passing on and utilising traditional and Indigenous knowledge (Ketlhoilwe 2013; Onyige 2017; Azong et al. 2018).

Higher female political participation, controlled for other factors, leads to higher stringency in climate policies, and results in lower GHG emissions (Cook et al. 2019). Gender equity also is correlated with lower per capita CO_2-eq emissions (Ergas and York 2012). In societies where women have more economic equity, their votes push political decision-making in the direction of environmental/sustainable development policies, less high-emission militarisation, and more emphasis on equity and social policies e.g. via wealth and capital gains taxes (Resurrección 2013; UNEP 2013; Glemarec et al. 2016; Bryan et al. 2018; Crawford 2019; Ergas and York 2012). Changing social norms on race and climate are linked and policy-relevant (Benegal 2018; Elias et al. 2018; Slocum 2018; Gach 2019; Wallace-Wells 2019; Temple 2020; Drolet 2021). For all these reasons, climate policies are strengthened by including more differently-situated knowledge and diverse perspectives, such as feminist expertise in the study of power (Bell et al. 2020a; Lieu et al. 2020); clarifying equity goals (e.g. distinguishing among 'reach, 'benefit', and 'empowerment'; obtaining disaggregated data and using clear empirical equity measures; and confronting deeply-engrained inequities in society (Lau et al. 2021). Inclusivity in climate governance spans mitigation-adaptation, supply-demand and formal-informal sector boundaries in its positive effects (Morello Frosch et al. 2009; Dankelman 2010; Bryan and Behrman 2013; Habtezion 2013; Godfrey and Torres 2016; Walsh 2016; Flatø et al. 2017; Wilson et al. 2018; Goodrich et al. 2019; Perkins 2019; Bell et al. 2020b; Gür 2020).

END BOX 5.4 HERE

5.3 Mapping the opportunity space

Reducing global energy demand and resource inputs while improving well-being for all requires an identification of options, services and pathways that do not compromise essentials of a decent living. To identify such a solution space, this section summarises socio-cultural, technological and infrastructural interventions through the avoid/shift/improve (ASI) concept. ASI (see Section 5.1) provides a categorisation of options aimed at continuously eliminating wastes in the current systems of service provision (see Section 5.3.1.1). It also concisely presents demand side options to reduce GHG emissions by individual choices which can be leveraged by supporting policies, technologies and infrastructure. Two key concepts for evaluating the efficiency of service provision systems are: resource cascades and exergy. These concepts provide powerful analytical lenses through which to identify and substantially reduce energy and resource waste in service provision systems both for decent living standards (see Section 5.3.2) and higher well-being levels. They typically focus on end-use conversion and service delivery improvements as the most influential opportunities for system-wide waste reductions. Review of the state of modelling low energy and resource demand pathways in long-term climate mitigation scenarios (recognising the importance of such scenarios for illuminating technology and policy pathways for more efficient service provision) and summary of the mitigation potentials estimated from relevant scenarios to date are in Section 5.3.3. Finally, it reviews the role of three megatrends that are transforming delivery of the services in innovative ways – digitalisation, the sharing economy, and the circular economy (see Section 5.3.4). The review of megatrends makes an assessment highlighting the potential risks of rebound effects, and even accelerated consumption; it also scopes for proactive and vigilant policies to harness their potential for future energy and resource demand reductions, and, conversely, avoiding undesirable outcomes.

5.3.1 Efficient service provision

This section organises demand reductions under the ASI framework. It presents service-oriented demand-side solutions consistent with decent living standards (Table 5.1) (Creutzig et al. 2018). The sharing economy, digitalisation, and the circular economy all can contribute to ASI strategies, with the circular economy tentatively more on the supply side, and the sharing economy and digitalisation tentatively more on the demand side (see Section 5.3.4). These new service delivery models go beyond sectoral boundaries (IPCC sector chapter boundaries explained in Chapter 12) and take advantage of technological innovations, design concepts, and innovative forms of cooperation cutting across sectors to contribute to systemic changes worldwide. Some of these changes can be realised in the short term, such as energy access, while others may take a longer period, such as radical and systemic eco-innovations like shared electric autonomous vehicles. It is important to understand benefits and distributional impacts of these systemic changes.

5.3.1.1 Integration of service provision solutions with A-S-I framework

Assessment of service-related mitigation options within the ASI framework is aided by decomposition of emissions intensities into explanatory contributing factors, which depend on the type of service delivered. Table 5.1 shows ASI options in selected sectors and services. It summarises resource, energy, and emissions intensities commonly used by type of service (Cuenot et al. 2010; Lucon et al. 2014; Fischedick et al. 2014). Also relevant: the concepts of service provision adequacy (Arrow et al. 2004; Samadi et al. 2017), establishing the extents to which consumption levels exceed (e.g., high-calorie diets contributing to health issues (Roy et al. 2012); excessive food waste) or fall short of (e.g., malnourishment) service level sufficiency (e.g., recommended calories) (Millward-Hopkins et al. 2020); and service level efficiency (e.g., effect of occupancy on the energy intensity of public transit passenger-km travelled (Schäfer and Yeh 2020). Service-oriented solutions in this chapter are discussed in the context of Table 5.1. Implementation of these solutions requires combinations of institutional, infrastructural, behavioural, socio-cultural, and business changes that are mentioned in Section 5.2 and discussed in Section 5.4.

Table 5.1 Avoid-Shift-Improve options in selected sectors and services. Many options, such as urban form and infrastructures are systemic, and influence several sectors simultaneously. Linkages to concepts presented in sectoral chapters are indicated in parentheses in the first column.

Source: adapted from Creutzig at al. 2018

Service	Emission decomposition factors	Avoid	Shift	Improve
Mobility [passenger-km] *(Ch 8,10, 11,16)*	kg CO_2 = (passenger km)*(MJ pkm^{-1})*(kg CO_2 MJ^{-1})	**Innovative mobility to reduce passenger-km:** Integrate transport & land use planning Smart logistics Tele-working Compact cities Fewer long-haul flights Local holidays	**Increased options for mobility MJ pkm^{-1}:** Modal shifts, from car to cycling, walking, or public transit from air travel to high speed rail	**Innovation in equipment design MJ pkm^{-1} and CO_2-eq MJ^{-1}:** Lightweight vehicles Hydrogen vehicles Electric vehicles Eco-driving
Shelter [Square meters] *(Ch 8,9, 11)*	kg CO_2 = (square meters)*(tons material m^{-2})*(kg CO_2 ton $material^{-1}$)	**Innovative dwellings to reduce square meters:** Smaller decent dwellings	**Material efficient housing tons material m^{-2}:** Less material-intensive dwelling designs	**Low emission dwelling design kgCO_2 ton^{-1} material:** Use wood as material

		Shared common spaces Multigenerational housing	Shift from single-family to multi-family dwellings	Use low-carbon production processes for building materials (e.g., cement and steel)
Thermal comfort [indoor temperature] *(Ch 9,16)*	kg CO_2 = (Δ°C m^3 to warm or cool) (MJ m^{-3})*(kg CO_2 MJ^{-1})	**Choice of healthy indoor temperature Δ°C m^3:** Reduce m^2 as above Change temperature set-points Change dressing code Change working times	**Design options to reduce MJ Δ°C^{-1} m^{-3}:** Architectural design (shading, natural ventilation, etc.)	**New technologies to reduce MJ Δ°C^{-1} m^{-3} and kgCO_2/MJ:** Solar thermal devices Improved insulation Heat pumps District heating
Goods [units] *(Ch 11,12)*	kg CO_2 = product units * (kg material $product^{-1}$)*(kg CO_2 kg $material^{-1}$)	**More service per product:** Reduce consumption quantities Long lasting fabric, appliances Sharing economy	**Innovative product design kg material product $^{-1}$:** Materials efficient product designs	**Choice of new materials kg CO_2 kg $material^{-1}$:** Use of low carbon materials New manufacturing processes and equipment use
Nutrition [Calories consumed] *(Ch 6,12)*	kg CO_2-eq = (calories consumed)*(calories produced calories $consumed^{-1}$)*(kg CO_2-eq calorie $produced^{-1}$)	**Reduce calories produced/calories consumed and optimize calories consumed:** Keep calories in line with daily needs and health guidelines Reduce waste in supply chain and after purchase	**Add more variety in food plate to reduce kg CO_2-eq cal^{-1} produced** Dietary shifts from ruminant meat and dairy to other protein sources while maintaining nutritional quality	**Reduce kg CO_2-eq cal^{-1} produced:** Improved agricultural practices Energy efficient food processing
Lighting [lumens] *(Ch 9, 16)*	kg CO_2 = lumens*(kWh $lumen^{-1}$)*(kg CO_2 kWh^{-1})	**Minimize artificial lumen demand:** Occupancy sensors Lighting controls	**Design options to increase natural lumen supply:** Architectural designs with maximal daylighting	**Demand innovation lighting technologies kWh $lumens^{-1}$ and power supply kg CO_2 kWh^{-1}:** LED lamps

Opportunities for avoiding waste associated with the provision of services, or avoiding overprovision of or excess demand for services themselves, exist across multiple service categories. Avoid options are relevant in all end-use sectors, namely, teleworking and avoiding long-haul flights, adjusting dwelling size to household size, avoiding short life span product, and food waste. Cities and built environments can play an additional role. For example, more compact designs and higher accessibility reduce travel demand and translate into lower average floor space and corresponding heating/cooling and lighting demand, and thus between 5% to 20% of GHG emissions of end-use sectors (Creutzig et al. 2021b). Avoidance of food loss and wastage – which equalled 8–10% of total anthropogenic GHG emissions from 2010-2016 (Mbow et al. 2019), while millions suffer from hunger and malnutrition – is a prime example (see Chapter 12). A key challenge in meeting global nutrition services is therefore to avoid food loss and waste while simultaneously raising nutrition levels to equitable standards globally. Literature results indicate that in developed economies consumers are the largest source of food waste, and that behavioural changes such as meal planning, use of leftovers, and avoidance of over-preparation can be important service-oriented solutions (Gunders et al. 2017; Schanes et al. 2018), while improvements to expiration labels by regulators would reduce unnecessary disposal of unexpired items (Wilson et al. 2017) and improved preservation in supply chains would reduce spoilage (Duncan and Gulbahar 2019). ~931 million tons of food waste was generated in 2019 globally, 61% of which came from households, 26% from food service and 13% from retail.

Demand side mitigations are achieved through changing ***S**ocio-cultural factors*, ***I**nfrastructure use* and ***T**echnology adoption* by various social actors in urban and other settlements, food choice and waste management (*high confidence*) (Figure 5.7). In all sectors, end-use strategies can help reduce the majority of emissions, ranging from 28.7% (4.13 $GtCO_2$-eq) emission reductions in the industry sector, to 44.2% (7.96 $GtCO_2$-eq) in the food sectors, to 66.75% (4.671 $GtCO_2$-eq) emission reductions in the land transport sector, and 66% (5.763 $GtCO_2$-eq) in the buildings sector. These numbers are median estimates and represent benchmark accounting. Estimates are approximations, as they are simple products of individual assessments for each of the three *SIT* options. If interactions were taken into account, the full mitigation potentials may be higher or lower, independent of relevant barriers to realizing the median potential estimates. See more in Supplementary Material II Chapter 5, Table SM2.

The technical mitigation potential of food loss and waste reductions globally has been estimated at 0.1-5.8 $GtCO_2$-eq (*high confidence*) (Poore and Nemecek 2018; Smith, et al. 2019) (Figure 5.7, 7.4.5, Table 12.3). Coupling food waste reductions with dietary shifts can further reduce energy, land, and resource demand in upstream food provision systems, leading to substantial GHG emissions benefits. The estimated technical potential for GHG emissions reductions associated with shifts to sustainable healthy diets is 0.5-8 $GtCO_2$-eq (Smith et al. 2013; Jarmul et al. 2020; Creutzig et al. 2021b) (Figure 5.7, Table 12.2) (*high confidence*). Current literature on health, diets, and emissions indicates that sustainable food systems providing healthy diets for all are within reach but require significant cross-sectoral action, including improved agricultural practices, dietary shifts among consumers, and food waste reductions in production, distribution, retail, and consumption (Table 12.9) (Erb et al. 2016; Muller et al. 2017; Willett and al. 2018; Graça et al. 2019).

Reduced food waste and dietary shifts have highly relevant repercussions in the land use sector that underpin the high GHG emission reduction potential. Demand side measure lead to changes in consumption of land-based resources and can save GHG emissions by reducing or improving management of residues or making land areas available for other uses such as afforestation or bioenergy production (Smith et al. 2013; Hoegh-Guldberg et al. 2019). Deforestation is the second largest source of anthropogenic greenhouse gas emissions, caused mainly by expanding forestry and agriculture and in many cases this agricultural expansion is driven by trade demand for food e. g. across the tropics, cattle and oilseed products accounts for half of the resulted deforestation carbon-emissions, embodied in international trade to China and Europe (Creutzig et al. 2019a; Pendrill et al. 2019). Benefits from shifts in diets and resulting lowered land pressure are also reflected in reductions of land degradation and improved.

Increased demand for biomass can increase the pressure on forest and conservation areas (Cowie et al. 2013) and poses an heightened risk for biodiversity, livelihoods, and intertemporal carbon balances (Creutzig et al. 2021c; Lamb et al. 2016) requiring policy and regulations to ensure sustainable forest management which depends on forest type, region, management, climate, and ownership. This suggests that demand-side actions hold sustainability advantages over the intensive use of bioenergy and BECCS, but also enable land use for bioenergy by saving agricultural land for food.

In the transport sector, ASI opportunities exist at multiple levels, comprehensively summarised in Bongardt et al (2013), Roy et al (2021) and Sims et al (2014) (Chapter 10). Modelling based on a plethora of bottom-up insights and options reveals that a balanced portfolio of ASI policies brings the global transport sector emissions in line with global warming of not more than 1.5°C (Gota et al. 2019). For example, telework may be a significant lever for avoiding road transport associated with daily commutes, achievable through digitalisation, but its savings depend heavily on the modes, distances, and types of office use avoided (Hook et al. 2020) and whether additional travel is induced due to greater available time (Mokhtarian 2002) or vehicle use by other household members (Kim et al. 2015; de Abreu e Silva and Melo 2018). More robustly, avoiding kilometres travelled through improved urban planning and smart logistical systems can lead to fuel, and, hence, emissions savings (IEA 2016, 2017a; Creutzig et al. 2015a; Wiedenhofer et al. 2018), or through avoiding long-haul flights (IEA 2021). For example, reallocating road and parking space to exclusive public transit lanes, protected bike lanes and pedestrian priority streets can reduce vehicle kilometres travelled in urban areas (ITF 2021). At the vehicle level, light weighting strategies (Fischedick et al. 2014) and avoiding inputs of carbon-intensive materials into vehicle manufacturing can also lead to significant emissions savings through improved fuel economy (Das et al. 2016; Hertwich et al. 2019; IEA 2019b).

Figure 5.7 shows Socio-cultural factors can contribute up to 15% to land transport GHG emissions reduction by 2050, with 5% as our central estimate. Active mobility, such as walking and cycling, has 2%-10% potential in GHG emissions reduction. Well-design teleworking and telecommuting policies can at least reduce transport related GHG emissions by 1%. A systematic review demonstrates that 26 of 39 studies identified suggest that teleworking reduces energy use, induced mainly by distance traveled, and only eight studies suggest that teleworking increases or has a neutral impact on energy use (Hook et al. 2020). Infrastructure use (specifically urban planning and shared pooled mobility) has about 20-50% (on average) potential in the land transport GHG emissions reduction, especially via redirecting the ongoing design of existing infrastructures in developing countries, and with 30% as our central estimate (see also 5.3.4.2). Technology adoption, particularly banning ICEs and 100% EV targets and efficient lightweight cars, can contribute to between 30 and 70% of GHG emissions reduction in land transport in 2050, with 50% as our central estimate. For details see Supplementary Material II Chapter 5, Table SM2 and Chapter 10.

Socio-cultural factors such avoid long-haul flights and shifting to train wherever possible can contribute between 10% and 40% to aviation GHG emissions reduction by 2050 (Figure 5.7). Maritime transport (shipping) emits around 940 $MtCO_2$ annually and is responsible for about 2.5% of global GHG emissions (IMO 2020). Technology measures and management measures, such as slow steaming, weather routing, contra-rotating propellers, and propulsion efficiency devices can deliver more fuel savings between 1% and 40% than the investment required (Bouman et al. 2017). For details see Supplementary Material II Chapter 5, Table SM2.

In the buildings sector, avoidance strategies can occur at the end use or individual building operation level. End use technologies/strategies such as the use of daylighting (Bodart and De Herde 2002) and lighting sensors can avoid demand for lumens from artificial light, while passive houses, thermal mass, and smart controllers can avoid demand for space conditioning services. Eliminating standby power losses can avoid energy wasted for no useful service in many appliances/devices, which may reduce household electricity use by up to 10% (Roy et al. 2012). At the building level, smaller dwellings can reduce overall demand for lighting and space conditioning services, while smaller dwellings, shared housing, and building lifespan extension can all reduce the overall demand for carbon-intensive building materials such as concrete and steel (Material Economics 2018; Pauliuk et al. 2021; Hertwich et al. 2019; IEA 2019b). Emerging strategies for materials efficiency, such as 3D printing to optimise the

geometries and minimise the materials content of structural elements, may also play a key role if thermal performance and circularity can be improved (Mahadevan et al. 2020; Adaloudis and Bonnin Roca 2021). Several scenarios estimate an 'avoid' potential in the building sector, which includes reducing waste in superfluous floor space, heating and IT equipment, and energy use, of between 10 and 30%, in one case even by 50% (Nadel, Steven and Ungar 2019). For details see Chapter 9.
Socio-cultural factors and behavioral and social practices in energy saving like adaptive hearing and cooling by changing temperature can contribute about 15% to Buildings GHG emissions reduction by 2050 (Figure 5.7). Infrastructure use such as compact city and urban planning interventions, living floor space rationalization, and access to low carbon architectural design has about 20% potential in the Buildings GHG emissions reduction. Technology adoption, particularly access to energy efficient technologies, and choice for installation of renewable can contribute between 30% and 70% to GHG emissions reeducation in Buildings sector. For details see Supplementary Material II Chapter 5, Table SM2 and Chapter 8 and 9 .

Service efficiency strategies are emerging to avoid materials demand at the product level, including dematerialisation strategies for various forms of packaging (Worrell and Van Sluisveld 2013) and the concept of "products as services," in which product systems are designed and maintained for long lifespans to provide a marketable service (Oliva and Kallenberg 2003), thereby reducing the number of products sold and tons of materials needed to provide the same service to consumers, consistent with circular economy and materials efficiency principles (see Chapter 11). Successful examples of this approach have been documented for carpets (Stubbs and Cocklin 2008), copiers (Roy 2000), kitchens (Liedtke et al. 1998), vehicles (Ceschin and Vezzoli 2010; Williams 2006) and more (Roy 2000).

Shift strategies unique to the service-oriented perspective generally involve meeting service demands at much lower life-cycle energy, emissions, and resource intensities (Roy and Pal 2009), through such strategies as shifting from single-family to multi-family dwellings (reducing the materials intensity per unit floor area (Ochsendorf et al. 2011)), shifting from passenger cars to rail or bus (reducing fuel, vehicle manufacturing, and infrastructure requirements (Chester and Horvath 2009), shifting materials to reduce resource and emissions intensities (e.g., low-carbon concrete blends (Scrivener and Gartner 2018)) and shifting from conventional to additive manufacturing processes to reduce materials requirements and improve end-use product performance (Huang et al. 2016, 2017).

An important consideration in all ASI strategies is the potential for unintended rebound effects (Sorrell et al. 2009; Brockway et al. 2021) as indicated in Figures 5.8, 5.12, and 5.13a, which must be carefully avoided through various regulatory and behavioural measures (Santarius et al. 2016) and in many developing country contexts rebound effects can help in accelerated provision of affordable access to modern energy and a minimum level of per capita energy consumption (Saunders et al. 2021; Chakravarty and Roy 2021). Extending the lifespan of energy inefficient products may lead to net increases in emissions (Gutowski et al. 2011), whereas automated car sharing may reduce the number of cars manufactured at the expense of increased demand for passenger kilometres due to lower travel opportunity cost (Wadud et al. 2016) (see also 5.3.2).

Avoid short life span products in favour of products with longer lifespan as a *socio-cultural factor*; *infrastructure use* such as increasing the re-usability and recyclability of product's components and materials; and adopting the materials-efficient services and CO_2-neutral materials have about 29% indicative potential by 2050. For details see Supplementary Material II Chapter 5, Table SM2 and Chapter 11.

In summary, sector specific demand side mitigation options reflect important role of socio-cultural, technological and infrastructural factors and interdependence among them (Figure 5.7). The assessment in Figure 5.7 shows by 2050 high emission reduction potential can be realised with demand side actions alone which can be complementary to supply side interventions with considerable impact by reducing need for capacity addition on the electricity supply system. Integrated cross sectoral actions shown through sector coupling is also important for investment decision making and policy framing going beyond sector boundaries (*high evidence and high agreement*).

Demand for service	Nutrition	Manufactured products	Mobility	Mobility	Mobility	Shelter
Socio-cultural factors	Shift in dietary choice with reduced animal protein; avoid food waste; avoid over-consumption	Avoid short life span products	Avoid long haul flights; shift to trains wherever possible	Currently not applicable	Teleworking or telecommuting; active mobility such as walking and cycling	Social practices in energy saving; and lifestyle and behavioural changes
Infrastructure use	Enhance the role of choice architectures & information; financial incentives; waste management; recycling infrastructure	Reuse and recycling	Currently not applicable	Currently not applicable	Public transport; shared mobility; compact city; spatial planning	Compact cities; built environment; living floor space rationalisation; architectural design; feedback control systems
Technology adoption	Currently not applicable	Access to materials-efficient services; access to energy-efficient and CO_2-neutral materials	Adoption of energy-efficient technologies; technologies with improved aerodynamics	Adoption of energy-efficient technology/systems	Electric vehicles; efficiency technologies	Adopting energy-efficient solutions; shift to renewables

Figure 5.7 Demand-side mitigation options and indicative potentials

Mitigation response options related to demand for services have been categorised into three domains: 'socio-cultural factors', related to social norms, culture, and individual choices and behaviour; 'infrastructure use', related to the provision and use of supporting infrastructure that enables individual choices and behaviour; and 'technology adoption', which refers to the uptake of technologies by end users. Potentials in 2050 are estimated using the International Energy Agency's 2020 World Energy Outlook STEPS (Stated Policy Scenarios) as a baseline. This scenario is based on a sector-by-sector assessment of specific policies in place, as well as those that have been announced by countries by mid-2020. This scenario was selected due to the detailed representation of options across sectors and sub-sectors. The heights of the coloured columns represent the potentials on which there is a high level of agreement in the literature, based on a range of case studies. The range shown by the dots connected by dotted lines represents the highest and lowest potentials reported in the literature which have low to medium levels of agreement. The demand side potential of socio-cultural factor in food has two parts. Economic potential of demand reduction through socio-cultural factors alone is 1.9 $GtCO_2eq$ without considering LUC by diversion of agricultural land from food production to carbon sequestration purposes. If further changes in choice architectures and LUC due to this change in demand is considered indicative potential becomes 7 $GtCO_2eq$. The electricity panel presents separately the mitigation potential from changes in electricity demand associated with enhanced electrification in end use sectors. Electrification increases electricity demand, while it is avoided though demand-side mitigation strategies. Load management refers to demand side flexibility that can be achieved through incentive design like time of use pricing/monitoring by artificial intelligence, diversification of storage facilities etc. NZE (IEA Net Zero Emissions by 2050 Scenario) is used to compute the impact of end use sector electrification,

while the impact of demand side response options is based on bottom-up assessments. Dark grey columns show the emissions that cannot be avoided through demand-side mitigation options.

The table indicates which demand-side mitigation options are included. Options are categorised according to: socio-cultural factors, infrastructure use, and technology adoption.
(5.3, Supplementary Material 5.II)

5.3.1.2 Household consumption options to reduce GHG emissions

A systematic review of options to reduce the GHG emissions associated with household consumption activities identified 6990 peer-reviewed journal papers, with 771 options that were aggregated into 61 consumption option categories ((Ivanova et al. 2020); Figure 5.8). In consistence with previous research (Herendeen and Tanaka 1976; Pachauri and Spreng 2002; Pachauri 2007; Ivanova et al. 2016), a hierarchical list of mitigation options emerges. Choosing low-carbon options, such as car-free living, plant-based diets without or very little animal products, low-carbon sources of electricity and heating at home as well as local holiday plans, can reduce an individual's carbon footprint by up to 9tCO_2-eq. Realising these options requires substantial policy support to overcome infrastructural, institutional and socio-cultural lock-in (see Sections 5.4 and 5.6).

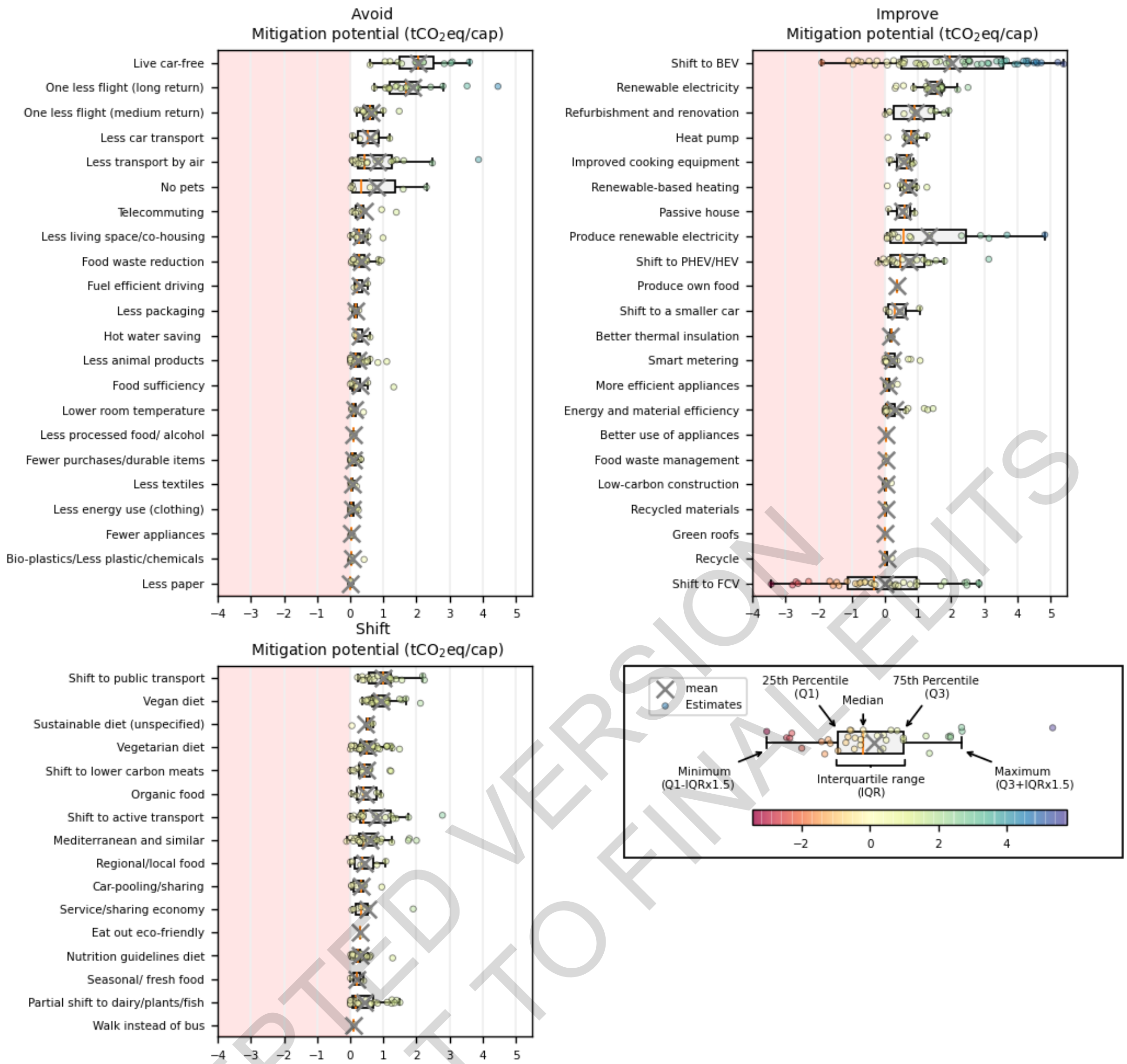


Figure 5.8 Synthesis of 60 demand side options ordered by the median GHG mitigation potential found across all estimates from the literature.
The x-s are averages. The boxes represent the 25th percentile, median and 75th percentiles of study results. The whiskers or dots show the minimum and maximum mitigation potentials of each option. Negative values (in the red area) represent the potentials for backfire due to rebound, i.e. a net-increase of GHG emissions due to adopting the option.
Source: Ivanova et al. 2020

5.3.2 Technical tools to identify Avoid-Shift-Improve options

Service delivery systems to satisfy a variety of service needs (e.g., mobility, nutrition, thermal comfort, etc.) comprise a series of interlinked processes to convert primary resources (e.g. coal, minerals) into useable products (e.g. electricity, copper wires, lamps, light bulbs). It is useful to differentiate between conversion and processing steps "upstream" of end-users (mines, power plants, manufacturing facilities) and "downstream", i.e. those associated with end-users, including service levels, and direct well-being benefits for people (Kalt et al. 2019). Illustrative examples of such resource processing systems steps and associated conversion losses drawn from the literature are shown in Figure 5.9. in the form of resource processing cascades for energy (direct energy conversion efficiencies (Nakićenović et al. 1993; De Stercke 2014)), water use in food production systems (water use efficiency and embodied water losses in food delivery and consumption (Lundqvist et al. 2008; Sadras et al. 2011)), and materials

(Ayres and Simonis 1994; Fischer-Kowalski et al. 2011) using the example of steel manufacturing, use and recycling at the global level (Allwood and Cullen 2012). Invariably, conversion losses along the entire service delivery systems are substantial, ranging from 83% (water) to 86% (energy) and 87% (steel) of primary resource inputs (TWI2050 2018). In other words, only between 14 to 17% of the harnessed primary resources remain at the level of ultimate service delivery.

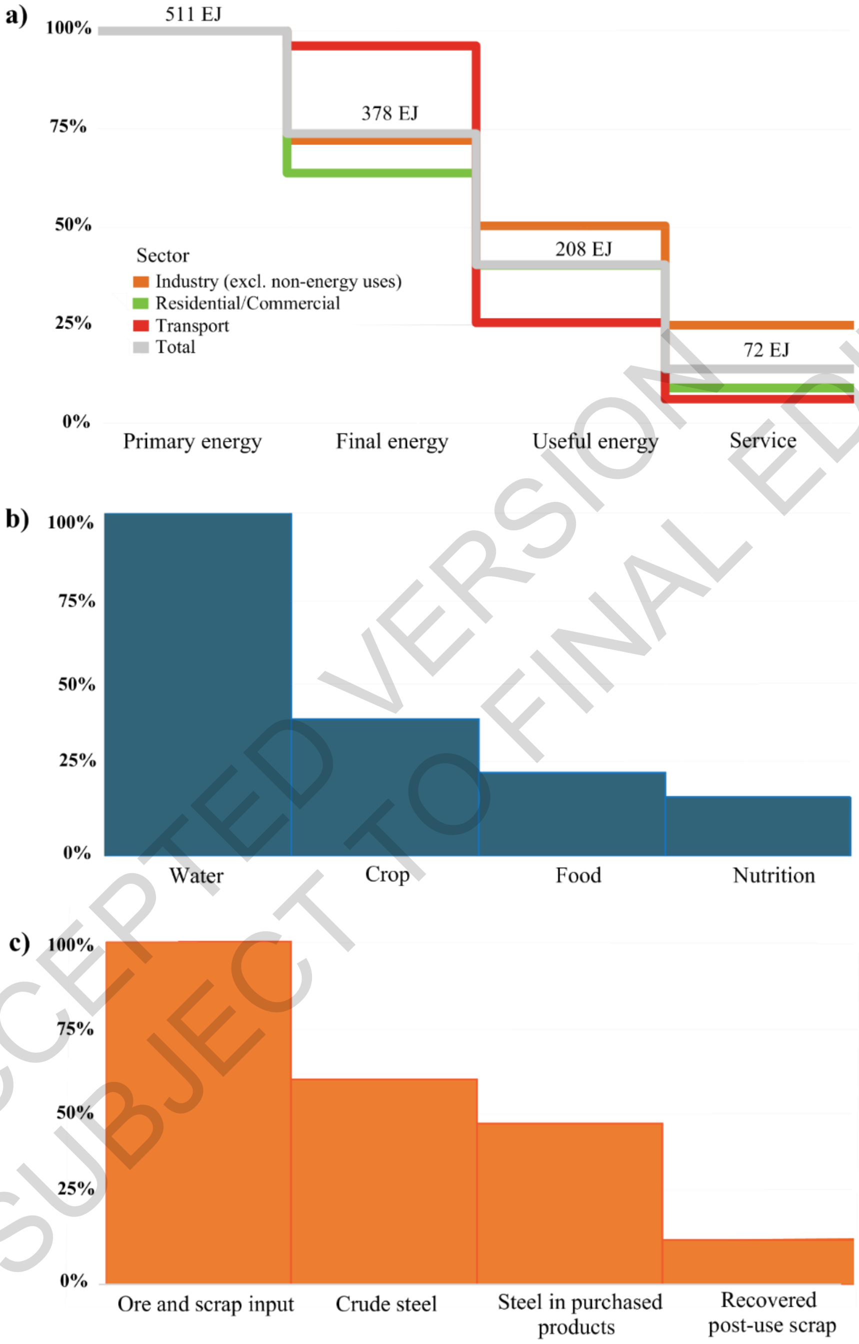


Figure 5.9 Resource processing steps and efficiency cascades (in percent of primary resource inputs [vertical axis] remaining at respective step until ultimate service delivery) for illustrative global service delivery systems for energy (top panel, disaggregated into three sectorial service types and the aggregate total), food (middle panel, water use in agriculture and food processing, delivery and use), and materials (bottom panel, example steel). The aggregate efficiencies of service delivery chains is with 13-17% low.
Source: TWI2050 2018

Examples of conversion losses at the supply side of resource processing systems include for instance for energy electricity generation (global output/input conversion efficiency of electric plants of 45% as shown in energy balance statistics (IEA 2020b); for water embodied in food irrigation water use efficiency (some 40% (Sadras et al. 2011)) and calorific conversion efficiency (food calories out/food calories in) in meat production of 60% (Lundqvist et al. 2008), or for materials where globally only 47% or primary iron ore extracted and recovered steel scrap end up as steel in purchased products, (i.e. a loss of 57%) (Allwood and Cullen 2012).

A substantial part of losses happen at the end-use point and in final service delivery (where losses account for 47 to 60% of aggregate systems losses for steel and energy respectively, and for 23% in the case of water embodied in food, i.e. food waste). The efficiency of service delivery (for a detailed discussion cf. (Brand-Correa and Steinberger 2017)) has usually both a technological component (efficiency of end-use devices such as cars, light bulbs) and a behavioural component (i.e. how efficiently end-use devices are used, e.g. load factors, for a discussion of such behavioural efficiency improvement options see e.g. (Dietz et al. 2009; Laitner et al. 2009; Ehrhardt-Martinez 2015; Kane and Srinivas 2014; Lopes et al. 2017; Thaler 2015; Norton 2012). Using the example of mobility where service levels are usually expressed by passenger-km, the service delivery efficiency is thus a function of the fuel efficiency of the vehicle and its drivetrain (typically only about 20%-25% for internal combustion engines, but close to 100% for electric motors) plus how many passengers the vehicle actually transports (load factor, typically as low as 20%-25%, i.e. one passenger per vehicle that could seat 4-5), i.e. an aggregate end-use efficiency of between 4-6% only. Aggregated energy end-use efficiencies at the global level are estimated as low as 20% (De Stercke 2014), 13% for steel (recovered post-use scrap, Allwood and Cullen, 2012), and some 70% for food (including distribution losses and food wastes of some 30%, (Lundqvist et al. 2008).

To harness additional gains in efficiency by shifting the focus in service delivery systems to the end-user can translate into large "upstream" resource reductions. For each unit of improvement at the end-use point of the service delivery system (examples shown in Figure 5.9), primary resource inputs are reduced between a factor of 6 to 7 units (water, steel, energy) (TWI2050 2018). For example, reducing energy needs for final service delivery equivalent to 1 EJ, reduces primary energy needs by some 7 EJ. There is thus *high evidence and high agreement* in the literature that the leverage effect for improvements in end-use service delivery efficiency through behavioural, technological, and market organisational innovations is very large, ranging from a factor 6-7 (resource cascades) to up to a factor 10 to 20 (exergy analysis) with the highest improvement potentials at the end-user and service provisioning levels (for systemic reviews see (Nakićenović et al. 1996a; Grubler et al. 2012b; Sousa et al. 2017). Also the literature shows *high agreement* that current conversion efficiencies are invariably low, particularly for those components at the end-use and service delivery back end of service provisioning systems. It also suggests that efficiencies might be actually even lower than those revealed by direct input-output resource accounting as discussed above (Figure 5.9). Illustrative exergy efficiencies of entire national or global service delivery systems range from 2.5% (USA, (Ayres 1989)) to 5% (OECD average, (Grubler et al. 2012b)) and 10% (global, Nakićenović et al., 1996) respectively. Studies that adopt more restricted systems boundaries either leaving out upstream resource processing/conversion or conversely end-use and service provision, show typical exergetic efficiencies between 15% (city of Geneva, cf. (Grubler et al. 2012a)) to below 25% (Japan, Italy, and Brazil, albeit with incomplete systems coverage that miss important conversion losses (Nakićenović et al. 1996b)). These findings are confirmed by more recent exergy efficiency studies that also include longitudinal time trend analysis (Cullen and Allwood 2010; Serrenho et al. 2014; Guevara et al. 2016; Brockway et al. 2014, 2015). Figure 5.10 illustrates how energy demand reductions can be realized by improving the resource efficiency cascades shown in Figure 5.9 above.

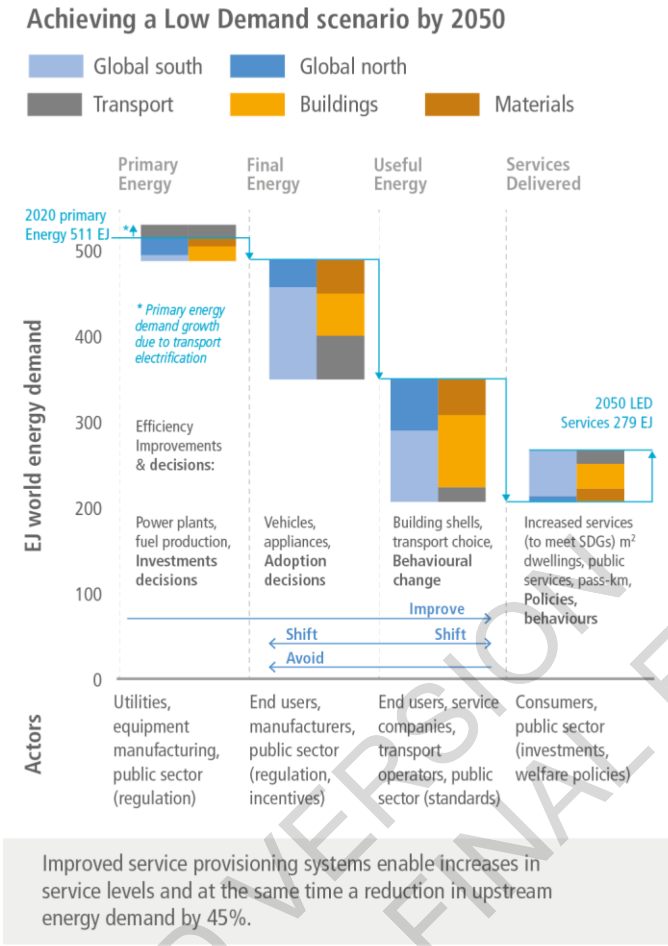


Figure 5.10 Realisable energy efficiency improvements by region and by end-use type between 2020 and 2050 in an illustrative Low Energy Demand scenario (in EJ). Efficiency improvements are decomposed by respective steps in the conversion chain from primary energy to final, and useful energy, and to service delivery and disaggregated by region (developed and developing countries) and end-use type (buildings, transport, materials). Improvements are dominated by improved efficiency in service delivery (153 EJ) and by more efficient end-use energy conversion (134 EJ). Improvements in service efficiency in transport shown here are conservative in this scenario but could be substantially higher with the full adoption of integrated urban shared mobility schemes. Increases in energy use due to increases in service levels and system effects of transport electrification (grey bars on top of first pair in the bar charts) that counterbalance some of the efficiency improvements are also shown. Examples of options for efficiency improvements and decision involved (grey text in the chart), the relative weight of generic demand-side strategies (improve, shift, avoid blue arrows), as well as prototype actors involved are also illustrated
Data: Figure 5.9 and Grubler et al. 2018.

5.3.3 Low demand scenarios

Long-term mitigation scenarios play a crucial role in climate policy design in the near term, by illuminating transition pathways, interactions between supply-side and demand-side interventions, their timing, and the scales of required investments needed to achieve mitigation goals (see Chapter 3). Historically, most long-term mitigation scenarios have taken technology-centric approaches with heavy reliance on supply-side solutions and the use of carbon dioxide removal, particularly in 1.5ºC scenarios (Rogelj et al. 2018). Comparatively less attention has been paid to deep demand-side reductions incorporating socio-cultural change and the cascade effects (see Section 5.3.2) associated with ASI strategies, primarily due to limited past representation of such service-oriented interventions in long-term integrated assessment models (IAMs) and energy systems models (ESMs) (Napp et al. 2019; van de Ven et al. 2018; Grubler et al. 2018). There is ample evidence of savings from sector- or issue-specific bottom-up studies (see Section 5.3.1.2). However, these savings typically get lost in the dominant narrative provided by IAMs and ESMs and in their aggregate-level evaluations of combinations of ASI and efficiency strategies. As a result, their interaction effects do not typically get equal focus alongside supply-side and carbon dioxide removal options (Van den Berg et al. 2019; Van Vuuren et al. 2018; Samadi et al. 2017).

In response to 1.5ºC ambitions, and a growing desire to identify participatory pathways with less reliance on carbon dioxide removal with high uncertainty, some recent IAM and ESM mitigation scenarios have explored the role of deep demand-side energy and resource use reduction potentials at global and regional levels. Table 5.2 summarises long-term scenarios that aimed to: minimise service-level energy and resource demand as a central mitigation tenet; specifically evaluate the role of behavioural change and ASI strategies; and/or to achieve a carbon budget with limited/no carbon dioxide removal. From assessment of this emerging body of literature, several general observations arise and are presented below.

First, socio-cultural changes within transition pathways can offer Gigaton-scale CO_2 savings potential at the global level, and therefore represent a substantial overlooked strategy in traditional mitigation scenarios. Two lifestyle change scenarios conducted with the IMAGE IAM suggested that behaviour and cultural changes such heating and cooling set-point adjustments, shorter showers, reduced appliance use, shifts to public transit, less meat intensive diets, and improved recycling can deliver an additional 1.7 Gt and 3 $GtCO_2$ savings in 2050, beyond the savings achieved in traditional technology-centric mitigation scenarios for the 2ºC and 1.5ºC ambitions, respectively (van Sluisveld et al. 2016; Van Vuuren et al. 2018). In its Sustainable Development Scenario, the IEA's behavioural change and resource efficiency wedges deliver around 3 $GtCO_2$-eq reduction in 2050, combined savings roughly equivalent to those of solar PV that same year (IEA 2019a). In Europe, a GCAM scenario evaluating combined lifestyle changes such as teleworking, travel avoidance, dietary shifts, food waste reductions, and recycling reduced cumulative EU-27 CO_2 emissions 2011-2050 by up to 16% compared to an SSP2 baseline (van de Ven et al. 2018). Also in Europe, a multi-regional input-output analysis suggested that adoption of low-carbon consumption practices could reduce carbon footprints by 25%, or 1.4 Gt (Moran et al. 2020). A global transport scenario suggests that transport sector emission can decline from business as usual 18 $GtCO_2$-eq to 2 $GtCO_2$-eq if ASI strategies are deployed (Gota et al. 2019), a value considerably below the estimates provided in IAM scenarios that have limited or no resolution in ASI strategies (compare with Chapter 10).

The IEA's Net Zero Emissions by 2050 (NZE) scenario, in which behavioural changes lead to 1.7 GtCO2 savings in 2030, expresses the substantial mitigation opportunity in terms of low-carbon technology equivalencies: to achieve same emissions reductions, the global share of EVs in the NZE would have to increase from 20% to 45% by 2030 or the number of installed heat pumps in homes in the NZE would have to increase from 440 to 660 million in 2030 (IEA 2021).
In light of the limited number of mitigation scenarios that represent socio-behavioural changes explicitly, there is *medium evidence* in the literature that such changes can reduce emissions at regional and global levels, but *high agreement* within that literature that such changes hold up to gigaton-scale CO_2 emissions reduction potentials.

Second, pursuant to the ASI principle, deep demand reductions require parallel pursuit of behavioural change and advanced energy efficient technology deployment; neither is sufficient on its own. The LED scenario (Figure 5.10) combines behavioural and technological change consistent with numerous ASI strategies that leverage digitalisation, sharing, and circular economy megatrends to deliver decent living standards while reducing global final energy demand in 2050 to 245 EJ (Grubler et al. 2018). This value is 40% lower than final energy demand in 2018 (IEA 2019a), and a lower 2050 outcome than other IAM/ESM scenarios with primarily technology-centric mitigation approaches (IEA 2017b; Teske et al. 2015). In the IEA's B2DS scenario, avoid/shift in the transport sector accounts for around 2 $GtCO_2$-eq yr^{-1} in 2060, whereas parallel vehicle efficiency improvements increase the overall mitigation wedge to 5.5 $GtCO_2$-eq yr^{-1} in 2060 (IEA 2017b). Through a combination of behavioural change and energy efficient technology adoption, the IEA's NZE requires only 340 EJ of global final energy demand with universal energy access in 2050, which is among the lowest of IPCC net zero SR1.5 scenarios (IEA 2021).

Third, low demand scenarios can reduce both supply side capacity additions and the need for carbon capture and removal technologies to reach emissions targets. Of the scenarios listed in Table 5.2 one (LED-MESSAGE) reaches 2050 emissions targets with no carbon capture or removal technologies (Grubler et al. 2018), whereas others report significant reductions in reliance on bioenergy with carbon capture and storage (BECCS) compared to traditional technology-centric mitigation pathways (Liu et al. 2018; Van Vuuren et al. 2018; Napp et al. 2019), with the IEA's NZE notably requiring the least carbon dioxide removal (CDR) (1.8 Gt in 2050) and primary bioenergy (100 EJ in 2050) compared to IPCC net zero SR1.5 scenarios (IEA 2021).

Fourth, the costs of reaching mitigation targets may be lower when incorporating ASI strategies for deep energy and resource demand reductions. The TIAM-Grantham low demand scenarios displayed reduction in mitigation costs (0.87–2.4% of GDP), while achieving even lower cumulative emissions to 2100 (228 to ~475 $GtCO_2$) than its central demand scenario (741 to 1066 $GtCO_2$), which had a cost range of (2.4–4.1% of GDP) (Napp et al. 2019). The GCAM behavioural change scenario concluded that domestic emission savings would contribute to reduce the costs of achieving the internationally agreed climate goal of the EU by 13.5% to 30% (van de Ven et al. 2018). The AIMS lifestyle case indicated that mitigation costs, expressed as global GDP loss, would be 14% lower than the SSP2 reference scenario in 2100, for both 2°C and 1.5°C mitigation targets (Liu et al. 2018). These findings mirror earlier AIM results, which indicated lower overall mitigation costs for scenarios focused on energy service demand reductions (Fujimori et al. 2014). In the IEA's NZE, behavioural changes that avoid energy and resource demand save USD4 trillion (cumulatively 2021-2050) compared to if those emissions reductions were achieved through low-carbon electricity and hydrogen deployment (IEA 2021).

Based on the limited number of long-term mitigation scenarios that explicitly represent demand reductions enabled by ASI strategies, there is *medium evidence* but with *high agreement* within that literature that such scenarios can reduce dependence on supply-side capacity additions and carbon capture and removal technologies with opportunity for lower overall mitigation costs.

If the limitations within most IAMs and ESMs regarding non-inclusion of granular ASI strategy analysis can be addressed, it will expand and improve long-term mitigation scenarios (Van den Berg et al. 2019). These include broader inclusion of mitigation costs for behavioural interventions (van Sluisveld et al. 2016), much greater incorporation of rebound effects (Krey et al. 2019), including from improved efficiencies (Brockway et al. 2021) and avoided spending (van de Ven et al. 2018), improved representation of materials cycle to assess resource cascades (Pauliuk et al. 2017), broader coverage of behavioural change (Samadi et al. 2017; Saujot et al. 2020), improved consideration of how economic development affects service demand (Semieniuk et al. 2021), explicit representation of intersectoral linkages related to digitalisation, sharing economy, and circular economy strategies (see Section 5.3.4), and institutional, political, social, entrepreneurial, and cultural factors (van Sluisveld et al. 2018). Addressing the current significant modelling limitations will require increased investments in data generation and collection, model development, and inter-model comparisons, with a particular focus on socio-behavioural research that has been underrepresented in mitigation research funding to date (Overland and Sovacool 2020).

Covid-19 interacts with demand-side scenarios (Box 5.2). Energy demand will mostly likely be reduced between 2020 and 2030 compared to default pathway, and if recovery is steered towards low energy demand, carbon prices for a 1.5 °C-consistent pathway will be by 19%, energy supply investments until 2030 by USD1.8 trillion reduced, and the pressure to rapidly upscale renewable energy technologies will be softened (Kikstra et al. 2021a).

1 **Table 5.2 Summary of long-term scenarios with elements that aimed to minimise service-level energy and resource demand**

Global scenarios										
#	**Scenario [Temp]**	**IAM/ ESM**	**Final energy**	**Focused demand reduction element(s)**			**Baseline scenario**	**Mitigation potential[c]**		
				Scope	**Sectors[a]**	**Key demand reduction measures considered (A, S, I) [b]**		**CO_2 (Gt)**	**Final energy**	**Primary energy**
a	Lifestyle change scenario [2ºC]	IMAGE	-	Whole scenario	R, T, I	A: Set points, smaller houses, reduced shower times, wash temperatures, standby loss, reduced car travel, reduced plastics S: from cars to bikes, rail I: improved plastic recycling	2ºC technology-centric scenario in 2050	1.9	-	-
b	Sustainable Development Scenario [1.8ºC]	World Energy Model (WEM)	398 EJ in 2040	Behavioural change wedge and resource efficiency wedge	T, I	A: shift from cars to mass transit, building lifespan extension, materials efficient construction, product reuse I: improved recycling	Stated policies in 2050	3	-	-
c	Beyond 2 Degrees Scenario [1.75ºC]	ETP-TIMES	377 EJ in 2050	Transport avoid/shift wedge and material efficiency wedge	T, I	A: shorter car trips, optimised truck routing and utilisation S: shifts from cars to mass transit I: plastics and metal recycling, production yield improvements	Stated policies in 2060	2.8	-	-
d	Lifestyle change scenario [1.5ºC]	IMAGE	322 EJ in 2050	Whole scenario	R, C, T, I	A: Set points, reduced appliance use S: from cars to mass transit, less meat intensive diets, cultured meat I: best available technologies across sectors	1.5ºC technology-centric scenario in 2050	3.1	-	-

e	Low Energy Demand Scenario [1.5ºC]	MESSAGE	245 EJ in 2050	Whole scenario	R, C, T, I, F	A: device integration, telework, shared mobility, material efficiency, dematerialisation, reduced paper S: multi-purpose dwellings, healthier diets I: best available technologies across sectors	Final energy in 2020	-	179 EJ	-
f	Advanced Energy [R]evolution	-	279 EJ in 2050	Whole scenario	R, C, T, I	S: shifts from cars to mass transit I: best available technologies across sectors	Continuation of current trends and policies in 2050	-	260 EJ	-
g	Limited BECCS – lifestyle change [1.5ºC]	IMAGE	-	Whole scenario	R, C, T, F	A: Set points, reduced appliance use S: from cars to mass transit, less meat intensive diets, cultured meat I: best available technologies across sectors	1.5ºC technology-centric scenario in 2050	2.2 Gt	-	82 EJ
h	Lifestyle scenario [1.5ºC]	AIM	374 EJ in 2050	Whole scenario	T, I, F	A: reduced transport services demand, reduced demand for industrial goods S: less meat-intensive diets	1.5ºC supply technology-centric scenario in 2050	-	42 EJ	-
i	Transport scenario [1.5ºC]	Bottom-up construction	-	Whole scenario	T	A: multiple options S: multiple options I: multiple options		89% vs BAU: $16GtCO_2$	-	-
j	Net Zero Emissions 2050 scenario	World Energy Model (WEM)	-	Behaviour change wedge	R, T	A: Set points, line drying, reduced wash temperatures, telework, reduced air travel S: shifts to walking, cycling I: eco-driving	Stated policies in 2030	2	-	-
k	Decent living with minimum energy	Bottom-up construction	149 EJ in 2050	Whole scenario	R, T, I, F	A: activity levels for mobility, shelter, nutrition, etc. consistent with decent living standards S: shifts away from animal-based foods, shifts to public transit, more	IEA Stated Policies Scenario in 2050	-	75%	-

						I: energy efficiency consistent with best available technologies				
l	Net-Zero Emissions by 2050 Scenario (NZE)	Hybrid model based on WEM and ETP-TIMES	340 EJ in 2050	Behavioural change reductions	R, C, T, I	A: heating, air conditioning, and hot water set points, reduce international flights, line drying, vehicle light-weighting, materials-efficient construction, building lifespan extension S: shift regional flights to high-speed rail, shift cars to walking, cycling or public transport, I: eco-driving, plastics recycling	Stated policies in 2050	2.6	37 EJ	
Regional scenarios										
m	Urban mitigation wedge	-	540 EJ in global cities in 2050	Whole scenario	R, C, T	A: reduced transport demand S: mixed-use developments I: vehicle efficiency, building codes and retrofits	Current trends to 2050	-	180 EJ	-
n	France 2072 collective society	TIMES-Fr	4.2 EJ in France in 2072	Whole scenario	R, T	A: less travel by car and plane, longer building and device lifespans, less spending S: shared housing, shifts from cars to walking, biking, mass transit	Final energy in 2014	-	1.7 EJ	-
o	EU-27 lifestyle change – enthusiastic profile	GCAM	-	Whole scenario	R, T, F	A: telework, avoid short flights, closer holidays, food waste reduction, car sharing, set points S: vegan diet, shifts to cycling and public transit I: eco-driving, composting, paper, metal, plastic, and glass recycling	SSP2, cumulative emissions 2011-2050	16%	-	-
p	Europe broader regime change scenario	IMAGE	35 EJ in EU in 2050	Whole scenario	R, T	A: reduced passenger and air travel, smaller dwellings, fewer appliances, reduced shower times, set points, avoid standby losses S: car sharing, shifts to public transit I: best available technologies	SSP2 in 2050	-	10 EJ	-

q	EU Carbon-CAP	EXIOBASE 3 MRIO	-	Whole scenario	R, T, F	90 demand-side behaviour change opportunities spanning A-S-I including changes to consumption patterns, reducing consumption, and switching to using goods with a lower-carbon production and low-carbon use phases.	Present day consumption footprint	1.4	-	-
r	France “Negawatt” scenario	Bottom-up construction		Sufficiency wedge	R, C, T, I, F	A: increase building capacity utilisation, reduced appliance use, carsharing, telework, reduced goods consumption, less packaging S: shift to attached buildings; shift from cars and air to public transit and active mobility, carsharing, freight shift to rail and water, shift away from animal proteins I: reduced speed limits, vehicle efficiency, increased recycling	Business as usual in 2050 (~2300 TWh primary energy)	-	-	~500 TWh
s	The Netherlands households energy behavioural changes	BENCH-NLD agent-based model	-	Individual energy behavioural changes and social dynamics; considering carbon pricing	R	A: reduce energy consumption through changing lifestyle, habits and consumption patterns S: to green energy provider; investment on solar PVs (prosumers) I: investment on insulation and energy-efficient appliances	SSP2 in 2030	50%	-	-
t	The Netherlands households energy behavioural changes	BENCH-NLD agent-based model	-	Individual energy behavioural changes and social dynamics	R	A: reduce energy consumption S: investment on solar PVs (prosumers) I: investment on insulation and energy-efficient appliances	SSP2 in 2050	56%	51-71%	
u	Spain households energy behavioural changes	BENCH-ESP agent-based model	-	Individual energy behavioural changes and social dynamics	R	A: reduce energy consumption S: investment on solar PVs (prosumers) I: investment on insulation and energy-efficient appliances	SSP2 in 2050	44%	16-64%	

v	A Societal Transformation Scenario for Staying Below 1.5°C	Global calculator	187 EJ in 2050	Whole scenario	R,C,I,F	A: reduce energy, material and land use consumption	n/a	Down to 9.1 GtCO2 in 2050

Sources: a (van Sluisveld et al. 2016), b (IEA 2019a), c (IEA 2017b), d (Van Vuuren et al. 2018), e (Grubler et al. 2018), f (Teske et al. 2015), g (Esmeijer et al. 2018), h (Liu et al. 2018), i (Gota et al. 2019), j (IEA 2020a), k (Millward-Hopkins et al. 2020), l (IEA 2021), m (Creutzig et al. 2015b), n (Millot et al. 2018), o (van de Ven et al. 2018), p (van Sluisveld et al. 2018), q (Moran et al. 2020), r (Negawatt 2018), s (Niamir et al. 2020c), t,u (Niamir et al. 2020a), v (Kuhnhenn et al. 2020)

[a] R = residential (Chapters 8, 9); C = commercial (Chapters 8, 9), T = transport (Chapters 8, 10), I = industry (Chapter 11), F = food (Chapters 6, 12),

[b] A= avoid; S = shift, I = improve

[c] Relative to indicated baseline scenario value in stated year

5.3.4 Transformative megatrends

The sharing economy, the circular economy, and digitalisation have all received much attention from the research, advocacy, business models and policy communities as potentially transformative trends for climate change mitigation (TWI2050 2019; IEA 2017a; Material Economics 2018). All are essentially emerging and contested concepts (Gallie 1955) that have the common goal of increasing convenience for users and rendering economic systems more resource-efficient, but which exhibit variability in the literature on their definitions and system boundaries. Historically, both sharing and circular economies have been commonplace in developing countries, where reuse, repair, and waste scavaging and recycling comprise the core of informal economies facilitated by human interventions (Wilson et al. 2006; Asim et al. 2012; Pacheco et al. 2012). Digitalisation is now propelling sharing and circular economy concepts in developed and developing countries alike (Roy et al. 2021), and the three megatrends are highly interrelated, as seen in Figure 5.11. For example, many sharing economy concepts rely on corporate or, to lesser degree, non-profit digital platforms that enable efficient information and opportunity sharing, thus making it part of the digitalisation trend. Parts of the sharing economy are also included in some circular economy approaches, as shared resource use renders utilisation of material more efficient. Digital approaches to material management also support the circular economy, such as through waste exchanges and industrial symbiosis. Digitalisation aims more broadly to deliver services in more efficient, timely, intelligent, and less resource-intensive ways (i.e., by moving bits and not atoms), though the use of increasingly interconnected physical and digital systems in many facets of economies. With rising digitalisation also comes the risk of increased electricity use to power billions of devices and the internet infrastructure that connects them, as well as growing quantities of e-waste, presenting an important policy agenda for monitoring and balancing the carbon and resource costs and benefits of digitalisation (Malmodin and Lundén 2018; TWI2050 2019). Rebound effects and instigated consumption of digitalisation are risking to lead to a net increase in GHG emissions (Belkhir and Elmeligi 2018). The determinants and possible scales of mitigation potentials associated with each megatrend are discussed below.

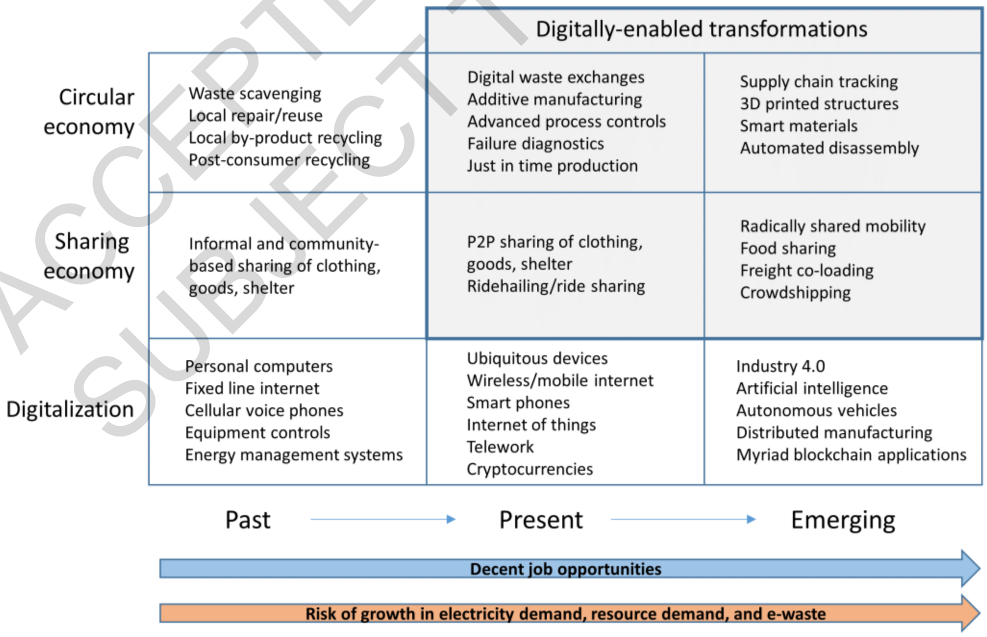


Figure 5.11 The growing nexus between digitalisation, the sharing economy, and the circular economy in service delivery systems. While these trends started mostly independently, rapid digitalisation is creating new synergistic opportunities with systemic potential to improve the quality of jobs, particularly in

developing economies. Widespread digitalisation may lead to net increases in electricity use, demand for electronics manufacturing resources, and e-waste, all of which must be monitored and managed via targeted policies

5.3.4.1 Digitalisation

In the context of service provision, there are numerous opportunities for consumers to buy, subscribe to, adopt, access, install or use digital goods and services (Wilson et al. 2020b). Digitalisation has opened up new possibilities across all domains of consumer activity, from travel and retail to domestic living and energy use. Digital platforms allow surplus resources to be identified, offered , shared, transacted and exchanged (Frenken 2017). Real-time information flows on consumers' preferences and needs mean service provision can be personalised, differentiated, automated, and optimised (TWI2050 2019). Rapid innovation cycles and software upgrades drive continual improvements in performance and responsiveness to consumer behaviour. These characteristics of digitalisation enable new business models and services that affect both service demand, from shared-ridehailing (ITF 2017a) to smart heating (IEA 2017a), and how services are provisioned, from online farmers' markets (Richards and Hamilton 2018) to peer-to-peer electricity trading to enable distributed power systems (Morstyn et al. 2018).

In many cases, digitalisation provides a 'radical functionality' that enables users to do or accomplish something that they could not do before (Nagy et al. 2016). Indeed the consumer appeal of digital innovations varies widely, from choice, convenience, flexibility and control to relational and social benefits (Pettifor and Wilson 2020). Reviewing over 30 digital goods and services for mobility, food buying and domestic living, Wilson et al. (2020b)also found shared elements of appeal across multiple innovations including (i) making use of surplus, (ii) using not owning, (iii) being part of wider networks, and (iv) exerting greater control over service provisioning systems. Digitalisation thus creates a strong value proposition for certain consumer niches. Concurrent diffusion of many digital innovations amplifies their disruptive potential (Schuelke-Leech 2018; Wilson et al. 2019b). Besides basic mobile telephone service for communication, digital innovations have been primarily geared to population groups with high purchasing power, and too little to the needs of poor and vulnerable people.

The long-term sustainability implications of digitalised services hinge on four factors: (1) the direct energy demands of connected devices and the digital infrastructures (i.e. data centres and communication networks) that provide necessary computing, storage, and communication services (Chapter 9.4.6); (2) the systems-level energy and resource efficiencies that may be gained through the provision of digital services (Wilson et al. 2020b); (3) the resource, material, and waste management requirements of the billions of ICT devices that comprise the world's digital systems (Belkhir and Elmeligi 2018; Malmodin and Lundén 2018) and (4) the magnitude of potential rebound effects or induced energy demands that might unleash unintended and unsustainable demand growth, such as autonomous vehicles inducing more frequent and longer journeys due to reduced travel costs (Wadud et al. 2016). Estimating digitalisation's direct energy demand has historically been hampered by lack of consistent global data on IT device stocks, their power consumption characteristics, and usage patterns, for both consumer devices and the data centres and communication networks behind them. As a result, quantitative estimates vary widely, with literature values suggesting that consumer devices, data centres, and data networks account for anywhere from 6% to 12% of global electricity use (Gelenbe and Caseau 2015; Cook et al. 2017; Malmodin and Lundén 2018). For example, within the literature on data centres, top-down models that project energy use on the basis of increasing demand for internet services tend to predict rapid global energy use growth, (Andrae and Edler 2015; Belkhir and Elmeligi 2018; Liu et al. 2020a), whereas bottom-up models that consider data center technology stocks and their energy efficiency trends tend to predict slower but still positive growth (Hintemann and Hinterholzer 2019; Masanet et al. 2020; Shehabi et al. 2018; Malmodin 2020). Yet there is growing concern that remaining energy efficiency improvements might be outpaced by rising demand for digital services, particularly as data-intensive technologies such as artificial intelligence, smart and connected energy systems, distributed manufacturing systems, and autonomous vehicles promise to increase demand for data services even further in the future (TWI2050 2019; Masanet et al. 2020; Strubell et al. 2020). Rapid digitalization is also contributing to an expanding e-waste problem, estimated to be the fastest growing domestic waste stream globally (Forti V., Baldé C.P., Kuehr R. 2020).

As digitalisation proliferates, an important policy objective is therefore to invest in data collection and monitoring systems and energy demand models of digitalised systems to guide technology and policy investment decisions for addressing potential direct energy demand growth (IEA 2017a) and potentially concomitant growth in e-waste.

However, the net systems-level energy and resource efficiencies gained through the provision of digital services could play an important role in dealing with climate change and other environmental challenges (Masanet and Matthews 2010; Melville 2010; Elliot 2011; Watson et al. 2012; Gholami et al. 2013; Añón Higón et al. 2017). As shown in Figure 5.12, assessments of numerous digital service opportunities for mobility, nutrition, shelter, and education and entertainment suggest that net emissions benefits can be delivered at the systems level, although these effects are highly context-dependent. Importantly, evidence of potential negative outcomes due to rebound effects, induced demand, or life-cycle trade-offs can also be observed. For example, telework has been shown to reduce emissions where long and/or energy-intensive commutes are avoided, but can lead to net emissions increases in cases where greater non-work vehicle use occurs or only short, low-emissions commutes (e.g., via public transit) are avoided (Viana Cerqueira et al. 2020; IEA 2020a; Hook et al. 2020). Similarly, substitution of physical media by digital alternatives may lead to emissions increases where greater consumption is fuelled, whereas a shift to 3D printed structures may require more emissions-intensive concrete formulations or result in reduced thermal energy efficiency leading to life-cycle emissions increases (Mahadevan et al. 2020; Yao et al. 2020).

Furthermore, digitalisation, automation and artificial intelligence, as general-purpose technologies, may lead to a plethora of new products and applications that are likely to be efficient on their own but that may also lead to undesirable changes or absolute increases in demand for products (Figure 5.12). For example, last-mile delivery in logistics is both expensive and cumbersome. Battery-powered drones enable a delivery of goods at similar life-cycle emissions to delivery vans (Stolaroff et al. 2018). At the same time, drone delivery is cheaper in terms of time (immediate delivery) and monetary costs (automation saves the highest cost component: personnel) (e.g. (Sudbury and Hutchinson 2016)). As a result, demand for package delivery may increase rapidly. Similarly, automated vehicles reduce the costs of time, parking, and personnel, and therefore may dramatically increase vehicle mileage (Wadud et al. 2016; Cohen and Cavoli 2019). On-demand electric scooters offer mobility access preferable to passenger cars, but can replace trips otherwise taken on public transit (de Bortoli and Christoforou 2020) and can come with significant additional energy requirements for night time system rebalancing (Hollingsworth et al. 2019, ITF 2020). The energy requirements of cryptocurrencies is also a growing concern, although considerable uncertainty exists surrounding the energy use of their underlying blockchain infrastructure (Vranken 2017; de Vries 2018; Stoll et al. 2019). For example, while it is clear that the energy requirements of global Bitcoin mining have grown significantly since 2017, recent literature indicates a wide range of estimates for 2020 (47 TWh to 125 TWh) due to data gaps and differences in modelling approaches (Lei et al. 2021). Initial estimates of the computational intensity of artificial intelligence algorithms suggest that energy requirements may be enormous without concerted effort to improve efficiencies, especially on the computational side (Strubell et al. 2020).

Efficiency gains enabled by digitalisation, in terms of reduced GHG emissions or energy use per service unit may be overcompensated by activity/scale effects.

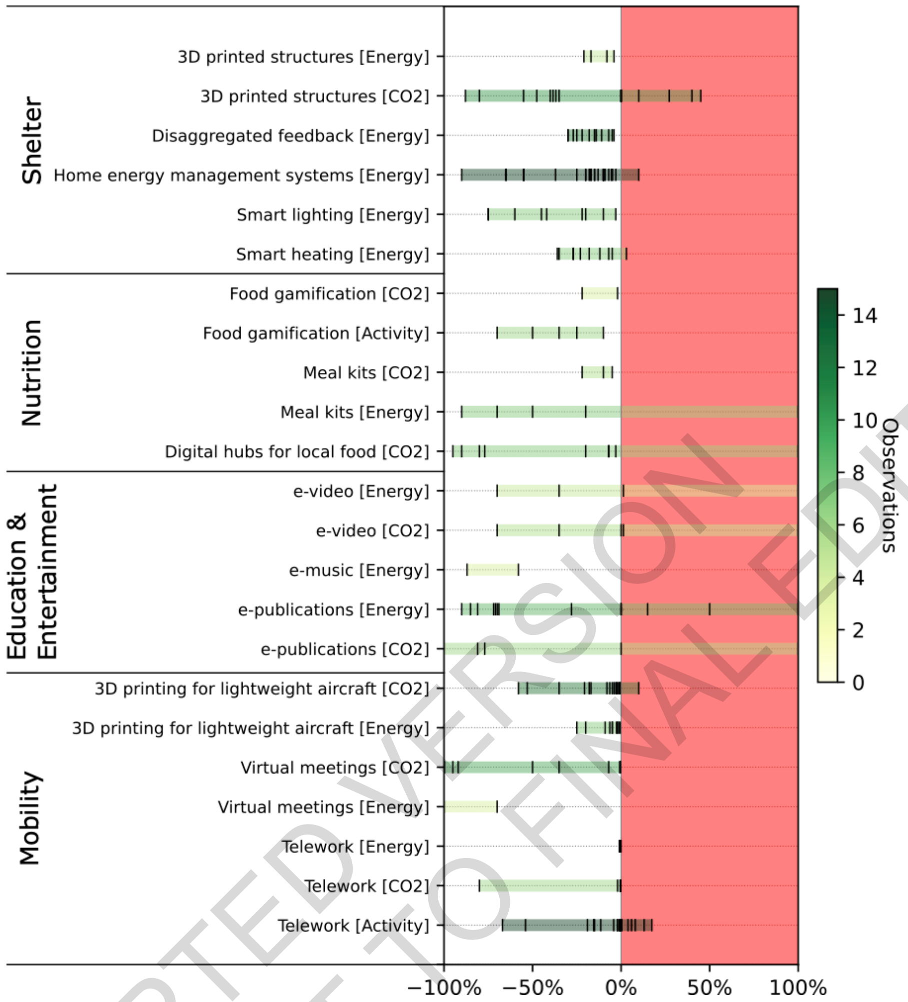


Figure 5.12 Studies assessing net changes in CO2 emissions, energy use, and activity levels indicate mitigation potentials for numerous end user-oriented digitalisation solutions, but also risk of increased emissions due to inefficient substitutions, induced demand, and rebound effects.
90 studies were assessed with 207 observations (indicated by vertical bars) including those based on empirical research, attributional and consequential life-cycle assessments, and techno-economic analyses and scenarios at different scales, which are not directly comparable but useful for indicating the directionality and determinants of net emissions, energy, and activity effects.
Sources: Erdmann and Hilty 2010; Gebler et al. 2014; Huang et al. 2016; Verhoef et al. 2018; Alhumayani et al. 2020; Court and Sorrell 2020; Hook et al. 2020; IEA 2020a; Saade et al. 2020; Torres-Carrillo et al. 2020; Yao et al. 2020; Wilson et al. 2020c; Muñoz et al. 2021

Maximising the mitigation potential of digitalisation trends involves diligent monitoring and proactive management of both direct and indirect demand effects, to ensure that a proper balance is maintained. Direct energy demand can be managed through continued investments in and incentives for energy-efficient data centres, networks, and end-use devices (Masanet et al. 2011; Avgerinou et al. 2017; IEA 2017a; Koronen et al. 2020). Shifts to low-carbon power are a particularly important strategy being undertaken by data centre and network operators (Cook et al. 2014; Huang et al. 2020), which might be adopted across the digital device spectrum as a proactive mitigation strategy where data demands outpace hardware efficiency gains, which may be approaching limits in the near future (Koomey et al. 2011). Most recently, data centres are being investigated as a potential resource for demand response and load balancing in renewable power grids (Zheng et al. 2020; Koronen et al. 2020), while a large bandwidth for improving software efficiency has been suggested for overcoming slowing hardware efficiency gains (Leiserson et al. 2020). Ensuring efficiency benefits of digital services while avoiding potential rebound effects and demand surges will require early and proactive public policies to avoid excess energy use (WBGU 2019; TWI2050 2019), which will also necessitate investments in data collection and monitoring systems to ensure that net mitigation benefits are realised and that unintended consequences can be identified early and properly managed (IEA 2017a).

Within a small but growing body of literature on the net effects of digitalisation, there is *medium evidence* that digitalised consumer services can reduce overall emissions, energy use, and activity levels, with *medium agreement* on the scale of potential savings with the important caveat that induced demand and rebound effects must be managed carefully to avoid negative outcomes.

5.3.4.2 The sharing economy

Opportunities to increase service per product includes peer-to-peer based sharing of goods and services such as housing, mobility, and tools. Hence, consumable products become durable goods delivering a "product service", which potentially could provide the same level of service with fewer products (Fischedick, M. et al. 2014).The sharing economy is an old practice of sharing assets between many without transferring ownership, which has been made new through focuses on sharing underutilised products/assets in ways that promotes flexibility and convenience, often in a highly developed context via gig economy/ online platforms. However, sharing economy offers the potential to shift from 'asset-heavy' ownership to 'asset-light' access, especially in developing countries (Retamal 2019). General conclusions on the sharing economy as a framework for climate change mitigation are challenging and are better broken down to specific subsystems (Mi and Coffman 2019). See more in Supplementary Material I Chapter 5, SM.5.4.3.

Shared mobility

Shared mobility is characterised by the sharing of an asset (e.g., a bicycle, e-scooter, vehicle), and the use of technology (i.e. apps and the Internet) to connect users and providers. It succeeded by identifying market inefficiencies and transferring control over transactions to consumers. Even though most shared mobility providers operate privately, their services can be considered as part of a public transport system in so far as it is accessible to most transport users and does not require private asset ownership. Shared mobility reduces GHG emissions if it substitutes for more GHG intensive travel (usually private car travel) (Martin and Shaheen 2011; Shaheen and Cohen 2019; Shaheen and Chan 2016; Santos et al. 2018; Axsen and Sovacool 2019), and especially if it changes consumer behaviour in the long run "by shifting personal transportation choices from ownership to demand-fulfilment" (Mi and Coffman 2019).

Demand is an important driver for energy use and emissions because decreased cost of travel time by sharing an asset (e.g. vehicle) could lead to an increase in emissions, but a high level of vehicle sharing could reduce negative impacts associated with this (Brown and Dodder 2019). One example is the megacity Kolkata, India, which has as many as twelve different modes of public transportation options that co-exist and offer means of mobility to its 14 million citizens (see Box 5.7). Most public transport modes are shared mobility options ranging from sharing between two people in a rickshaw or between a few hundred in metro or sub-urban trains. Sharing also happens informally as daily commuters avail shared taxis and neighbours borrow each other's car or bicycle for urgent or day trips.

Shared mobility using private vehicle assets is categorised into four models (Santos et al. 2018): peer-to-peer (P2P) platforms where individuals can rent the vehicle when not in use (Ballús-Armet et al. 2014); short term rental managed and owned by a provider (Enoch and Taylor 2006; Schaefers et al.

2016; Bardhi and Eckhardt 2012); Uber-like ridehailing services (Wallsten 2015; Angrist et al. 2017); and ride pooling using private vehicles shared by passengers to a common destination (Liyanage et al. 2019; Shaheen and Cohen 2019). The latest model – ride pooling – is promising in terms of congestion and per capita CO_2 emissions reductions and is a common practice in developing countries, however is challenging in terms of waiting and travel time, comfort, and convenience, relative to private cars (Santos et al. 2018; Shaheen and Cohen 2019). The other three models often yield profits to private parties, but remain mostly unrelated to reduction in CO_2 emissions (Santos et al. 2018). Shared travel models, especially Uber-like models, are criticised because of the flexibilisation of labour, especially in developing countries, in which unemployment rates and unregulated labour markets lie a foundation of precarity that lead many workers to seek out wide-ranging means towards patching together a living (Ettlinger 2017; Wells et al. 2020). Despite the advantages of the shared mobility such as convenience and affordability, consumers may also perceive risk formed by possible physical injury from strangers or unexpected poor service quality (Hong et al. 2019).

From a mitigation perspective, the current state of shared mobility looks at best questionable (Fishman et al. 2014; Ricci 2015; Zhang et al. 2019; Zhang and Mi 2018; Creutzig et al. 2019b; Martin 2016; Mi and Coffman 2019). Transport entrepreneurs and government officials often conflate 'smart' and "shared' vehicle with 'sustainable' mobility, a conflation not withstanding scrutiny (Noy and Givoni 2018). Surveys demonstrate that many users take free-floating car sharing instead of public transit, rather than to replace their private car (Herrmann et al. 2014); while in the United States, ride hailing and sharing data indicate that these services have increased road congestion and lowered transit ridership, with an insignificant change in vehicle ownership, and may further lead to net increases in energy use and CO2 emissions due to deadheading (Diao et al. 2021; Ward et al. 2021). If substitution effects and deadheading, which is the practice of allowing employees of a common carrier to use a vehicle as a non-revenue passenger, are accounted for, flexible motor-cycle sharing in Djakarta is at best neutral to overall GHG emissions (Suatmadi et al. 2019). Passenger surveys conducted in Denver indicated that around 22% of all trips travelled with Uber and Lyft would have been travelled by transit, 12% would have walked or biked, and another 12% of induced demand or passengers that would not have travelled at all (Henao and Marshall 2019).

Positive effects can be realised directly in bike sharing due to its very low marginal transport emissions. For example, in 2016, bike sharing in Shanghai reduced CO_2 emissions by 25ktCO_2 with additional benefits to air quality (Zhang and Mi 2018). However, also bike-sharing can increase emissions from motor vehicle usage when inventory management is not optimised during maintenance, collection, and redistribution of dock-less bikes (Fishman et al. 2014; Zhang et al. 2019; Mi and Coffman 2019).

Shared mobility scenarios demonstrate that GHG emission reduction can be substantial when mobility systems and digitalisation is regulated. Some studies model that ride pooling with electric cars (6 to 16 seats, which shifts the service to a more efficient transport mode (e.g., electric vehicle) and improves its carbon intensity by cutting GHG emissions by one-third (International Transport Forum 2016), and 63-82% per mile compared to a privately owned hybrid vehicle in 2030, 87 to 94% lower than a privately owned, gasoline-powered vehicle in 2014 (Greenblatt and Saxena 2015). This also realises 95% reduction in space required for public parking; total vehicle kilometres travelled would be 37% lower than the present day, although each vehicle would travel ten times the total distance of current vehicles (International Transport Forum 2016). Studies of Berlin and Lisbon demonstrate that sharing strategies could reduce the number of cars by more than 90%, also saving valuable street space for human-scale activity (Bischoff and Maciejewski 2016; Martinez and Viegas 2017; Creutzig et al. 2019b). The impacts will also depend on sharing levels – concurrent or sequential – and the future modal split among public transit, automated electric vehicles fleets, and shared or pooled rides.

Evidence from attributional life-cycle assessments (LCAs) of ride-hailing, whether Uber-like or by taxi, suggests that the key determinants of net emissions effects are average vehicle occupancy and vehicle powertrain, with high-occupancy and electric drivetrain cars deliver the greatest emissions benefits, even rivalling traditional metro/urban rail and bus options (Figure 5.13b). It is possible that shared automated electric vehicles fleets could become widely used without many shared rides, and single or even zero occupant vehicles will continue to dominate the majority of vehicle trips. It is also feasible that shared rides could become more common, if automation makes route deviation more efficient, more cost-effective, and more convenient, increasing total travel substantially (Wadud et al. 2016). Car sharing with automated vehicles could even worsen congestion and emissions by generating additional travel demand (Rubin et al. 2016). Travel time in autonomous vehicles can be used for other activities but driving and travel costs are expected to decrease, which most likely will induce additional demand for auto travel (Moeckel and Lewis 2017) and could even create incentives for further urban sprawl. More generally, increased efficiency generated by big data and smart algorithms may generate rebound effects in demand and potentially compromise the public benefits of their efficiency promise (Gossart 2015).

In many countries, shared mobility and ride pooling is often the norm. Here the challenge is to improve service quality to keep users in shared mobility and public transport (see Box 5.7). A key barrier in cities like Nairobi is the lack of public involvement of users and sustainability experts in designing transport systems, leaving planning to transport engineers, and thus preventing inclusive shared mobility system design (Klopp 2012).

Altogether, travel behaviour, business models, and especially public policy will be key components in determining how pooling and shared automated electric vehicles impacts unfold (Shaheen and Cohen 2019). Urban-scale governance of smart mobility holds potential for prioritizing public transit and the use of public spaces for human activities, managing the data as a digital sustainable commons (e.g., via the installation of a Central Information Officer, as in Tel Aviv), and managing the social and environmental risks of smart mobility to realise its benefits (Creutzig et al. 2019b). Pricing of energy use and GHG emissions will be helpful to achieve these goals. The governance of shared mobility is complicated, as it involves many actors, and is key to realise wider benefits of shared mobility (Akyelken et al. 2018). New actors, networks and technologies enabling shared mobility are already fundamentally challenging how transport is governed worldwide. This is not a debate about state versus non-state actors but instead about the role the state takes within these new networks to steer, facilitate and also reject different elements of the mobility system (Docherty et al. 2018).

Shared accommodation

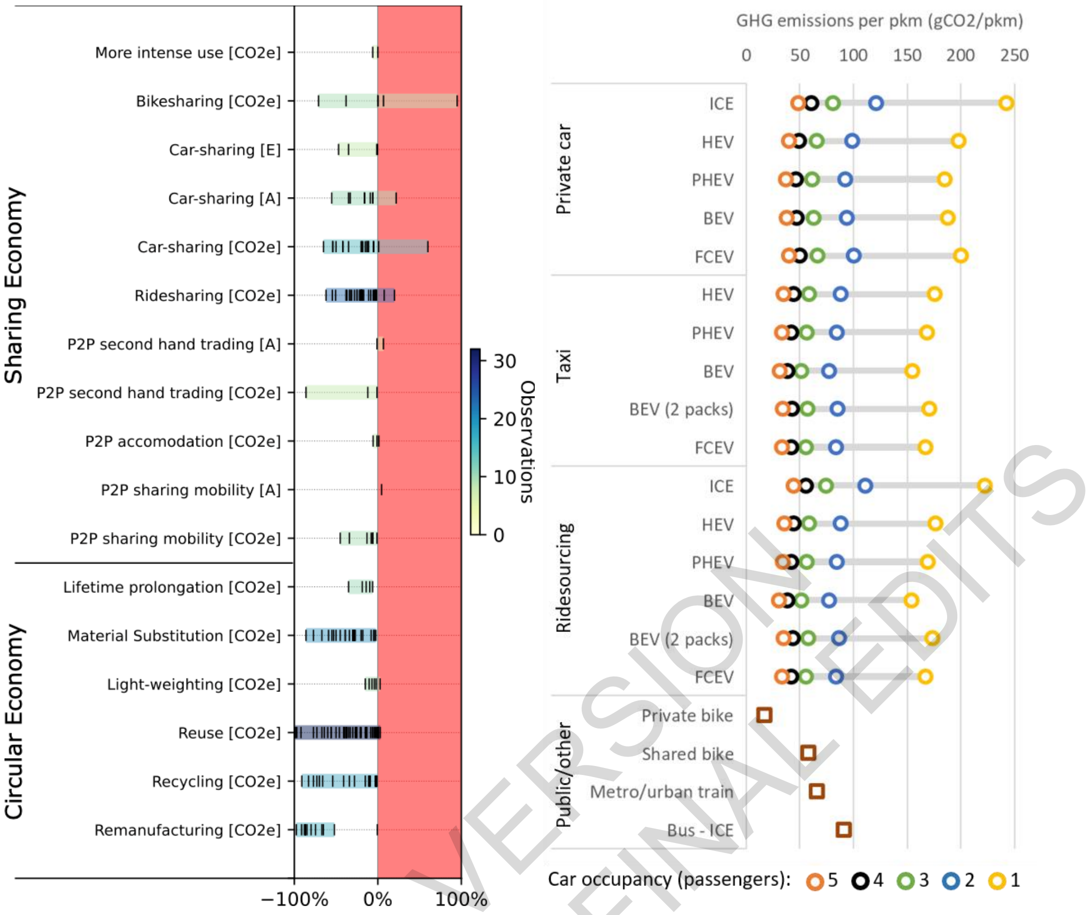
In developing countries and in many student accommodations globally, shared accommodation allows affordable housing for a large part of the population. For example, living arrangements are built expressly around the practice of sharing toilets, bathrooms and kitchens. While the sharing of such facilities does connote a lower level of service provision and quality of life, it provides access to a consumer base with very low and unreliable incomes. Thus, sharing key facilities can help guarantee the provision of affordable housing (Gulyani et al. 2018). In developed countries, large-scale developments are targeting students and 'young professionals' by offering shared accommodation and services. Historically shared accommodation has been part of the student life due to its flexible and affordable characteristics. However, the expansion of housing supply through densification can use shared facilities as an instrument to *"commercialize small housing production, while housing affordability and accessibility are threatened"* (Uyttebrouck et al. 2020).

With respect to travel accommodations, several models are emerging in which accommodation is offered to, or shared with, travellers by private people organised by business-driven or non-profit online platforms. Accommodation sharing includes P2P, ICT-enabled, short-term renting, swapping, borrowing or lending of existing privately-owned idling lodging facilities (Voytenko Palgan et al. 2017; Möhlmann 2015).

With shared accommodation services via the platform economy, there may be risks of negative sustainability effects, such as rebound effects caused by increased travel frequency (Tussyadiah and Pesonen 2016). This is particularly a problem if apartments are removed from long-term rental markets, thus indirectly inducing construction activities, with substantial GHG emissions on their own. However, if a host shares their accommodation with a guest, the use of some resources, such as heating and lighting, is shared, thereby leading to more efficient resource use per capita (Chenoweth 2009; Voytenko Palgan et al. 2017). Given the nascence of shared accommodation via the platform economy, quantifications of its systems-level energy and emissions impacts are lacking in the literature, representing an important area for future study.

Mitigation potentials of sharing economy strategies

Sharing economy initiatives play a central role in enabling individuals to share underutilised products. While the literature on the net effects of sharing economy strategies is still limited, available studies have presented different mitigation potentials to date, as shown in Figure 5.13. For many sharing economy strategies, there is a risk of negative rebound and induced demand effects, which may occur by changing consuming patterns, e.g., if savings from sharing housing are used to finance air travel. Thus, the mitigation potentials of sharing economy strategies will depend on stringent public policy and consumer awareness that reigns in run-away consumption effects. Shared economy solutions generally relate to the "Avoid" and "Shift" strategies (see Sections 5.1 and 5.3.2). On the one hand, they hold potential for providing similar or improved services for well-being (mobility, shelter) at reduced energy and resource input, with the proper policy signals and consumer responses. On the other hand, shared economy strategies may increase emissions, e.g., shared mobility may shift activity away from public transit and lead to lower vehicle occupancy, deadheading, and use of inefficient shared vehicles (Merlin 2019; Jones and Leibowicz 2019; Bonilla-Alicea et al. 2020; Ward et al. 2021). Similarly to digitalisation, there is *medium evidence* that sharing economy can reduce overall emissions, energy use, and activity levels, with *medium agreement* on the scale of potential savings if induced demand and rebound effects can be carefully managed to avoid negative outcomes.



(a) **(b)**

Figure 5.13

(a) Published estimates from 72 studies with 185 observations (indicated by vertical bars) of the relative mitigation potential of different shared and circular economy strategies, demonstrating limited observations for many emerging strategies, a wide variance in estimated benefits for most strategies, and within the sharing economy risk of increased emissions due to inefficient substitutions, induced demand, and rebound effects. Mitigation potentials are conditional on corresponding public policy and/or regulation. (b) Attributional LCA comparisons of ridesharing mobility options, which highlight the large effects of vehicle occupancy and vehicle technology on total CO2 emissions per passenger-km and the preferability of high-occupancy and non-ICE configurations for emissions reductions compared to private cars. Also indicated are possible emissions increases associated with shared car mobility when it substitutes for non-motorised and public transit options.

BEV = battery electric vehicle; FCEV = fuel cell electric vehicle; HEV = hybrid electric vehicle; ICE=internal combustion engine; PHEV = plug-in hybrid electric vehicle.

Sources: Jacobson and King 2009; Firnkorn and Müller 2011; Baptista et al. 2014; Liu et al. 2014; Nijland et al. 2015; Namazu and Dowlatabadi 2015; IEA 2016; Koh 2016; Martin and Shaheen 2016; Rabbitt and Ghosh 2016; Bruck et al. 2017; Bullock et al. 2017; Clewlow and Mishra 2017; Fremstad 2017; ITF 2017a,b,c; Nijland and van Meerkerk 2017; Nasir et al. 2017; Skjelvik et al. 2017; Yin et al. 2017; Campbell 2018; Ghisellini et al. 2018; Favier et al. 2018; Hopkinson et al. 2018; IEA 2018; ITF 2018; Lokhandwala and Cai 2018; Malmqvist et al. 2018; Makov and Font Vivanco 2018; Material Economics 2018; Rademaekers et al. 2017; Nasr et al. 2018; Yu et al. 2018; Zhang and Mi 2018; Brambilla et al. 2019; Brütting et al. 2019; Buyle et al. 2019; Castro and Pasanen 2019; Coulombel et al. 2019; Eberhardt et al. 2019; IEA 2019b; ITF 2019; Jones and Leibowicz 2019; Ludmann 2019; Merlin 2019; Nußholz et al. 2019; Bonilla-Alicea et al. 2020; Cantzler et al. 2020; Churkina et al. 2020; Gallego-Schmid et al. 2020; Hertwich et al. 2020; ITF 2020a,b; Liang et al. 2020; Miller 2020; Wilson et al. 2020c; Yan et al. 2020; Cordella et al. 2021; Diao et al. 2021; Pauliuk et al. 2021; Ward et al. 2021; Wolfram et al. 2021

The circular economy

While the demands for energy and materials will increase until 2060 following the traditional linear model of production and consumption, resulting in serious environmental consequences (OECD 2019b), the circular economy (CE) provides strategies for reducing societal needs for energy and primary materials to deliver the same level of service with lower environmental impacts. The CE framework embodies multiple schools of thought with roots in a number of related concepts (Blomsma and Brennan 2017; Murray et al. 2017), including cradle to cradle (McDonough and Braungart 2002), performance economy (Stahel 2016), biomimicry (Benyus 1997), green economy (Loiseau et al. 2016) and industrial ecology (Saavedra et al. 2018). As a result, there are also many definitions of CE: a systematic literature review identified 114 different definitions (Kirchherr et al. 2017). One of the most comprehensive models is suggested by the Netherlands Environmental Assessment Agency (Potting et al. 2018), which defines ten strategies for circularity: Refuse (R0), Rethink (R1), Reduce (R2), Reuse (R3), Repair (R4), Refurbish (R5), Remanufacture (R6), Repurpose (R7), Recycle (R8), and Recover energy (R9). Overall, the definition of CE is contested, with varying boundary conditions chosen. As illustrated in Figure 5.11, the CE overlaps with both the sharing economy and digitalisation megatrends.

In line with the principles of SDG12 (responsible consumption and production), the essence of building CE is to retain as much value as possible from products and components when they reach the end of their useful life in a given application (Linder and Williander 2017; Lewandowski 2016; Lieder and Rashid 2016; Stahel 2016). This requires an integrated approach during the design phase that, for example, extends product usage and ensures recyclability after use (de Coninck et al. 2018). While traditional “improve” strategies tend to focus on direct energy and carbon efficiency, service-oriented strategies focus on reducing life-cycle emissions through harnessing the leverage effect (Creutzig et al. 2018). The development of closed-loop models in service-oriented businesses can increase resource and energy efficiency, reducing emissions and contributing to climate change mitigation goals on national, regional, and global levels (Johannsdottir 2014; Korhonen et al. 2018). Key examples include remanufacturing of consumer products to extend lifespans while maintaining adequate service levels (Klausner et al. 1998), reuse of building components to reduce demand for primary materials and construction processes (Shanks et al. 2019), and improved recycling to reduce upstream resource pressures (IEA 2019b, 2017b).

Among the many schools of thought on the CE and climate change mitigation, two different trends can be distinguished from the literature to date. First, there are publications, many of them non peer-reviewed, that eulogize the perceived benefits of the CE, but in many cases stop short of providing a quantitative assessment. Promotion of CE from this perspective has been criticised as a greenwashing attempt by industry to avoid serious regulation (Isenhour 2019). Second, there are more methodologically rigorous publications, mostly originating in the industrial ecology field, but sometimes investigating only limited aspects of the CE (Bocken et al. 2017; Cullen 2017; Goldberg 2017). Conclusions on CE’s mitigation potential also differ with diverging definitions of the CE. A systematic review identified 3244 peer-reviewed articles addressing CE and climate change , but only 10% of those provide insights on how the CE can support mitigation, and most of them found only small potentials to reduce GHG emissions (Cantzler et al. 2020). Recycling is the CE category most investigated, while reuse and reduce strategies have seen comparatively less attention (Cantzler et al. 2020). However, mitigation potentials were also context- and material-specific, as illustrated by the ranges shown in Figure 5.13a.

There are three key concerns relating to the effectiveness of the CE concept. First, many proposals on the CE insufficiently reflect on thermodynamic constraints that limit the potential of recycling from both mass conservation and material quality perspectives or ignore the considerable amount of energy needed so reuse materials (Cullen 2017). Second, demand for materials and resources will likely outpace efficiency gains in supply chains, becoming a key driver of GHG emissions and other environmental problems, rendering the CE alone an insufficient strategy to reduce emissions (Bengtsson et al. 2018). In fact, the empirical literature points out that only 6.5% of all processed materials (4 Gt yr^{-1}) globally originate from recycled sources (Haas et al. 2015). The low degree of circularity is explained by the high proportion of processed materials (44%) used to provide energy thus not available for recycling; and the high rate of net additions to stocks of 17 Gt yr^{1}. As long as long-lived material stocks (e.g., in buildings and infrastructure) continue to grow, strategies targeting end-of-pipe materials cannot keep pace with primary materials demand (Krausmann et al. 2017; Haas et al. 2020). Instead, a significant reduction of societal stock growth, and decisive eco-design is suggested to advance the CE (Haas et al. 2015). Third, cost-effectiveness underlying CE activities may concurrently also increase energy intensity and reduce labour intensity, causing systematically undesirable effects. To a large extent, the distribution of costs and benefits of material and energy use depends on institutions in order to include demand-side solutions. Thus, institutional conditions have an essential role to play in setting rules differentiating profitable from nonprofitable activities in CE (Moreau et al. 2017). Moreover, the prevalence CE practices such as reuse, refurbishment, and recycling can differ substantially between developed and developing economies, leading to highly context-specific mitigation potentials and policy approaches (McDowall et al. 2017).

One report estimates that the CE can contribute to more than 6 $GtCO_2$ emission reductions in 2030, including strategies such as material substitution in buildings (Blok et al. 2016). Reform of the tax system towards GHG emissions and the extraction of raw materials substituting taxes on labour is key precondition to achieve such a potential. Otherwise rebound effects tends to take back a high share of marginal CE efforts. A 50% reduction of GHG emissions in industrial processes, including the production of goods in steel, cement, plastic, paper, and aluminium from 2010 until 2050 are impossible to attain only with reuse and radical product innovation strategies, but will need to also rely on the reduction of primary input (Allwood et al. 2010).

CE strategies generally correspond to the “Avoid” strategy for primary materials (see Sections 5.1 and 5.3.2). CE strategies in industrial settings improve well-being mostly indirectly, via the reduction of environmental harm and climate impact. They can also save monetary resources of consumers by reducing the need for consumption. It may seem counterintuitive, but reducing consumers' need for consumption of a particular product/service (e.g. reducing energy consumption) may increase a consumption of another one (e.g. travels) associated with some type of energy use, or lead to greater consumption if additional secondary markets are created. Hence, carbon emissions could rise if the rebound effect is not considered (Chitnis et al. 2013; Zink and Geyer 2017).

Looking at “Shift” strategy (see Sections 5.1 and 5.3.2), the role of individuals as consumers/users has received less attention than other aspects of the CE (e.g. technological interventions as “Improve” strategy and waste minimisation as “Avoid” strategy) within mainstream debates to date. One explanation is CE has roots in the field of Industrial Ecology, which has historically emphasized materials systems more than the end-user. By shifting this perspective from the supply-side to the demand-side in the CE, users are, for the most part, discussed as social entities that now must form new relations with businesses to meet their needs. That is, the demand-side approach largely replaces the concept of a consumer with that of a user, who must either accept or reject new business models for service provision, stimulated by the pushes and pulls of prices and performance (Hobson 2019).
Relevant contributions to climate change mitigation at Gigaton scale by the CE will remain out of scope if decision makers and industry fail to reduce primary inputs (*high confidence*). Systemic

(consequential) analysis is required to avoid the risk that scaling effects negate efficiency gains; such analysis is however rarely applied to date. For example, material substitution or refurbishment of buildings brings risk of increasing emissions despite improving or avoiding current materials (Eberhardt et al. 2019; Castro and Pasanen 2019) Besides, CE concepts that extend the lifetime of products and increase the fraction of recycling are useful but are both thermodynamically limited and will remain relatively small in scale as long as demand of primary materials continue to grow, and scale effects dominate. In spite of presenting a large body of literature on CE in general, only a small but growing body of literature exists on the net effects of its strategies from a quantitative perspective, with key knowledge gaps remaining on specific CE strategies. There is *medium evidence* that CE can reduce overall emissions, energy use, and activity levels, with *medium evidence* that sharing economy can reduce overall emissions, energy use, and activity levels, with *medium agreement* on the scale of potential savings.

5.4 Transition toward high well-being and low-carbon demand societies

Demand-side mitigation involves individuals (e.g. consumption choices), culture (e.g. social norms, values), corporate (e.g. investments), institutions (e.g. political agency), and infrastructure change (*high evidence, high agreement*). These five drivers of human behaviour either contribute to the status-quo of a global high-carbon, consumption, and GDP growth oriented economy or help generate the desired change to a low-carbon energy-services, well-being, and equity oriented economy (Jackson 2017; Cassiers et al. 2018; Yuana et al. 2020)(Figure 5.14). Each driver has novel implications for the design and implementation of demand-side mitigation policies. They show important synergies, making energy demand mitigation a dynamic problem where the packaging and/or sequencing of different policies play a role in their effectiveness, demonstrated in Sections 5.5 and 5.6. The Social Science Primer (Supplementary Material I Chapter 5) describes theory and empirical insights about the interplay between individual agency, the social and physical context of demand-side decisions in the form of social roles and norms, infrastructure and technological constraints and affordances, and other formal and informal institutions. Incremental interventions on all five fronts change social practices, effecting simultaneously energy and well-being (Schot and Kanger 2018). Transformative change will require coordinated use of all five drivers, as described in Figure 5.14 and Table 5. using novel insights about behaviour change for policy design and implementation (*high evidence, high agreement)*. In particular, socio-economic factors, such as equity, public service quality, electricity access and democracy are found to be highly significant in enabling need satisfaction at low energy use, whereas economic growth beyond moderate incomes and extractive economic activities are observed to be prohibiting factors (Vogel et al. 2021).

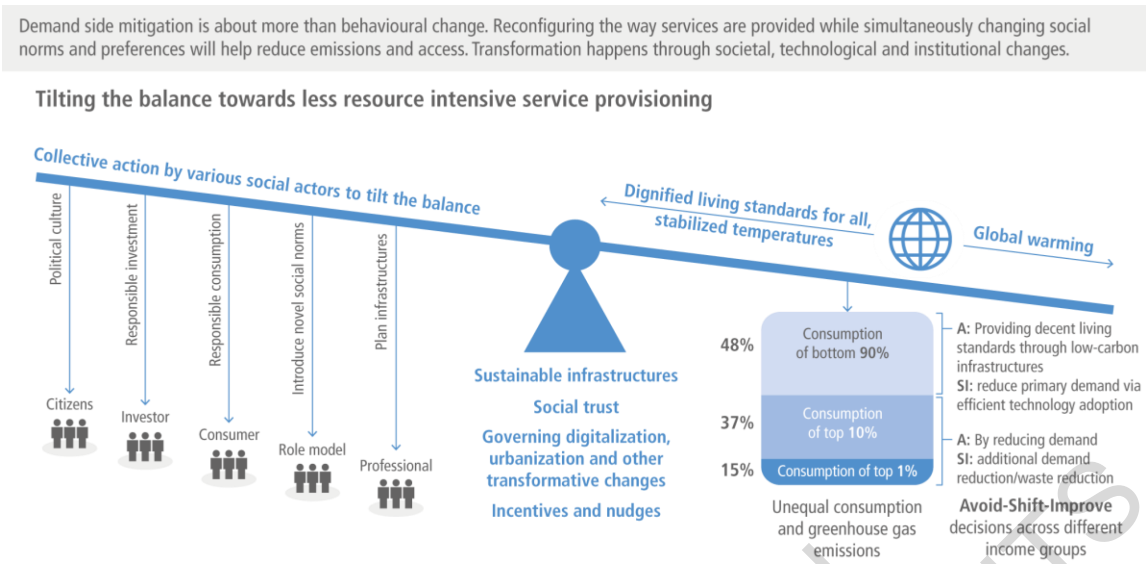


Figure 5.14 Role of people, demand-side action and consumption in reversing a planetary trajectory to a warming Earth towards effective climate change mitigation and dignified living standards for all

5.4.1 Behavioural Drivers

Behaviour change by individuals and households requires both *motivation* to change and *capacity* for change (option availability/knowledge; material/cognitive resources to initiate and maintain change) (Moser and Ekstrom 2010; Michie et al. 2011) and is best seen as part of more encompassing collective action. Motivation for change for collective good comes from economic, legal, social incentives, regard for deeper intrinsic value of concern for others over extrinsic values. Capacity for change varies; people in informal settlements or rural areas are incapacitated by socio-political realities and have limited access to new energy-service options.

Motivation and effort required for behaviour change increase from Improve to Shift to Avoid decisions. 'Improve' requires changes in personal purchase decisions, 'shift' involves changes in behavioural routines, 'avoid' also involves shifts in deeper values or mindsets. People set easy goals for themselves and more difficult ones for others (Attari et al. 2016) and underestimate the energy savings of behaviour changes that make a large difference (Attari et al. 2010). Most personal actions taken so far have small mitigation potential (recycling, ecodriving), and people refrain from options advocated more recently with high impact (less flying, living car free) (Dubois et al. 2019).

As individuals pursue a broad set of goals and use calculation-, emotion-, and rule-based processes when they make energy decisions, demand-side policies can use a broad range of behavioural tools that complement subsidies, taxes, and regulations (Chakravarty and Roy 2016; Mattauch et al. 2016; Niamir 2019) *(high evidence, high agreement*). The provision of targeted information, social advertisements, and influence of trusted in-group members and/role models or admired role models like celebrities can be used to create better climate change knowledge and awareness (Niamir et al. 2020c,b; Niamir 2019). Behavioural interventions like communicating changes in social norms can accelerate behaviour change by creating tipping points (Nyborg et al. 2016). When changes in energy-demand decisions (such as switching to a plant-based diet, Box 5.5) are motivated by the creation and activation of a social identity consistent with this and other behaviours, positive spillover can accelerate behaviour change (Truelove et al. 2014), both within a domain or across settings, e.g., from work to home (Maki and Rothman 2017).

START BOX 5.5 HERE

Box 5.5 Dietary shifts in UK society towards lower emission foods

Meat eating is declining in the UK, alongside a shift from carbon-intensive red meat towards poultry. This is due to the interaction of behavioural, socio-cultural and organisational drivers (Vinnari and Vinnari 2014). Reduced meat consumption is primarily driven by issues of personal health and animal welfare, instead of climate or environment concerns (Latvala et al. 2012; Dibb and Fitzpatrick 2014; Hartmann and Siegrist 2017; Graça et al. 2019). Social movements have promoted shifts to a vegan diet (Morris et al. 2014; Laestadius et al. 2016) yet their impact on actual behaviour is the subject of debate (Taufik et al. 2019; Harguess et al. 2020; Sahakian et al. 2020). Companies have expanded new markets in non-meat products (MINTEL 2019). Both corporate food actors and new entrants offering more innovative 'meat alternatives' view consumer preferences as an economic opportunity, and are responding by increasing the availability of meat replacement products. No significant policy change has taken place in the UK to enable dietary shift (Wellesley and Froggatt 2015); however the Committee on Climate Change has recommended dietary shift in the Sixth Carbon Budget(Climate Change Committee 2020), involving reduced consumption of high-carbon meat and dairy products by 20% by 2030, with further reductions in later years in order to reach net zero by 2050. Agricultural policies serve to support meat production with large subsidies that lower production cost and effectively increase the meat intensity of diets at a population level (Simon 2003; Godfray et al. 2018). Deeper, population wide reductions in meat consumption are hampered by these lock-in mechanisms which continue to stabilise the existing meat production-consumption system. The extent to which policymakers are willing to actively stimulate reduced meat consumption thus remains an open question (Godfray et al. 2018). See more in Supplementary Material I Chapter 5, SM5.6.4.

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People's general perceptions of climate risks, first covered in AR5, motivate behaviour change; more proximate and personal feelings of being at risk triggered by extreme weather and climate-linked natural disasters will increase concern and willingness to act (Bergquist et al. 2019), though the window of increased support is short (Sisco et al. 2017). 67% of individuals in 26 countries see climate change as a major threat to their country, an increase from 53% in 2013, though 29% also consider it a minor or no threat (Fagan and Huang 2019). Concern that the COVID-19 crisis may derail this momentum due to a finite pool of worry (Weber 2006) appears to be unwarranted: Americans' positions on climate change in 2020 matched high levels of concern measured in 2019 (Leiserowitz et al. 2020). Younger, female, and more educated individuals perceive climate risks to be larger (Weber 2016; Fagan and Huang 2019). Moral values and political ideology influence climate risk perception and beliefs about the outcomes and effectiveness of climate action (Maibach et al. 2011). Motivation for demand-side solutions can be increased by focusing on personal health or financial risks and benefits that clearly matter to people (Petrovic et al. 2014). Consistent with climate change as a normally distant, non-threatening, statistical issue (Gifford 2011; Fox-Glassman and Weber 2016), personal experience with climate-linked flooding or other extreme weather events increases perceptions of risk and willingness to act (Weber 2013; Atreya and Ferreira 2015; Sisco et al. 2017) when plausible mediators and moderators are considered (Brügger et al. 2021), confirmed in all 24 countries studied by Broomell et al (2015)(Broomell et al. 2015). Discounting the future matters (Hershfield et al. 2014): across multiple countries, individuals more focused on future outcomes more likely engage in environmental actions (Milfont et al. 2012).

There is *medium evidence and high agreement* that demographics, values, goals, personal and social norms differentially determine ASI behaviours, in the Netherlands and Spain (Abrahamse and Steg

2009; Niamir 2019; Niamir et al. 2020b), the OECD (Ameli and Brandt 2015), and 11 European countries (Mills and Schleich 2012; Roy et al. 2012). Education and income increase Shift and Improve behaviour, whereas personal norms help to increase the more difficult Avoid behaviours (Mills and Schleich 2012). Sociodemographic variables (household size and income) predict energy use, but psychological variables (perceived behavioural control, perceived responsibility) predict *changes* in energy use; younger households are more likely to adopt Improve decisions, whereas education increases Avoid decisions (Ahmad et al. 2015). In India and developing countries, Avoid decisions are made by individuals championing a cause, while Improve and Shift behaviour are increases by awareness programmes and promotional materials highlighting environmental and financial benefits (Roy et al. 2018a; Chakravarty and Roy 2016). Cleaner cookstove adoption (see Box 5.6), a widely studied Improve solution in developing countries (Nepal et al. 2010; Pant et al. 2014), goes up with income, education, and urban location. Female education and investments into reproductive health are evident measures to reducing world population growth (Abel et al. 2016).

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Box 5.6 Socio-behavioural aspects of deploying cookstoves

Universal access to clean and modern cooking energy could cut premature death from household air pollution by two-thirds, while reducing forest degradation and deforestation and contribute to the reduction of up to 50% of CO_2 emissions from cooking (relative to baseline by 2030) (IEA 2017c; Hof et al. 2019). However, in the absence of policy reform and substantial energy investments, 2.3 billion people will have no access to clean cooking fuels such as biogas, LPG, natural gas or electricity in 2030 (IEA 2017c). Studies reveal that a combination of drivers influence adoption of new cookstove appliances including affordability, behavioural and cultural aspects (lifestyles, social norms around cooking and dietary practices), information provision, availability, aesthetic qualities of the technology, perceived health benefits and infrastructure (spatial design of households and cooking areas). The increasing efficiency *improvements* in electric cooking technologies, could enable households to *shift* to electrical cooking at mass scale. The use of pressure cookers and rice cookers is now widespread in South Asia and beginning to penetrate the African market as consumer attitudes are changing towards household appliances with higher energy efficiencies (Batchelor et al. 2019). *Shifts* towards electric and LPG stoves in Bhutan (Dendup and Arimura 2019), India (Pattanayak et al. 2019), Ecuador (Martínez et al. 2017; Gould et al. 2018) and Ethiopia (Tesfamichael et al. 2021); and *improved* biomass stoves in China (Smith et al. 1993). Significant subsidy, information (Dendup and Arimura 2019), social marketing and availability of technology in the local markets are some of the key policy instruments helping to adopt ICS (Pattanayak et al. 2019). There is no one-size-fits-all solution to household air pollution – different levels of shift and improvement occur in different cultural contexts, indicating the importance of socio-cultural and behavioural aspects in shifts in cooking practices. See more in Supplementary Material Chapter 5, SM5.6.2.

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There is *high agreement* in the literature that the updating of educational systems from a commercialised, individualised, entrepreneurial training model to an education cognizant of planetary health and human well-being can accelerate climate change awareness and action (Mendoza and Roa 2014; Dombrowski et al. 2016) (also see Supplementary Material Chapter 5).

There is *high evidence and high agreement* that people's core values affect climate-related decisions and climate policy support by shaping beliefs and identities (Dietz 2014; Steg 2016; Hayward and Roy 2019). People with altruistic and biospheric values are more likely to act on climate change and support climate policies than those with hedonic or egoistic values (Taylor et al. 2014), because these values are associated with higher awareness and concern about climate change, stronger belief that personal actions can help mitigating climate change, and stronger feelings of responsibility for taking climate action (Dietz 2014; Steg 2016). Research also suggest that egalitarian, individualistic, and hierarchical worldviews (Wildavsky and Dake 1990) have their role, and that successful solutions require policy makers of all three worldviews to come together and communicate with each other (Chuang et al. 2020).

Core values also influence which costs and benefits are considered (Hahnel et al. 2015; Gölz and Hahnel 2016; Steg 2016). Information provision and appeals are thus more effective when tailored to those values (Bolderdijk et al. 2013; Boomsma and Steg 2014), as implemented by the energy-cultures framework (Stephenson et al. 2015; Klaniecki et al. 2020). Awareness, personal norms, and perceived behavioural control predict willingness to change energy-related behaviour above and beyond traditional sociodemographic and economic predictors (Schwartz 1977; Ajzen 1985; Stern 2000), as do perceptions of self-efficacy (Bostrom et al. 2019). However, such motivation for change is often not enough, as actors also need capacity for change and help to overcome individual, institutional and market barriers (Young et al. 2010; Carrington et al. 2014; Bray et al. 2011).

Table 5.4 describes common obstacles to demand-side energy behaviour change, from loss aversion to present bias (for more detail see Supplementary Material Chapter 5). Choice architecture refers to interventions ("nudges") that shape the choice context and how choices are presented, with seemingly-irrelevant details (e.g., option order or labels) often more important than option price (Thaler and Sunstein 2009). There is *high evidence and high agreement* that choice architecture nudges shape energy decisions by capturing deciders' attention; engaging their desire to contribute to the social good; facilitating accurate assessment of risks, costs, and benefits; and making complex information more accessible (Yoeli et al. 2017; Zangheri et al. 2019). Climate-friendly choice architecture includes the setting of proper defaults, the salient positioning of green options (in stores and online), forms of framing, and communication of social norms (Johnson et al. 2012). Simplifying access to greener options (and hence lowering effort) can promote ASI changes (Mani et al. 2013). Setting effective "green" defaults may be the most effective policy to mainstream low-carbon energy choices (Sunstein and Reisch 2014), adopted in many contexts (Jachimowicz et al. 2019) and deemed acceptable in many countries (Sunstein et al. 2019). Table 5.3a lists how often different choice-architecture tools were used in many countries over the past 10 years to change ASI behaviours, and how often each tool was used to enhance an economic incentive. These tools have been tested mostly in developed countries. Reduction in energy use (typically electricity consumption) is the most widely studied behaviour (because metering is easily observable). All but one tool was applied to increase this Avoid behaviour, with demand-side reductions from 0% to up to 20%, with most values below 3% (see also meta-analyses by (Hummel and Maedche 2019; Nisa et al. 2019; van der Linden and Goldberg 2020; Stankuniene et al. 2020; Khanna et al. 2021). Behavioural, economic, and legal instruments are most effective when applied as an internally consistent ensemble where they can reinforce each other, a concept referred to as "policy packaging" in transport policy research (Givoni 2014). A meta-analysis, combining evidence of psychological and economic studies, demonstrates that feedback, monetary incentives and social comparison operates synergistically and is together more effective than the sum of individual interventions (Khanna et al. 2021). The same meta-analysis also shows that combined with monetary incentives, nudges and choice architecture can reduce global GHG emissions from household energy use by 5-6% (Khanna et al. 2021).

Choice architecture has been depicted as an anti-democratic attempt at manipulating the behaviour of actors without their awareness or approval (Gumbert 2019). Such critiques ignore the fact that there is no neutral way to present energy-use related decisions, as every presentation format and choice environment influences choice, whether intentionally chosen or not. Educating households and policy makers about the effectiveness of choice architecture and adding these behavioural tools to existing market- and regulation-based tools in a transparent and consultative way can provide desired outcomes with increased effectiveness, while avoiding charges of manipulation or deception. People consent to choice architecture tools if their use is welfare-enhancing, policymakers are transparent about their goals and processes, public deliberation and participation is encouraged, and the choice architect is trusted (Sunstein et al. 2019).

Table 5.3a Inventory of behavioural interventions experimentally tested to change energy behaviours

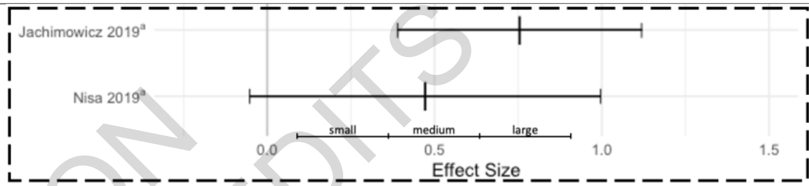
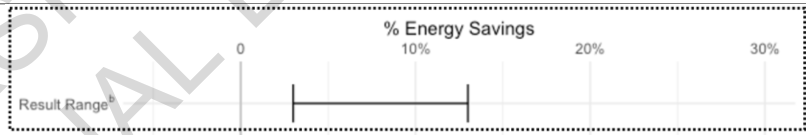
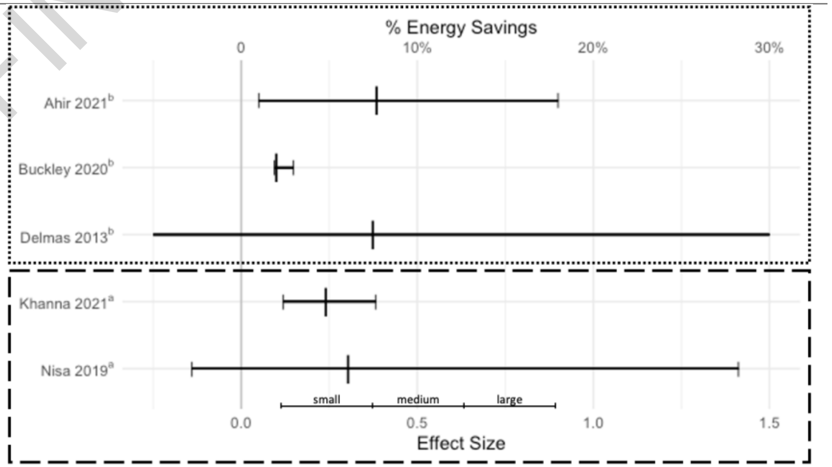
Behavioural Tool	# of Papers	# in Developed Countries	# in Other Countries	Energy Demand Behaviour	Avoid	Shift	Improve	Economic Incentive
Set the Proper Defaults	27	26	1	Carbon Offset Program (3) (Löfgren et al. 2012; Araña and León 2013) Energy Source (4) (Kaiser et al. 2020); (Wolske et al. 2020)* Energy Use (16) (Jachimowicz et al. 2019; Nisa et al. 2019; Grilli and Curtis 2021)* Investment in Energy Efficiency (7) (Theotokis and Manganari 2015; Ohler et al. 2020) Mode of Transportation (1) (Goodman et al. 2013)	11	12	9	6
Reach Out During Transitions	10	9	1	Energy Use (4) (Verplanken 2006; Jack and Smith 2016); (Iweka et al. 2019)* Investment in Energy Efficiency (4) (Gimpel et al. 2020) Mode of Transportation (2) (Verplanken et al. 2008)	1	3	7	1
Provide Timely Feedback & Reminders	256	246	10	Energy Use (252) (Darby 2006; Buckley 2019)* (Abrahamse et al. 2005; Fischer 2008; Steg 2008; Faruqui et al. 2010; Delmas et al. 2013; McKerracher and Torriti 2013; Karlin et al. 2015; Andor and Fels 2018; Bergquist et al. 2019; Iweka et al. 2019; Nisa et al. 2019; Zangheri et al. 2019; Ahir and Chakraborty 2021; Grilli and Curtis 2021; Khanna et al. 2021)* Mode of Transportation (3) (Steg 2008; Sanguinetti et al. 2020)*	244	6	7	33

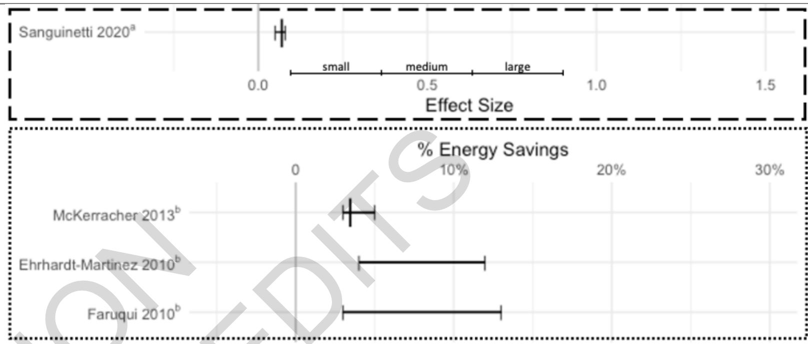
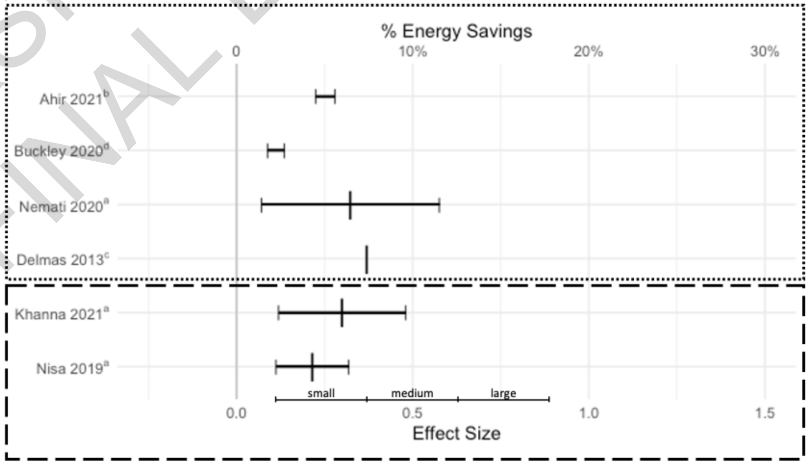
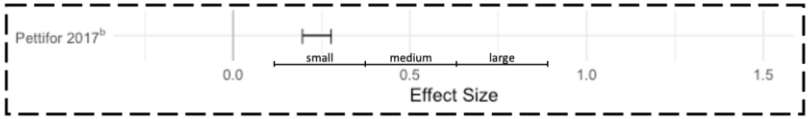
Make Information Intuitive & Easy to Access	247	235	12	<u>Energy Source (3)</u> (Havas et al. 2015; Jagger et al. 2019) <u>Energy Use (202)</u> (Henryson et al. 2000; Darby 2006; Carlsson-Kanyama and Lindén 2007; Chen et al. 2017; Iwafune et al. 2017; Burkhardt et al. 2019; Henry et al. 2019; Wong-Parodi et al. 2019; Mi et al. 2020; Stojanovski et al. 2020) (Abrahamse et al. 2005; Ehrhardt-Martinez and Donnelly 2010; Delmas et al. 2013; Andor and Fels 2018; Bergquist et al. 2019; Buckley 2019; Iweka et al. 2019; Nisa et al. 2019; Zangheri et al. 2019; Wolske et al. 2020; Ahir and Chakraborty 2021; Grilli and Curtis 2021; Khanna et al. 2021)* <u>Investment in Energy Efficiency (30)</u> (Larrick and Soll 2008); (Steg 2008; Andor and Fels 2018)* <u>Mode of Transportation (19)</u> (Steg 2008; Pettifor et al. 2017)*	197	38	24	33
Make Behaviour Observable & Provide Recognition	58	53	5	<u>Energy Use (24)</u> (Abrahamse et al. 2005; Delmas et al. 2013; Bergquist et al. 2019; Iweka et al. 2019; Nisa et al. 2019; Grilli and Curtis 2021)* <u>Investment in Energy Efficiency (30)</u> (Pettifor et al. 2017)* <u>Mode of Transportation (4)</u> (Pettifor et al. 2017)*	27	28	5	6
Communicate a Norm	138	131	7	<u>Energy Source (1)</u> (Hafner et al. 2019) <u>Energy Use (116)</u> (Nolan et al. 2008; Ayers and Forsyth 2009; Allcott 2011; Costa and Kahn 2013; Allcott and Rogers 2014) (Abrahamse et al. 2005; Abrahamse and Steg 2013; Delmas et al. 2013; Andor and Fels 2018; Bergquist et al. 2019; Buckley 2019; Iweka et al. 2019; Nisa et al. 2019; Ahir and Chakraborty 2021; Khanna et al. 2021)* <u>Investment in Energy Efficiency (15)</u> (Niamir et al. 2020b); (Pettifor et al. 2017; Grilli and Curtis 2021)* <u>Mode of Transportation (7)</u> (Bamberg et al. 2007); (Bergquist et al. 2019)*	106	21	16	15
Reframe Consequences	74	68	6	<u>Energy Source (5)</u>	41	18	19	18

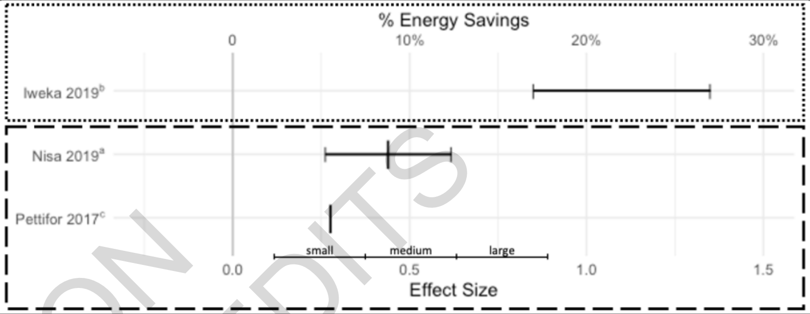
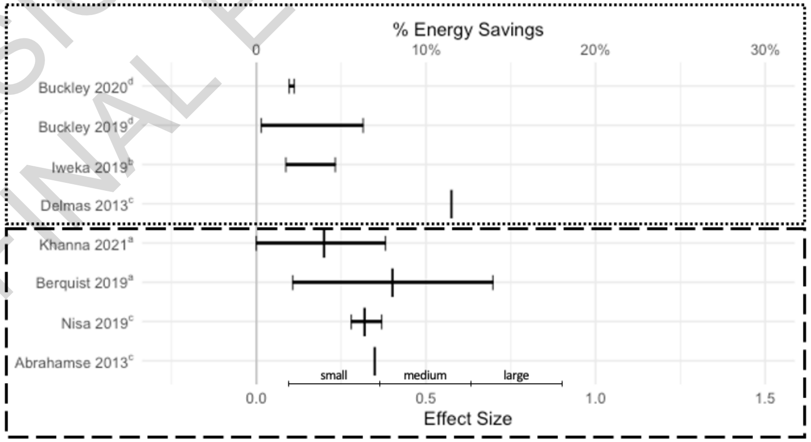
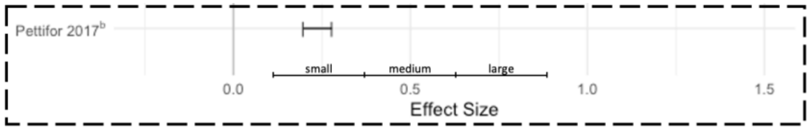
in Terms People Care About				(Wolske et al. 2018; Hafner et al. 2019); (Grilli and Curtis 2021)* Energy Use (47) (Chen et al. 2017; Eguiguren-Cosmelli 2018; Ghesla et al. 2020; Mi et al. 2020) (Abrahamse et al. 2005; Darby 2006; Delmas et al. 2013; Bergquist et al. 2019; Khanna et al. 2021)* Investment in Energy Efficiency (22) (Forster et al. 2021); (Andor and Fels 2018)* Mode of Transportation (2) (Nepal et al. 2010; Mattauch et al. 2016)				
Obtain a Commitment	52	47	5	Energy Source (1) (Jagger et al. 2019) Energy Use (47) (Ghesla et al. 2020) (Abrahamse et al. 2005; Steg 2008; Delmas et al. 2013; Andor and Fels 2018; Iweka et al. 2019; Nisa et al. 2019; Grilli and Curtis 2021; Khanna et al. 2021)* Investment in Energy Efficiency (1) (Steg 2008)* Mode of Transportation (5) (Matthies et al. 2006); (Steg 2008)*	45	4	4	10

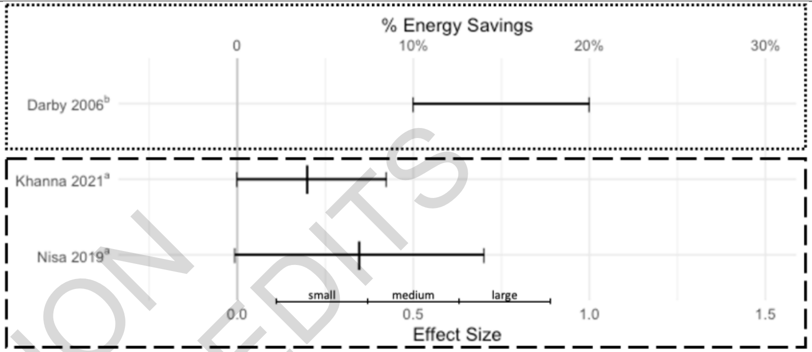
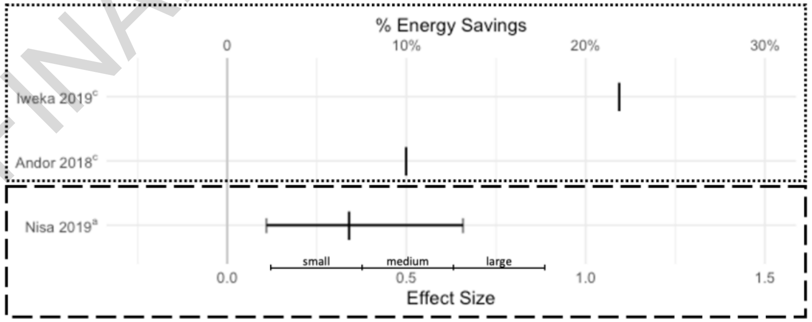
Note: Papers in this review of behavioural interventions to reduce household energy demand were collected through a systemic literature search up to August 2021. Studies are included in the reported counts if they are (1) experimental, (2) peer-reviewed or highly cited reports, (3) the intervention is behavioural, and (4) the targeted behaviour is household energy demand. 559 papers are included in the review. Each paper was coded for: type of behavioural intervention, country of study, energy demand behaviour targeted, whether the target is an avoid, shift, or improve behaviour, and whether the intervention includes an economic incentive. Some papers do not report all elements. The energy demand behaviour column provides the count of papers that focus on each behaviour type (in parentheses after the behaviour). The citations that follow are not exhaustive but exemplify papers in the category, selected for impact, range, and recency. The asterisk (*) indicates references that are meta-analyses or systematic reviews. Papers within meta-analyses and systematic reviews that meet the inclusion criteria are counted individually in the total counts. The full reference list is available at https://osf.io/9463u/.

Table 5.3b Summary of effects of behavioural interventions in Table 5.3a.

Behavioural Tool	Results (expressed in household energy savings, unless otherwise stated)	Results Summary
Set Proper Default	Meta-analyses find a medium to strong effect of defaults on environmental behaviour. Jachimowicz et al. (2019) report a strong average effect of defaults on environmental behaviour (Cohen's d=.75, confidence interval 0.39 - 1.12), though not as high as for consumer decisions. They find that defaults, across domains, are more effective when they reflect an endorsement (recommendation by a trusted source) or endowment (reflecting the status quo). Nisa et al. (2019)* report a medium average effect size (Cohen's d = 0.35; range 0.04 - 0.55).	
Reach Out During Transitions	The few interventions that focus on transitions and measure behaviour change (rather than energy savings) report mixed, moderate effect sizes. People were unwilling to change their behaviour if they are satisfied with current options (Mahapatra and Gustavsson 2008). Iweka et al. (2019)find that effective messages can prompt habit disruption.	
Timely Feedback & Reminders	The average effects of meta-analyses of feedback interventions on household energy use reductions range from 1.8% to 7.7%, with large variations (Delmas et al. 2013; Buckley 2019; Nisa et al. 2019; Buckley 2020; Ahir and Chakraborty 2021; Khanna et al. 2021). The same is true for two literature reviews (Abrahamse et al. 2005; Bergquist et al. 2019). Most studies find a 4% - 10% average reduction during the intervention; some studies find a non-significant result (Dünnhoff and Duscha 2008) or a negative reduction (Winett et al. 1978). Real-time feedback is most effective, followed by personalized feedback (Buckley 2019, 2020). A review by Darby et al. (2006) finds direct feedback (from the meter or display monitor) is more effective than indirect feedback (via billing) (5 - 15% savings vs. 0 - 10% savings). Feedback effects (Cohen's d= .241) are increased when combined with a monetary incentive (Cohen's d=.96) and with a social comparison and a monetary incentive (Cohen's d=.714) (Khanna et al. 2021) Sanguinetti et al. (2020) find that onboard feedback results in a 6.6% improvement in the fuel economy of cars (Cohen's d: .07, [.05,.08]).	

	The effectiveness of feedback from in home displays (IHDs) is highly studied. Two reviews find them to have a 2 - 14% energy saving (Ehrhardt-Martinez and Donnelly 2010; Faruqui et al. 2010). A meta-analysis by McKerracher and Torriti (2013)finds a smaller range of results, with 3 - 5% energy savings.	
Make Information Intuitive & Easy to Access	Meta-analyses of information interventions on household energy use find average energy savings between 1.8 - 7.4% and Cohen's d effect sizes between .05 and .30 (Delmas et al. 2013; Buckley 2019, 2020; Nemati and Penn 2020; Ahir and Chakraborty 2021; Khanna et al. 2021); (Nisa et al. 2019)*. Study quality affects the measured effect—small sample sizes, shorter measurement windows, and self-selection are correlated with larger effects (Nisa et al. 2019; Nemati and Penn 2020). RCTs have a smaller effect size, 5.2% savings (95% CI [0.5%,9.5%]) (Nemati and Penn 2020). Information combined with comparative feedback is more effective than information alone (d=.34 vs. .30, (Khanna et al. 2021); 8.5% vs. 7.4%, Delmas et al. 2013). Monetary incentives make information interventions more effective (Khanna et al. 2021). Energy efficiency labeling has a heterogenous effect on investment in energy efficiency(Abrahamse et al. 2005; Andor and Fels 2018). Efficiency labels on houses lead to higher price mark ups (Jensen et al. 2016) and house prices (Brounen and Kok 2011). Energy star labels lead to significantly higher willingness to pay for refrigerators (Houde et al. 2013), but energy and water conservation varies by appliance from 0 - 23% (Kurz et al. 2005). A meta-analysis of interventions to increase alternative fuel vehicle adoption find a small effect (d=.20 - .28) (Pettifor et al. 2017).	 

Make Behaviour Observable & Provide Recognition	Making behaviour observable and recognition lead to 6-7% energy savings (Winett et al. 1978; Handgraaf et al. 2013; Nemati and Penn 2020) and a large effects size (Cohen's d = [.79,1.06); Nisa et al. 2019*). Community-wide interventions result in 17-27% energy savings (Iweka et al. 2019). Neighborhood social influence has a small (d=.28) effect on alternative fuel vehicle adoption (Pettifor et al. 2017).	
Communicate a Norm	The effect of social norm information on household energy savings ranges from 1.7-11.5% (Delmas et al. 2013; Buckley 2020) and Cohen's d from .08-.32,(Abrahamse and Steg 2013; Bergquist et al. 2019; Khanna et al. 2021); (Nisa et al. 2019)*, with similar effects on choice of mode of transportation. Pettifor et al. (2017) report a small effect (d=.20-.28) on selecting a more energy efficient car. The Opower study (Allcott 2011), prototypical for the impact of social norms on household energy consumption, finds 2% reduction in long-term energy use and 11-20% energy reduction in the short run (Allcott 2011; Ayres et al. 2013; Costa and Kahn 2013; Allcott and Rogers 2014). Impact decays over time (Allcott and Rogers 2012). Norm interventions are less effective for low energy users (Schultz et al. 2007; Andor et al. 2017). Moral licensing and negative spillover can reduce the overall positive feedback of normative feedback (Tiefenbeck et al. 2013). Interventions are more effective when the norm is implicitly inducted, in individualistic countries, and when people care about the norm (Nolan et al. 2008; Bergquist et al. 2019; Khanna et al. 2021). Descriptive norm interventions (social comparisons) are more effective when communicated online/email or through in-home displays compared to billing letters (Andor and Fels 2018), when the reference group is more specific (Shen et al. 2015). Dolan and Metcalfe (2013) find conservation increased from 4% to 11% when energy savings tips are added.	 

Reframe Consequences in Terms People Care About	A meta-analysis by Khanna et al. (Khanna et al. 2021) finds a small and variable effect of motivational interventions that reframe consequences (Cohens's d = [0,.423]); Effect are larger when reframing is combined with monetary incentives and feedback (d = .96). Darby et al. (2006) report 10-20% savings for US pay-as-you-go systems. Providing lifecycle cost information increases likelihood of purchasing eco-innovative products (Kaenzig and Wüstenhagen 2010). Long term (10-year) operating cost information leads to higher WTP for energy efficiency compared to short term (1-year) cost information (Heinzle and Wüstenhagen 2012). Monetary information increases the success of energy reduction interventions (Newell and Siikamäki 2014; Andor and Fels 2018). Reframing interventions are more effective when combined with feedback (d = .24-.96) and with social comparisons and feedback (d = .42) (Khanna et al. 2021)	
Obtain a Commitment	Commitment and goal interventions result in significant energy reduction in half of studies(Abrahamse et al. 2005; Andor and Fels 2018); (Nisa et al. 2019)*. Nisa et al. (2019) report a moderate average effect (Cohen's d = 0.34, [.11, .66]). When results are significant, the energy savings are around 10% (Andor and Fels 2018). Self-set goals perform better than assigned goals (van Houwelingen and van Raaij 1989; McCalley and Midden 2002; Andor and Fels 2018) and reasonable goals perform better than unreasonably high or low goals (van Houwelingen and van Raaij 1989; Abrahamse et al. 2007; Harding and Hsiaw 2014). Interventions are more effective when the commitment is public (Pallak and Cummings 1976) and when combined with information and rewards (Slavin et al. 1981; Völlink and Meertens 1999).	

Note: The second column describes the effects of each of the eight behavioural tools. The third column plots the results of meta-analyses and reviews that focus on each tool. Effects are reported as described in the referenced paper, either as percentage of energy saved (dotted box) or by the effect size, measured as Cohen's D (dashed box).
*Two responses to Nisa et al. (2019) challenge their conclusion that behavioural interventions have a small impact on household energy use (Stern 2020; van der Linden & Goldberg, 2020). We report the raw data collected and used in Nisa et al. (2019). Our data summary supports the arguments by Stern (2020) and van der Linden (2020) that interventions should be evaluated in combination, as well as individually, and that the results are highly sensitive to the chosen estimator.
[a] Range reported as 95% confidence interval of results used in the meta-analysis or review.
[b] Range reported as all results included in the meta-analysis or review.
[c] No range reported.
[d] Range indicates the reported results within a meta-analysis; this applies when multiple intervention types in a meta-analysis are classified as a single behavioural tool.

5.4.2 Socio-cultural drivers of climate mitigation

Collective behaviours and social organisation is part of everyday life, and feeling part of active collective action renders mitigation measures efficient and pervasive (Climact 2018). Social and cultural processes play an important role in shaping what actions people take on climate mitigation, interacting with individual, structural, institutional and economic drivers (Barr and Prillwitz 2014). Just like infrastructures, social and cultural processes can 'lock-in' societies to carbon-intensive patterns of service delivery. They also offer potential levers to change normative ideas and social practices in order to achieve extensive emissions cuts (*high confidence*, see Table 5.4).

In terms of cultural processes, we can distinguish two levels of analysis: specific meanings associated with particular technologies or practices, and general narratives about climate change mitigation. Specific **meanings** (e.g. comfort, status, identity and agency) are associated with many technologies and everyday social practices that deliver energy services, from driving a car to using a cookstove (*high evidence*, *high agreement*, see Section 5.5). Meanings are symbolic and influence the willingness of individuals to use existing technologies or shift to new ones (Wilhite and Ling 1995; Wilhite 2009; Sorrell 2015). Symbolic motives are more important predictors of technology adoption than instrumental motives (Steg 2005; Noppers et al. 2014, 2015, 2016) (see mobility case study on app-cabs in Kolkata, Box 5.8). If an invidiual's pro-environmental behavior is associated with personal meaning than it also increases subjective wellbeing (Zawadzki et al. 2020). Status consciousness is highly relevant in high GHG emission intensive consumption choices (cars, houses). However, inversely framing energy saving behaviour as high status is a promising strategy for emission reduction (Ramakrishnan and Creutzig 2021).

At a broader level, **narratives** about climate mitigation circulate within and across societies, as recognised in SR15, and are broader than the meanings associated with specific technologies (*high evidence, high agreement)*. Narratives enable people to imagine and make sense of the future through processes of interpretation, understanding, communication and social interaction (Smith et al. 2017). Stories about climate change are relevant for mitigation in numerous ways. They can be utopian or dystopian (e.g. The great derangement by Amitav Ghosh) (Ghosh 2016), for example presenting apocalyptic stories and imagery to capture people's attention and evoke emotional and behavioural response (O'Neill and Smith 2014). Reading climate stories has been shown to cause short-term influences on attitudes towards climate change, increasing the belief that climate change is human caused and increasing its issue priority (Schneider-Mayerson et al. 2020). Climate narratives can also be used to justify scepticism of science, drawing together coalitions of diverse actors into social movements that aim to prevent climate action (Lejano and Nero 2020). Narratives have been used by indigenous communities to imagine climate futures divergent from top-down narratives (Streeby 2018). Narratives are also used in integrated assessment and energy system models that construct climate stabilisation scenarios, for example in the choice of parameters, their interpretation and model structure (Ellenbeck and Lilliestam 2019). One important narrative choice of many models involves framing climate change as market failure (which leads to the result that carbon pricing is required). While such a choice can be justified, other model framings can be equally justified (Ellenbeck and Lilliestam 2019). Power and agency shape which climate narratives are told and how prevalent they are (O'Neill and Smith 2014; Schneider-Mayerson et al. 2020). For example, narratives have been used by indigenous communities to imagine climate futures divergent from top-down, government-led narratives (Streeby 2018). The uptake of new climate narratives is influenced by political beliefs and trust. Policy makers can enable emissions reduction by employing narratives that have broad societal appeal, encourage behavioural change and complement regulatory and fiscal measures (Terzi 2020). Justice narratives may not have universal appeal - in a UK study, justice narratives polarised individuals along ideological lines, with lower support amongst individual with right-wing beliefs; by contrast, narratives centred on saving energy, avoiding waste and patriotic values were more widely supported across society

(Whitmarsh and Corner 2017). More research is needed to assess if these findings are prevalent in diverse socio-cultural contexts, as well the role played by social media platforms to influence emerging narratives of climate change (Pearce et al. 2019).

Trust in organisations is a key predictor of the take-up of novel energy services (Lutzenhiser 1993), particularly when financial incentives are high (Stern et al. 1985; Joskow 1995). Research has shown that, if there is low public trust in utility companies, service delivery by community-based non-profit organisations in the US (Stern et al. 1985) or public/private partnerships in Mexico (Friedmann and Sheinbaum 1998), offer more effective solutions, yet only if public trust is higher in these types of organisations. UK research shows that acceptance of shifts to less-resource intensive service provision (e.g. more resource efficient products, extending product lifetimes, community schemes for sharing products) varies depending on factors including trust in suppliers and manufacturers, affordability, quality and hygiene of shared products, and fair allocation of responsibilities (Cherry et al. 2018). Trust in other people plays an important role in the sharing economy (Li and Wang 2020), for example predicting shifts in transport mode, specifically car-sharing involving rides with strangers (Acheampong and Siiba 2019) (sharing economy see Section 5.3.4.2).

Action on climate mitigation is influenced by our perception of what other people commonly do, think or expect, known as social norms *(high evidence, high agreement)* (Cialdini 2006) (see Table 5.3), even though people often do not acknowledge this (Nolan et al. 2008; Noppers et al. 2014). Changing social norms can encourage societal transformation and social tipping points to address climate mitigation(Nyborg et al. 2016; Otto et al. 2020). Providing feedback to people about how their own actions compare to others can encourage mitigation (Delmas et al. 2013), although the overall effect size is not strong (Abrahamse and Steg 2013). Trending norms are behaviours that are becoming more popular, even if currently practised by a minority. Communicating messages that the number of people engaging in a mitigation behaviour (e.g. giving a financial donation to an environmental conservation organisation) is increasing – a simple low cost policy intervention - can encourage shifts to the targeted behaviour, even if the effect size is relatively small (Mortensen et al. 2019).

Socially comparative feedback seems to be more effective when people strongly identify with the reference group (De Dominicis et al. 2019). Descriptive norms (perceptions of behaviours common in others) are more strongly related to mitigation actions when injunctive norms (perceptions of whether certain behaviours are commonly approved or disapproved) are also strong, when people are not strongly personally involved with mitigation topics (Göckeritz et al. 2010), when people are currently acting inconsistently with their preferences, when norm-based interventions are supported by other interventions and when the context supports norm-congruent actions (Miller and Prentice 2016). A descriptive norm prime ("most others try to reduce energy consumption") together with injunctive norm feedback ("you are very good in saving energy") is a very effective combination to motivate further energy savings (Bonan et al. 2020). Second-order beliefs (perceptions on what others in the community believe) are particularly important for leveraging descriptive norms (Jachimowicz et al. 2018).

Behavioural contagion, which describes how ideas and behaviours often spread like infectious diseases, is a major contributor to the climate crisis (Sunstein 2019). But harnessing contagion can also mitigate warming. Carbon-heavy consumption patterns have become the norm only in part because we're not charged for environmental damage we cause (Pigou 1920). The deeper source of these patterns has been peer influence (Frank 1999), because what we do influences others. A rooftop solar installation early in the adoption cycle, for example, spawns a copycat installation in the same neighbourhood within four months, on average. With such installations thus doubling every four months, a single new order results in 32 additional installations in just two years. And contagion doesn't stop there, since each family also influences friends and relatives in distant locations.

Harnessing contagion can also underwrite the investment necessary for climate stability. If taxed more heavily, top earners would spend less, shifting the frames of reference that shape spending of those just below, and so on—each step simultaneously reducing emissions and liberating resources for additional green investment (Frank 2020). Many resist, believing that higher taxes would make it harder to buy life's special extras. But that belief is a cognitive illusion (Frank 2020). Acquiring special things, which are inherently in short supply, requires outbidding others who also want them. When top tax rates rise in tandem, relative bidding power is completely unchanged, so the same penthouse apartments would end up in the same hands as before. More generally, behavioural contagion is important to leverage all relevant social tipping points for stabilising Earth's climate (Otto et al. 2020).

For new climate policies and mitigation technologies to be rapidly and extensively implemented, they must be socially acceptable to those who are directly impacted by those policies and technologies (*medium evidence, high agreement*). Policies that run counter to social norms or cultural meanings are less likely to be effective in reducing emissions (Demski et al. 2015; Perlaviciute et al. 2018; Roy et al. 2018b). More just and acceptable implementation of renewable energy technologies requires taking account of the cultural meanings, emotional attachments and identities linked to particular landscapes and places where those technologies are proposed (Devine-Wright 2009) and enabling fairness in how decisions are taken and costs and benefits distributed (Wolsink 2007). This is important for achieving the goal of SDG7 (i.e. increased use of renewable energy resources) in deveolping countries while achieving energy justice (Calzadilla and Mauger 2017). 'Top-down' imposition of climate policies by governments can translate into local opposition when perceived to be unjust and lacking transparency (*high evidence, high agreement*). Policy makers can build trust and increase the legitimacy of new policies by implementing early and extensive public and stakeholder participation, avoiding 'NIMBY' (Not In My Back Yard) assumptions about objectors and adopting 'Just Transition' principles (Owens 2000; Wolsink 2007; Wüstenhagen et al. 2007; Dietz and Stern 2008; Devine-Wright 2011; Heffron and McCauley 2018). Participatory mechanisms that enable deliberation by a representative sample of the public (Climate Assembly UK 2020) can inform policy making and increase the legitimacy of new and difficult policy actions (Dryzek et al. 2019).

Collective action by civil society groups and social movements can work to enable or constrain climate mitigation. Civil society groups can advocate policy change, provide policy research and open up opportunities for new political reforms (high evidence, high agreement) as recognised in previous IPCC reports (IPCC 2007). Grassroots environmental initiatives, including community energy groups, are collective responses to, and critiques of, normative ways that everyday material needs (e.g. food, energy, making) are produced, supplied and circulated (Schlosberg and Coles 2016). Such initiatives can reconcile lower carbon footprints with higher life satisfaction and higher incomes(Vita et al. 2020). Local initiatives such as Transition Towns and community energy can lead to improvements in energy efficiency, ensure a decent standard of living and increase renewable energy uptake, while building on existing social trust, and in turn, building social trust and initiating engagement, capacity building, and social capital formation(Hicks and Ison 2018). Another example are grassroot initiatives that aim to reduce food loss and waste, even as overall evidence on their effectiveness remains limited (Mariam et al. 2020). However, community energy initiatives are not always inclusive and require policy support for widespread implementation across all socio-economic groups (Aiken et al. 2017) In addition, more evidence is required of the impacts of community energy initiatives (Creamer et al. 2018; Bardsley et al. 2019).

Civil society social movements are a primary driver of social and institutional change (high evidence, high agreement) and can be differently positioned as, on the one hand, 'insider' social movements (e.g. World Wildlife Fund) that seek to influence existing state institutions through lobbying, advice and research and, on the other hand, 'outsider' social movements (e.g. Rising Tide, Extinction Rebellion) that advocate radical reform through protests and demonstrations(Newell 2005; Caniglia et al. 2015). Civil society social movements frame grievances that resonate with society, mobilise resources to coordinate and sustain mass collective action, and operate within – and seek to influence - external conditions that enable or constrain political change (Caniglia et al. 2015). When successful, social movements open up windows of opportunity (so called 'Overton Windows') to unlock structural change (high evidence, high agreement) (Szałek 2013; Piggot 2018).

Climate social movements advocate new narratives or framings for climate mitigation (e.g. climate 'emergency') (della Porta and Parks 2014); criticise positive meanings associated with high emission technologies or practices (see Diet and Solar PV Case Studies, Box 5.5 and 5.7); show disapproval for high emission behaviours (e.g. through 'flight shaming'); model behaviour change (e.g. shifting to veganism or public transport – see Case Study on Mobility in Kolkata, Box 5.8); demonstrate against extraction and use of fossil-fuels(Cheon and Urpelainen 2018); and aim to increase a sense of agency amongst certain social groups (e.g. young people or indigenous communities) that structural change is possible. Climate strikes have become internationally prevalent, for example the September 2019 strikes involved participants in more than 180 countries (Rosane 2019; Fisher and Nasrin 2020; Martiskainen et al. 2020). Enabled by digitalisation, these have given voice to youth on climate (Lee et al. 2020) and created a new cohort of active citizens engaged in climate demonstrations (Fisher 2019). Research on bystanders shows that marches increase positive beliefs about marchers and collective efficacy (Swim et al. 2019).

Countermovement coalitions work to oppose climate mitigation *(high confidence)*. Examples include efforts in the US to oppose mandatory limits on carbon emissions supported by organisations from the coal and electrical utility sectors (Brulle 2019) and evidence that US opposition to climate action by carbon-connected industries is broad-based, highly organized, and matched with extensive lobbying (Cory et al., 2021). Social movements can also work to prevent policy changes, for example in France the Gilet Jaunes objected to increases in fuel costs on the grounds that they unfairly distributed the costs and benefits of price rises across social groups, for example between urban, peri-urban and rural areas (Copland 2019).

Religion could play an important role in enabling collective action on climate mitigation by providing cultural interpretations of change and institutional responses that provide resources and infrastructure to sustain collective actions (Roy et al. 2012; Haluza-DeLay 2014; Caniglia et al. 2015; Hulme 2015). Religion can be an important cultural resource towards sustainability at individual, community and institutional levels(Ives and Kidwell 2019) , providing leverage points for inner transformation towards sustainability (Woiwode et al. 2021). Normative interpretations of climate change for and from religious communities are found in nearly every geography, and often observe popular movements for climate action drawing on religious symbols or metaphors (Jenkins et al. 2018). This suggests the value for policy makers of involving religious constituencies as significant civil society organisations in devising and delivering climate response.

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Box 5.7 Solar PV and the agency of consumers

As an innovative technology, solar PV was strongly taken up by consumers (Nemet 2019). Several key factors explain its success. First, modular design made it applicable to different scales of deployment in different geographical contexts (e.g. large-scale grid-connected projects and smaller-scale off-grid projects) and allowed its application by companies taking advantage of emerging markets (Shum and Watanabe 2009). Second, culturally, solar PV symbolised an environmentally progressive technology that was valued by users (Morris and Jungjohann 2016). Large-scale adoption led to policy change (i.e. the introduction of feed-in tariffs that guaranteed a financial return) that in turn enabled improvements to the technology by companies. Over time, this has driven large-scale reductions in cost and increase in deployment worldwide. The relative importance of drivers varied across contexts. In Japan, state subsidies were lower yet did not hinder take-up because consumer behaviour was motivated by non-cost symbolic aspects. In Germany, policy change arose from social movements that campaigned for environmental conservation and opposed nuclear power, making solar PV policies politically acceptable. In summary, the seven-decade evolution of solar PV shows an evolution in which the agency of consumers has consistently played a key role in multiple countries, such that deriving 30-50% of global electricity supply from solar is now a realistic possibility (Creutzig et al. 2017). See more in Supplementary Material Chapter 5, SM5.6.1.

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5.4.3 Business and Corporate Drivers

Businesses and corporate organisations play a key role in the mitigation of global warming, through their own commitments to zero-carbon footprints (Mendiluce 2021) decisions to invest in researching and implementing new energy technologies and energy efficient measures, and the supply side interaction with changing consumer preferences and behaviours, e.g. via marketing. Business models and strategies work both as a barrier to and as accelerator of decarbonisation. Still existing lock-in in infrastructures and business models advantages fossil fuel industry over renewable and energy efficient end use industry (Klitkou et al. 2015). The fossil fuel energy generation and delivery system therefore epitomises a barrier to the acceptance and implementation of new and cleaner renewable energy technologies (Kariuki 2018). A good number of corporate agents have attempted to derail climate change mitigation by targeted lobbying and doubt-inducing media strategies (Oreskes and Conway 2011). A number of corporations that are involved in the supply chain of both upstream and downstream of fossil fuel companies, make up the majority of organizations opposed to climate action (Dunlap and McCright 2015; Cory et al. 2021; Brulle 2019). Corporate advertisement and brand building strategies also attempt to deflect corporate responsibility to individuals, and/or to appropriate climate care sentiments in their own brand building; climate change mitigation is uniquely framed through choice of products and consumption, avoiding the notion of the political collective action sphere (Doyle 2011; Doyle et al. 2019).

Business and corporations are also agents of change towards decarbonisation, as demonstrated in the case of PV and battery electric cars (Teece 2018). Beyond new low-carbon technologies, strong sustainability business models (SSBM) are characterised by identifying nature as the primary stakeholder, strong local anchorage, the creation of diversified income sources, and deliberate limitations on economic growth (Brozovic 2019). However, SSBM are difficult to maintain if generally traditional business models prevail, requiring short-term accounting.

Liability of fossil fuel business models and insurance against climate damages are key concerns of corporations and business. Limitations and regulation on GHG emissions will compel the demand for fossil fuel companies' products (Porter and Kramer 2006). According to a European Systemic Risk Board (ESRB 2016) report of the Advisory Scientific Committee, insurance industries are very likely to incur losses due to liability risks. The divestment movement adds additional pressure on fossil fuel related investments (Braungardt et al. 2019), even though fossil fuel financing remains resilient (Curran 2020). Companies, businesses and organisations might face liability claims for their contribution to changes especially in the carbon intensive energy sector. A late transition to a low-carbon economy would exacerbate the physical costs of climate change on governments, businesses and corporations (ESRB 2016).

Despite these seemingly positive roles that Businesses and corporate organisations tend to play towards sustainable transitions, there is a need to highlight the dynamic relationship between sustainable and unsustainable trends (Antal et al. 2020). For example, the production of Sports Utility Vehicles (SUVs) in the automobile market at the same time that car manufacturers are producing electric vehicles. An analysis of the role of consumers as drivers of unsustainability for Businesses and Corporate organisations is very important here as this trend will offset the sustainability progress being made by these businesses and organisations (Antal et al. 2020).

Professional actors, such as building managers, landlords, energy efficiency advisers, technology installers and car dealers, influence patterns of mobility and energy consumption (Shove 2003) by acting as 'middle actors' (Janda and Parag 2013; Parag and Janda 2014) or 'intermediaries' in the provision of building or mobility services (Grandclément et al. 2015; De Rubens et al. 2018). Middle actors can bring about change in several different directions be it, upstream, or downstream or sideways. They can redefine professional ethics around sustainability issues, and as influencers on the process of diffusion of innovations (Rogers 2003), professionals can enable or obstruct improvements in efficient service provision or shifts towards low-carbon technologies (LCTs) (e.g. air and ground source heat pumps, solar hot water, underfloor heating, programmable thermostats, and mechanical ventilation with heat recovery) and mobility (e.g. electric vehicles) technologies.

5.4.4 Institutional Drivers

The allocation of political power to incumbent actors and coalitions has contributed to lock-in of particular institutions, stabilising the interests of incumbents through networks that include policymakers, bureaucracies, advocacy groups and knowledge institutions (*high agreement*, *high evidence*). There is high evidence and high agreement in that institutions are central in addressing climate change mitigation. Indeed, social provisioning contexts including equity, democracy, public services and high quality infrastructure are found to facilitate high levels of need satisfaction at lower energy use, whereas economic growth beyond moderate incomes and dependence on extractive industries inhibit it (Vogel et al. 2021). They shape and interact with technological systems (Unruh 2000; Foxon et al. 2004; Seto et al. 2014) and represent rules, norms and conventions that organise and structure actions (Vatn 2015) and help create new path dependency or strengthen existing path dependency (Mattioli et al. 2020) (also see case studies in Box 5.5-5.8 and Supplementary Material Chapter 5). These drive behaviour of actors through formal (e.g., laws, regulations, and standards) or informal (e.g., norms, habits, and customs) processes, and can create constraints on policy options (Breukers and Wolsink 2007). For example, 'the car dependent transport system' is maintained by interlocking elements and institutions, consisting of i) the automotive industry; ii) the provision of car infrastructure; iii) the political economy of urban sprawl; iv) the provision of public transport; v) cultures of car consumption (Mattioli et al. 2020). The behaviour of actors, their processes and implications on policy options and decisions is discussed further in Section 5.6.

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Box 5.8 Shifts from private to public transport in Indian megacities

In densely populated, fast-growing megacities, policy makers face the difficult challenge of preventing widespread adoption of petrol or diesel fuelled private cars as a mode of transport. The megacity of Kolkata in India provides a useful case study. As many as twelve different modes of public transportation, each with its own system structure, actors and meanings co-exist and offers means of mobility to its 14 million citizens. Most of the public transport modes are shared mobility options ranging from sharing between two people in a rickshaw or between a few hundred in metro or sub-urban trains. Sharing also happens informally as daily commuters avail shared taxis and neighbours borrow each other's car or bicycle for urgent or day trips.

A key role is played by the state government, in collaboration with other stakeholders, to improve the system as whole and formalise certain semi-formal modes of transport. An important policy consideration has been to make Kolkata's mobility system more efficient (in terms of speed, reliability and avoidance of congestion) and sustainable through strengthening coordination between different mode-based regimes (Ghosh 2019) and comfortable with airconditioned space in a hot and humid climate (Roy et al. 2018b). Policy makers have introduced multiple technological, behavioural and socio-cultural measures to tackle this challenge. New buses have been purchased by public authorities (Ghosh and Schot 2019). These have been promoted to middle-class workers in terms of modernity, efficiency and comfort, and implemented using premium-fares. Digitalisation and the sharing economy has encouraged take-up of shared taxi rides ('app cabs'), being low cost and fast, but also influenced by levels of social trust involved in rides with strangers (Acheampong and Siiba 2019; Ghosh and Schot 2019). Rickshaws have been improved through use of LNG and cycling has been banned from busy roads. These measures contributed positively in bringing down the trend of greenhouse gas emissions per unit of GDP to half in one decade within the Kolkata metropolitan area, with potential for further reduction (Colenbrander et al. 2016). However, social movements have opposed some changes due to concerns about social equity, since many of the new policies cater to middle class aspirations and preferences, at the cost of low income and less privileged communities.

To conclude, urban mobility transitions in Kolkata shows interconnected policy, institutional and socio-cultural drivers for socio-technical change. Change has unfolded in complex interactions between multiple actors, sustainability values and megatrends, where direct causalities are hard to identify. However, the prominence of policy actors as change-agents is clear as they are changing multiple regimes from within. The state government initiated infrastructural change in public bus systems, coordinated with private and non-governmental actors such as auto-rickshaw operators, app-cab owners who hold crucial agency in offering public transport services in the city. The latter can directly be attributed to the global momentum of mobility-as-a-service platforms, at the intersection of digitalisation and sharing economy trends. More thoughtful action at a policy level is required to sustain and coordinate the diversity of public transport modes through infrastructure design and reflecting on the overall directionality of change (Schot and Steinmueller 2018; Roy et al. 2018b). See more in Supplementary Material Chapter 5, SM5.6.3.

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5.4.5 Technological/Infrastructural Drivers

Technologies and infrastructures shape social practices and their design matters for effective mitigation measures (*high evidence, high agreement*). There are systemic interconnections between infrastructures and practices (Cass et al. 2018; Haberl et al. 2021), and their intersection explains their relevance (Thacker et al. 2019). The design of a new electricity system to meet new emerging demand based on intermittent renewable, can lead to a change in consumption habits and the adaption of lifestyles compliant with more power supply interruption (Maïzi et al. 2017; Maïzi and Mazauric 2019). The quality of the service delivery impacts directly the potential user uptake of low-carbon technologies. In the state of Himachal Pradesh of India, shift from LPG to electricity, with induction stove, has been successful due to the availability of stable and continuous electricity which has been difficult to achieve in any other Indian state (Banerjee et al. 2016). In contrast, in South Africa, where people who were using electricity earlier are now adopting LPG to diversify the energy source for cooking due to high electricity tariff and frequent blackouts (Kimemia and Annegarn 2016) (see Box 5.5 and Supplementary Material Chapter 5).

From a welfare point of view, infrastructure investments are not constrained by revealed or stated preferences (*high evidence*, *high agreement*). Preferences change with social and physical environment, and infrastructure interventions can be justified by objective measures, such as public health and climate change mitigation, not only given preferences *(high agreement, high evidence)*. Specifically, there is a case for more investment in low-carbon transport infrastructure than assumed in environmental economics as it induces low-carbon preferences (Creutzig et al. 2016a; Mattauch et al. 2018, 2016). Changes in infrastructure provision for active travel may contribute to uptake of more walking and cycling (Frank et al. 2019). These effects contribute to higher uptake of low-carbon travel options, albeit the magnitude of effects depends on design choices and context (Goodman et al. 2013, 2014; Song et al. 2017; Javaid et al. 2020; Abraham et al. 2021). Infrastructure is thus not only required to make low-carbon travel possible but can also be a pre-condition for the formation of low-carbon mobility preferences (also see mobility case study in Box 5.7).

The dynamic interaction of habits and infrastructures also predict CO_2-intensive choices. When people move from a city with good public transport to a car-dependent city, they are more likely to own fewer vehicles due to learned preferences for lower levels of car ownership (Weinberger and Goetzke 2010). When individuals moving to a new city with extensive public transport were given targeted material about public transport options, the modal share of public transport increased significantly (Bamberg et al. 2003). Similarly, an exogenous change to route choice in public transport makes commuters change their habitual routes (Larcom et al. 2017).

Table 5.4 Main features, insights, and policy implications of five drivers of decision and action. Entries in each column are independent lists, not intended to line up with each other.

Driver	How does driver contribute to status quo bias?	What needs to change?	Driver's policy implications	Examples
Behavioural	Habits and routines formed under different circumstances do not get updated. Present-bias penalises upfront costs and discourages energy efficiency investments. Loss aversion magnifies the costs of change.	New goals (sustainable lifestyle) New capabilities (online real-time communication) New resources (increased education) Use of full range of incentives and mechanisms to change demand-side behaviour	Policies need to be context specific and coordinate economic, legal, social, and infrastructural tools and nudges Relate climate action to salient local risks and issues.	India's new LPG scale up policy uses insights about multiple behavioural drivers of adoption and use. Rooftop solar adoption expanded in Germany, when FITs removed risk from upfront-cost recovery Nuclear power policies in

	When climate change is seen as distant, it is not feared. Nuclear power and accident potential score high on psychological dread			Germany post Fukushima affected by emotional factors
Socio-Cultural	Cultural norms (e.g. status, comfort, convenience) support existing behaviour. Lack of social trust reduces willingness to shift behaviour (e.g. adopt car-sharing). Fear of social disapproval decreases willingness to adopt new behaviours. Lack of opportunities to participate in policy create reactance against 'top down' imposition. Unclear or dystopian narratives of climate response reduce willingness to change and to accept new policies and technologies.	Create positive meanings and norms around low-emission service delivery (e.g. mass transit). Community initiatives to build social trust and engagement, capacity building, and social capital formation. Climate movements that call out the insufficient, highly problematic state of delayed climate action. Public participation in policy making and technology implementation that increases trust, builds capacity and increases social acceptance. Positive narratives about possible futures that avoid emissions (e.g. emphasis upon health and slow/active travel).	Embed policies in supportive social norms. Support collective action on climate mitigation to create social trust and inclusion. Involve arts and humanities to create narratives for policy process	Communicate descriptive norms to electricity end users. Community energy initiative RESCOOP. Friday For Future.
Business and Corporate	Lock-in mechanisms that make incumbent firms reluctant to change: core capabilities, sunk investments in staff and factories, stranded assets.	New companies (like car sharing companies, renewable energy start-ups) that pioneer new business models or energy service provisions.	Influence consumer behaviour via product innovation Provide capital for clean energy innovation.	Electrification of transport opens up new markets for more than a hundred million new vehicles.
Institutional	Lock-in mechanisms related to power struggles, lobbying, political economy.	New policy instruments, policy discussions, policy platforms, implementation agencies, including capacity.	Feed-in Tariffs and other regulations that turn energy consumers into prosumers.	Mobility case study, India's LPG policy sequence.
Infrastructural	various lock-in mechanisms such as	many emerging technologies, which are	systemic governance to	Urban walking and bike paths.

	sunk investments, capabilities, embedding in routines/lifestyles.	initially often more expensive, but may benefit from learning curves and scale economies that drive costs down.	avoid rebound effects.	Stable and continuous electricity supply fostering induction stoves.

5.5 An integrative view on transitioning

5.5.1 Demand-side transitions as multi-dimensional processes

Several integrative frameworks including social practice theory (Røpke 2009; Shove and Walker 2014), the energy cultures framework (Stephenson et al. 2015; Jürisoo et al. 2019) and socio-technical transitions theory (McMeekin and Southerton 2012; Geels et al. 2017) conceptualise demand-side transitions as multi-dimensional and interacting processes (*high evidence, high agreement*). Social practice theory emphasises interactions between artefacts, competences, and cultural meanings (Røpke 2009; Shove and Walker 2014)(Shove and Walker 2014; Røpke 2009). The energy cultures framework highlights feedbacks between materials, norms, and behavioural practices (Stephenson et al. 2015; Jürisoo et al. 2019). Socio-technical transitions theory addresses interactions between technologies, user practices, cultural meanings, business, infrastructures, and public policies (McMeekin and Southerton 2012; Geels et al. 2017) and can thus accommodate the five drivers of change and stability discussed in Section 5.4.

Section 5.4 shows with *high evidence and high agreement* that the relative influence of different drivers varies between demand-side solutions. The deployment of 'improve' options like LEDs and clean cookstoves mostly involves technological change, adoption by consumers who integrate new technologies in their daily life practices (Smith et al. 1993; Sanderson and Simons 2014; Franceschini and Alkemade 2016), and some policy change. Changes in meanings are less pertinent for those 'improve'-options that are primarily about technological substitution. Other improve-options, like clean cookstoves, involve both technological substitution and changes in cultural meanings and traditions.
Deployment of 'shift' options like enhanced public transport involves substantial behavioural change and transitions to new or expanded provisioning systems, which may include new technologies (buses, trams), infrastructures (light rail, dedicated bus lanes), institutions (operational licenses, performance contracts), financial arrangements, and new organisations (with particular responsibilities and oversight) (*high evidence, high agreement*) (Deng and Nelson 2011; Turnheim and Geels 2019). Changes in cultural meanings can facilitate 'shift' options. Shifts towards low-meat diets, for instance, are motivated by costs and by beliefs about the undesirability of meat that relate more to issues like health, nutrition and animal welfare than climate change (De Boer et al. 2014; Mylan 2018).

'Avoid' options that reduce service levels (e.g. sufficiency or downshifting) imply very substantial behavioural and cultural changes that may not resonate with mainstream consumers (Dubois et al. 2019). Other 'avoid' options like tele-working also require changes in cultural meanings and beliefs (about the importance of supervision, coaching, social contacts, or office politics), as well as changes in behaviour, institutions, business, and technology (including good internet connections and office space at home). Because these interconnected changes were not widespread, tele-working remained stuck in small niches and did not diffuse widely before the COVID-19 crisis (Hynes 2014, 2016; Belzunegui-Eraso and Erro-Garcés 2020; Stiles 2020). As preferences change, new infrastructures and social settings can also elicit new desirabilities associated with emerging low-energy demand service provisioning systems (see 5.4.5).

Demand-side transitions involve interactions between radical social or technical innovations (such as the avoid, shift, improve options discussed in Section 5.3) and existing socio-technical systems, energy cultures, and social practices (*high evidence, high agreement*) (Stephenson et al. 2015; Geels et al. 2017). Radical innovations such as tele-working, plant-based burgers, car sharing, vegetarianism, or electric vehicles initially emerge in small, peripheral niches (Kemp et al. 1998; Schot and Geels 2008), constituted by R&D projects, technological demonstration projects (Borghei and Magnusson 2016; Rosenbloom et al. 2018b), local community initiatives or grassroots projects by environmental activists (Hargreaves et al. 2013a; Hossain 2016). Such niches offer protection from mainstream selection pressures and nurture the development of radical innovations (Smith and Raven 2012). Many low-carbon niche-innovations, such as those described in Section 5.3, face uphill struggles against existing socio-technical systems, energy cultures, and social practices that are stabilised by multiple lock-in mechanisms (*high evidence, high agreement*) (Klitkou et al. 2015; Seto et al. 2016; Clausen et al. 2017; Ivanova et al. 2018). Demand-side transitions therefore do not happen easily and involve interacting processes and struggles on the behavioural, socio-cultural, institutional, business and technological dimensions (Nikas et al. 2020) (see also Section 5.4).

5.5.2 Phases in transitions

Transitions often take several decades, unfolding through several phases. Although there is variability across innovations, sectors, and countries, the transitions literature distinguishes four phases, characterised by generic core processes and challenges: 1) emergence, 2) early adaptation, 3) diffusion, 4) stabilisation (*high confidence*) (Rotmans et al. 2001; Markard et al. 2012; Geels et al. 2017) (Cross-Chapter Box 12 in Chapter 16). These four phases do not imply that transitions are linear, teleological processes, because set-backs or reversals may occur as a result of learning processes, conflicts, or changing coalitions (*very high confidence*) (Geels and Raven 2006; Messner 2015; Davidescu et al. 2018). There is also no guarantee that technological, social, or business model innovations progress beyond the first phase.

In the first phase, radical innovations emerge in peripheral niches, where researchers, inventors, social movement organisations or community activists dedicate time and effort to their development (*high confidence*) (Kemp et al. 1998; Schot and Geels 2008). Radical social, technical and business model innovations are initially characterised by many uncertainties about technical performance, consumer interest, institutions and cultural meanings. Learning processes are therefore essential and can be stimulated through R&D, demonstration projects, local community initiatives or grassroots projects (Borghei and Magnusson 2016; Hossain 2016; Rosenbloom et al. 2018b; van Mierlo and Beers 2020). Typical challenges are fragmentation and high rates of project failure (den Hartog et al. 2018; Dana et al. 2021), limited funding (Auerswald and Branscomb 2003), limited consumer interest, and socio-cultural acceptance problems due to being perceived as strange or unfamiliar (Lounsbury and Glynn 2001) .

In the second phase, social or technical innovations are appropriated or purchased by early adopters, which increases visibility and may provide a small but steady flow of financial resources (*high evidence, high agreement*) (Zimmerman and Zeitz 2002; Dewald and Truffer 2011). Learning processes, knowledge sharing and codification activities help stabilise the innovation, leading to best practice guidelines, standards, and formalised knowledge (*high evidence, high agreement*) (Raven et al. 2008; Borghei and Magnusson 2018). User innovation may lead to the articulation of new routines and social practices, often in tandem with the integration of new technologies into people's daily lives (Nielsen et al. 2016; Schot et al. 2016). Radical innovations remain confined to niches in the second phase because adoption is limited to small, dedicated groups (Schot et al. 2016), innovations are expensive or do not appeal to wider groups, or because complementary infrastructure are missing (Markard and Hoffmann 2016).

In the third phase, radical innovations diffuse into wider communities and mainstream markets. Typical drivers are performance improvements, cost reductions, widespread consumer interest, investments in infrastructure and complementary technologies, institutional support and strong cultural appeal (*high evidence, high agreement)* (Wilson 2012; Markard and Hoffmann 2016; Raven et al. 2017; Malone et al. 2017; Kanger et al. 2019). The latter may be related to wider cultural shifts such as increased public attention to climate change and new framings like 'climate emergency' which gained traction before the Covid-19 pandemic (Bouman et al. 2020b). These concerns may not last, however, since public attention typically follows cycles (Downs 1972; Djerf-Pierre 2012).

This phase often involves multiple struggles: economic competition between low-carbon innovations and existing technologies and practices, business struggles between incumbents and new entrants (Hockerts and Wüstenhagen 2010), cultural and framing struggles in public opinion arenas (Kammermann and Dermont 2018; Rosenbloom 2018; Hess 2019a), and political struggles over adjustments in policies and institutions, which shape markets and innovations (Meadowcroft 2011; Roberts and Geels 2019). The lock-in mechanisms of existing practices and systems tend to weaken in the third phase, either because competing innovations erode their economic viability, cultural legitimacy or institutional support (Turnheim and Geels 2012; Roberts 2017; Kuokkanen et al. 2018; Leipprand and Flachsland 2018) or because exogenous shocks and pressures disrupt the status quo (Kungl and Geels 2018; Simpson 2019).

In the fourth phase, the diffusing innovations replace or substantially reconfigure existing practices and systems, which may lead to the downfall or reorientation of incumbent firms (Bergek et al. 2013; McMeekin et al. 2019). The new system becomes institutionalised and anchored in professional standards, technical capabilities, infrastructures, educational programs, regulations and institutional logics, user habits, and views of normality, which create new lock-ins (Galaskiewicz 1985; Shove and Southerton 2000; Barnes et al. 2018)

Avoid, shift and improve options vary with regard to the four transition phases. Incremental 'improve' options, such as energy-efficient appliances or stand-alone insulation measures, are not transitions but upgrades of existing technologies. They have progressed furthest since they build on existing knowledge and do not require wider changes (Geels et al. 2018). Some radical 'improve' options, which have a different technological knowledge base, are beginning to diffuse, moving from phase two to three in multiple countries. Examples are electric vehicles, light-emitting diodes, or passive house designs (Franceschini and Alkemade 2016; Berkeley et al. 2017). Many 'shift' and 'avoid/reduce' options like heat pumps, district heating, passive house designs, compact cities, less meat initiatives, flight and car use reduction have low momentum in most countries, and are mostly in the first phase of isolated initiatives and projects (Bergman 2013; Morris et al. 2014; Bows-Larkin 2015; Bush et al. 2016; Kivimaa and Martiskainen 2018; Hoolohan et al. 2018). Structural transitions in Dutch cities, Copenhagen, and more recently Paris, however, demonstrate that transitions towards low-carbon lifestyles, developed around cycling, are possible (Colville-Andersen 2018). Low-carbon demand-side transitions are often still in early phases (*high evidence, high agreement*).

5.5.3 Feasible rate of change

Transitional change is usually slow in the first and second transition phase, because experimentation, social and technological learning, and stabilisation processes take a long time, often decades, and remain restricted to small niches (*high confidence*) (Wilson 2012; Bento 2013; Bento et al. 2018b).

Transitional change accelerates in the third phase, as radical innovations diffuse from initial niches into mainstream markets, propelled by the self-reinforcing mechanisms, discussed above. The rate of adoption (diffusion) of new practices, processes, artefacts, and behaviours is determined by a wide range of factors at the macro- and micro-scales, which have been identified by several decades of diffusion research in multiple disciplines (for comprehensive reviews see, e.g. (Mansfield 1968; Martino et al. 1978; Davis 1979; Mahajan et al. 1990; Ausubel 1991; Grubler 1991; Feder and Umali 1993; Bayus 1994; Comin and Hobijn 2003; Rogers 2003; Van den Bulte and Stremersch 2004; Meade and Islam 2006; Peres et al. 2010)).

Diffusion rates are determined by two broad categories of variables, those intrinsic to the technology/product/practice under consideration (typically performance, costs, benefits), and those intrinsic to the adoption environment (e.g., socio-economic and market characteristics).
Despite differences, the literature offers three robust conclusions on acceleration (*high evidence, high agreement*): First, size matters. Acceleration of transitions is more difficult for social, economic, or technological systems of larger size (in terms of number of users, financial investments, infrastructure, powerful industries) (Wilson 2009, Wilson 2012). Size also matters at the level of the systems component involved in a transition. Components with smaller unit-scale ("granular" and thus relatively cheap), such as light bulbs or household appliances, turn over much faster (often within a decade) than large-scale, capital-intensive lumpy technologies and infrastructures (such as transport systems) where rates of change involve typically several decades, even up to a century (Grubler 1991; Leibowicz 2018). Also, the creation of entirely new systems (diffusion) takes longer time than replacements of existing technologies/practices (substitution) (Grübler et al. 1999); and late adopters tend to adopt faster than early pioneers (Wilson 2012; Grubler 1996).

Arguments about scale in the energy system date back at least to the 1970s when Schumacher, Lovins and others argued the case for smaller-scale, distributed technologies (Schumacher 1974; Lovins 1976, 1979). In 'Small is Profitable' Lovins and colleagues evidenced over 200 reasons why decentralised energy resources, from distributed generation to end-use efficiency, made good business sense in addition to their social, human-centred benefits (Lovins et al. 2003). More recent advances in digital, solar and energy storage technologies have renewed technical and economic arguments in favour of adopting decentralised approaches to decarbonisation (Cook et al. 2016; Jain et al. 2017; Lovins et al. 2018). Smaller-scale technologies from microprocessors to solar panels show dramatically faster cost and performance improvement trajectories than large-scale energy supply facilities (Trancik 2014; Sweerts et al. 2020, Creutzig et al, 2021, Fig. 5.15). Analysing the performance of over 80 energy technologies historically, Wilson et al. (2020) found that smaller scale, more 'granular' technologies are empirically associated with faster diffusion, lower investment risk, faster learning, more opportunities to escape lock-in, more equitable access, more job creation, and higher social returns on innovation investment. These advantages of more granular technologies are consistent with accelerated low-carbon transformation (Wilson et al. 2020a).

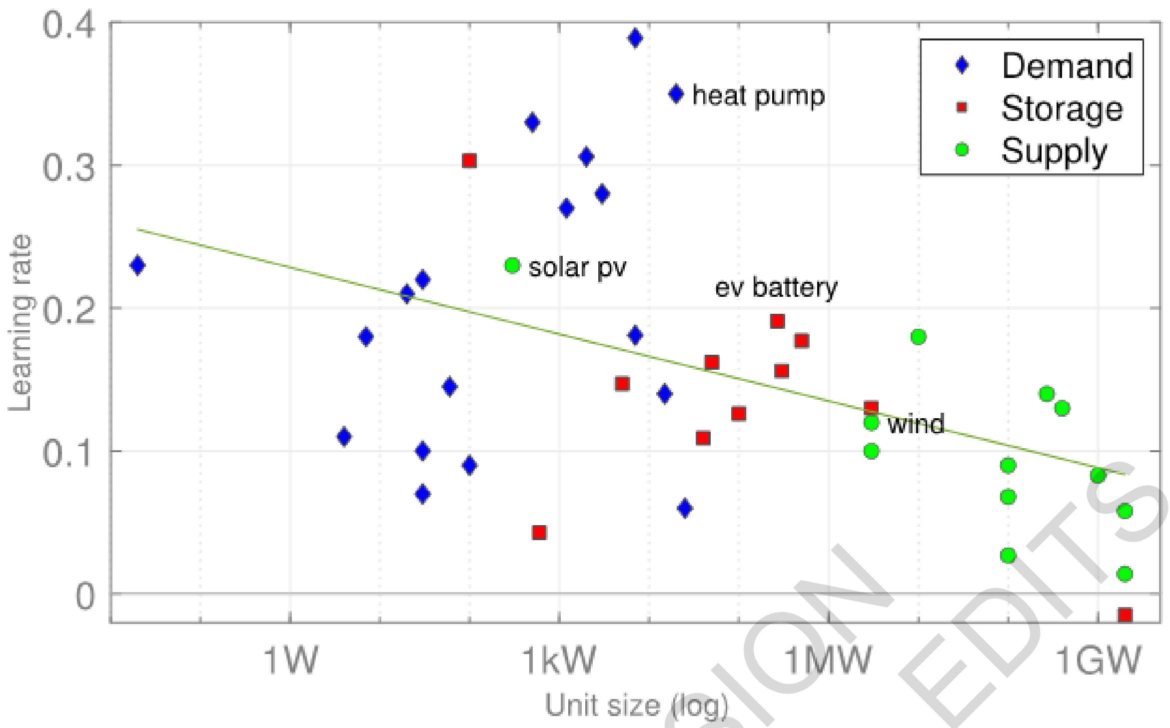

Figure 5.15 Demand technologies show high learning rates. Learning from small-scale granular technologies outperforms learning in larger supply side technologies. Line is linear fit of log unit size to learning rate for all 41 technologies plotted.

Source: Creutzig et al, 2021; based on Sweerts et al 2020.

Second, complexity matters, which is often related to unit-scale (Ma et al. 2008). Acceleration is more difficult for options with higher degrees of complexity (e.g., carbon capture, transport and storage, or a hydrogen economy) representing higher technological and investment risks that can slow down change. Options with lower complexity are easier to accelerate because they involve less experimentation and debugging and require less adoption efforts and risk.

Third, agency, structure and meaning can accelerate transitions. The creation and mobilisation of actor coalitions is widely seen as important for acceleration, especially if these involve actors with technical skills, financial resources and political capital (Kern and Rogge 2016; Hess 2019b; Roberts and Geels 2019). Changes in policies and institutions can also accelerate transitions, especially if these create stable and attractive financial incentives or introduce technology-forcing standards or regulations (Brand et al. 2013; Kester et al. 2018; Roberts et al. 2018). Changes in meanings and cultural norms can also accelerate transitions, especially when they affect consumer practices, enhance social acceptance, and create legitimacy for stronger policy support (Lounsbury and Glynn 2001; Rogers 2003; Buschmann and Oels 2019). Adoption of most advanced practices can support leapfrogging polluting technologies (Box 5.9).

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Box 5.9 Is leapfrogging possible?

The concept of leapfrogging emerged in development economics (Soete 1985), energy policy (Goldemberg 1991) and environmental regulation (Perkins 2003), which provides a first critical review of the concept), and refers to a development strategy that skips traditional and polluting development in favour of the most advanced concepts. For instance, in rural areas without telephone landlines or electricity access (cables), a direct shift to mobile telephony or distributed, locally-sourced energy systems is promoted, or economic development policies for pre-industrial economies forego the traditional initial emphasis of heavy industry industrialisation, instead of focusing on services like finance or tourism. Often leapfrogging is enabled by learning and innovation externalities where improved knowledge and technologies become available for late adopters at low costs. The literature highlights many cases of successful leapfrogging but also highlights limitations (for a review see Watson and Sauter (Watson and Sauter 2011); with example case studies for China e.g. Gallagher (Gallagher 2006) or Chen and Li-Hua (Chen and Li-Hua 2011); Mexico (Gallagher and Zarsky 2007); or Japan and Korea, e.g. Cho et al. (Cho et al. 1998). Increasingly the concept is being integrated into the literature of low-carbon development, including innovation and technology transfer policies (for a review see Pigato (Pigato et al. 2020)), highlighting in particular the importance of contextual factors of successful technology transfer and leapfrogging including: domestic absorptive capacity and technological capabilities (Cirera and Maloney 2017); human capital, skills, and relevant technical know-how (Nelson and Phelps 1966); the size of the market (Keller 2004); greater openness to trade (Sachs and Warner 1995; Keller 2004); geographical proximity to investors and financing (Comin et al. 2012); environmental regulatory proximity (Dechezleprêtre et al. 2015); and stronger protection of intellectual property rights (Dechezleprêtre et al. 2013; Dussaux et al. 2017). The existence of a technological potential for leapfrogging therefore needs to be considered within a wider context of social, institutional, and economic factors that influence if leapfrogging potentials can be realised (*high evidence, high agreement*).

END BOX 5.9 HERE

There are also some contentious topics in the debate on accelerated low-carbon transitions. First, while acceleration is desirable to mitigate climate change, there is a risk that accelerating change too much may short-cut crucial experimentation and social and technological learning in "formative phases" (Bento 2013; Bento et al. 2018b) and potentially lead to a pre-mature lock-in of solutions that later turn out to have negative impacts (Cowan 1990, 1991) (*high evidence, medium agreement*).

Second, there is an ongoing debate about the most powerful leverage points and policies for speeding up change in social and technological systems. Farmer et al. 2019 suggested "sensitive intervention points" for low-carbon transitions, but do not quantify the impacts on transformations. Grubler et al. 2018 proposed an end-user and efficiency-focused strategy to achieve rapid emission reductions and quantified their scenario with a leading IAM. However, discussion of the policy implications of such a strategy have only just started (Wilson et al. 2019a) suggesting an important area for future research.
The last contentious issue is if policies can/should substitute for lack of economic/social appeal of change or for technological risks. Many large-scale supply-side climate mitigation options such as CCS or nuclear power involve high technological risks, critically depend on a stable carbon price, and are controversial in terms of social and environmental impacts (cf. the reviews in (Sovacool et al. 2014; Wilson et al. 2020a) and the comprehensive discussion in (Smith et al. 2016) *(high evidence, medium agreement*). There is continuing debate if and how policies could counterbalance these impacts in order to accelerate transitions (Nordhaus 2019; Lovins 2015). Some demand-side options like large-scale public transport infrastructures such as "Hyperloop" (Decker et al. 2017) or concepts such as "Asian Super Grid" (maglev fast train coupled with superconducting electricity transmission networks) (AIGC 2017) may face similar challenges, which adds weight and robustness to those demand-side options that are more decentralised, granular in scale and provide potential tangible consumer benefits besides being low-carbon (like more efficient buildings and appliances, "soft" urban mobility options (walking and cycling), digitalisation, among others, cf. Grubler et al. 2018).

A robust conclusion from this review is that there are no generic acceleration policies that are independent from the nature of what changes, by whom and how. Greater contextualisation and granularity in policy approaches is therefore important to address the challenges of rapid transitions towards zero-carbon systems *(high evidence, high agreement*).

5.6 Governance and policy

5.6.1 Governing mitigation: participation and social trust

In demand side mitigation, governance is key to drive the multidimensional changes needed to meet service needs within a society that provide people with a decent living while increasingly reducing resource and energy input levels (Rojas-Rueda et al. 2012; Batchelor et al. 2018; OECD 2019a). Impartial governance, understood as equal treatment of everyone by the rule of law, creates social trust and is thus a key enabler of inclusive and participatory demand-side climate policies (Rothstein 2011). Inclusive and broad-based participation itself also leads to greater social trust and thus is also a key enabler of demand-side climate mitigation (see Section 5.2 for details). Higher social trust and inclusive participatory processes also reduce inequality, restrain opportunistic behaviour and enhance cooperation (Drews and van den Bergh 2016; Gür 2020) (see also Section 5.2). Altogether, broad-based participatory processes are central to the successful implementation of climate policies (Rothstein and Teorell 2008; Klenert et al. 2018) (*high evidence , medium agreement)*. A culture of cooperation feeds back to increase social trust and enables action that reduce GHG emissions (Carattini et al. 2015; Jo and Carattini 2021), and requires including explicit consideration of the informal sector (Box 5.10). More equitable societies also have the institutional flexibility to allow for mitigation to advance faster, given their readiness to adopt locally appropriate mitigation policies; they also suffer less from policy lock-in (Tanner et al. 2009; Lorenz 2013; Chu 2015; Cloutier et al. 2015; Martin 2016; Vandeweerdt et al. 2016; Turnheim et al. 2018; Seto et al. 2016).

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Box 5.10 The informal sector and climate mitigation

The informal economy represents a large and growing portion of socio-economic activities (Charmes 2016; Muchie et al. 2016; Mbaye and Gueye 2018), including much of the work done by women worldwide. It accounts for an estimated 61% of global employment in the world; 90% in developing countries, 67% in emerging countries, and 18% in developed countries (Berik 2018), representing roughly 30% of GDP across a range of countries (Durán Heras 2012; Narayan 2017). Due to its importance, policies which support informal-sector climate mitigation activities may be extremely efficient (Garland and Allison M. 2015). For example, environmental and energy taxes may have negative gross costs when the informal sector dominates economic activity since these taxes indirectly tax the informal sector; informal production may substitute for energy-intensive goods, with strong welfare-enhancing effects (Bento et al. 2018a). The informal sector can assemble social and financial capital, create jobs, and build low-carbon local economies (Ruzek 2015). Constraints on small and informal-sector firms' ability to build climate resilience include financial and data barriers, limited access to information technology, and policy exclusion (Kraemer-Mbula and Wunsch-Vincent 2016; Crick et al. 2018a,b).

Informal-sector innovation is often underrated. It gives marginalised people access to welfare-enhancing innovations, building on alternative knowledge and socially-embedded reciprocal exchange (Jaffe and Koster 2019; Sheikh 2019; Sheikh and Bhaduri 2020). Large improvements in low-emission, locally-appropriate service provision are possible by facilitating informal-sector service providers' access to low-energy technologies (while taking care not to additionally burden the unpaid and marginalised), through such means as education, participatory governance, government policies to assist the informal sector, social services, healthcare, credit provision, and removing harmful policies and regulatory silos. The importance of the informal economy, especially in low-income countries, opens many possibilities for new approaches to DLS service provision along with climate resilience (Rynikiewicz and Chetaille 2006; Backstränd et al. 2010; Porio 2011; Kriegler et al. 2014; Taylor and Peter 2014; Brown and McGranahan 2016; Chu 2016; Boran 2019; Hugo and du Plessis 2019; Satterthwaite et al. 2018; Schröder et al. 2019; Javaid et al. 2020).

Public information and understanding of the CO_2-eq emissions implied by consumption patterns can unleash great creativity for meeting service needs fairly and with lower emissions (Darier and Schüle 1999; Sterman and Sweeney 2002; Lorenzoni et al. 2007; Billett 2010; Marres 2011; Zapico Lamela et al. 2011; Polonsky et al. 2012; Williams et al. 2019). Community-based mapping, social learning, green infrastructure development, and participatory governance facilitate such information-sharing (Tauhid and Zawani 2018; Mazeka et al. 2019; Sharifi 2020), strengthening mitigation policies (Loiter et al. 1999; Stokes and Warshaw 2017; Zhou et al. 2019).

Since informal settlements are usually dense, upgrading them supports low-carbon development pathways which leapfrog less-efficient housing, transport and other service provision, using locally-appropriate innovations (Satterthwaite et al. 2018). Examples of informal-sector mitigation include digital banking in Africa; mobility in India using recycled motors and collective transport; food production, meal provision, and reduction of food waste in Latin America (e.g. soup kitchens in Brazil, community kitchens in Lima, Peru); informal materials recycling, space heating and cooling, and illumination (Hordijk 2000; Baldez 2003; Maumbe 2006; Gutberlet 2008; Chaturvedi and Gidwani 2011; Nandy et al. 2015; Rouse and Verhoef 2016; Ackah 2017).

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5.6.2 Policies to strengthen Avoid-Shift-Improve

There is high untapped potential of demand-side mitigation options if considered holistically within the domains of avoid-shift-improve (Sections 5.3 and 5.4; Tables 5.1, 5.2, 5.3a, and 5.3b). Within the demand-side mitigation options opportunity space, policies currently focus more on efficiency and 'improve' options and relatively less on 'shift' and 'avoid' options (Dubois et al. 2019; Moberg et al. 2019). Current demand side policies are fragmented, piecemeal and too weak to drive demand-side transitions commensurate with 1.5ºC or 2ºC climate goals (Wilson et al. 2012; Fawcett et al. 2019; Mundaca et al. 2019; Moberg et al. 2019) (*high evidence, high agreement)*. However, increasingly policy mix in a number of countries has seen a rise in prohibitions on fossil fuel use as a way to weaken lock-ins, for example, in fossil fuel heating in favour of low carbon alternatives (Rosenbloom et al. 2020). Policies that are aimed at behaviour and lifestyle changes carry a perception of political risks for policy makers, which may explain why policy instruments focus more on information provision and adoption of incentives than on regulation and investment (Rosenow et al. 2017; Moberg et al. 2019). Acceleration of demand-side transitions would thus require both a broadening of demand-side options and the creation of comprehensive and targeted policy mixes (Kern et al. 2017; Rosenow et al. 2017; IPCC 2018) that strengthens five drivers of decision and action identified in Section 5.4, Table 5. and in the tables below *(high evidence, high agreement)*. Demand-side transitions in developing and emerging economies would also require stronger administrative capacity as well as technical and financial support (UN-Habitat 2013; Creutzig et al. 2016b).

Systematic categorisation of demand-side policy options in different sectors and services through the avoid-shift-improve (ASI) framework enables identification of major entry points and possible associated social struggles to overcome for the policy instruments/interventions as discussed below.

5.6.2.1 Avoid policies

There is high evidence and agreement that "Avoid' policies that affect lifestyle changes offer opportunities for cost-effective reductions in energy use and emissions, but would need to overcome political sensitivities around government efforts to shape and modify individual-level behaviour (see Table 5.5) (Grubb et al. 2020; Rosenow et al. 2017). These policies include ways to help avoid travel growth through integrated city planning or building retrofits to help avoid demand for transport, heating or cooling (Bakker et al. 2014; Lucon et al. 2014; de Feijter et al. 2019), which interact with existing infrastructure. Dense pedestrianised cities and towns and medium-density transit corridors are better placed to implement policies for car reductions than 'sprawled' cities characterised by low-density, auto-dependent and separated land uses (Seto et al. 2014; Newman and Kenworthy 2015; Newman et al. 2017; Bakker et al. 2014).

Cities face pressing priorities like poverty reduction, meeting basic services and building human and institutional capacity. These are met with highly accessible walkable and cyclable cities, connected with public transit corridors, enabling equal accessibility for all citizens, and enabling a high level of service provisioning (UN-Habitat 2013; Creutzig et al. 2016b). Infrastructure development costs less than for car dependent cities. However, it requires a mindset shift for urban and transport planners (*medium evidence, high agreement*).

Policies that support the avoidance of higher emission lifestyles and improve wellbeing are facilitated by the introduction of smart technologies, infrastructures and practices (Amini et al. 2019). They include regulations and measures for investment in high-quality ICT infrastructure, regulations to restrict number plates as well as company policy around flexible working conditions (Lachapelle et al. 2018; Shabanpour et al. 2018). Working-from-home arrangements may advantage certain segments of society such as male, older, higher educated and highly paid employees, potentially exacerbating existing inequalities in the labour market (Lambert et al. 2020; Bonacini et al. 2021). In the absence of distributive or other equity-based measures, the potential gains in terms of emissions reduction may therefore be counteracted by the cost of increasing inequality. This potential growth in inequality is likely to be more severe in poorer countries that will additionally suffer from a lack of international funding for achieving the SDGs (Barbier and Burgess 2020; UN 2020) (*high evidence, medium agreement*).

Table 5.5 Examples of policies to enable "avoid" options

Mitigation Option	Perceived struggles to overcome	Policy to overcome struggles (Incentives)
Reduce passenger km	Overcoming existing paradigms and planning practices and car dependency (Rosenow et al. 2017; Grubb et al. 2020).	Integrated city planning to avoid travel growth, car reduction, building retrofits to avoid heating or cooling demand (Bakker et al. 2014; Lucon et al. 2014; de Feijter et al. 2019).
	Financial and capacity barrier in many developing countries.	Public-private partnership to overcome financial barrier. (see Box 5.7) (Roy et al. 2018b).
	Status dimension of private cars	Taxation of status consumption; reframing of low-carbon transport as high status (Hoor 2020; Ramakrishnan and Creutzig 2021).

Reduce/avoid food waste	Little visible political and social momentum to prevent food waste in the Global North.	Strengthen national nutrition guidelines for health safety, Improve education/awareness on food waste; policies to eliminate ambiguous food labelling include well-defined and clear date labelling systems for food (Wilson et al. 2017); policies to support R&D to improve packaging to extend shelf life (Thyberg and Tonjes 2016). Charging according to how much food households throw away.
Reduce size of dwellings	Size of residents/dwelling getting smaller in many countries.	Compact city design, taxing residential properties with high per capita area, progressive taxation of high status consumption (Ramakrishnan and Creutzig 2021).
Reduce/avoid heating, cooling and lighting in dwellings	Change in individual behaviour in dress codes and working times	Temperature set point as norm; building energy codes that set building standards; bioclimatic or/and zero emissions; cities and buildings that incorporate features like daylighting and increased building depth, height, and compactness (Steemers 2003; Creutzig et al. 2016a).
Sharing economy for more service per product	Inclusivity and involvement of users in design. Digital divide, unequal access and unequal digital literacy (Pouri and Hilty 2018). Political or power relations among actors involved in the sharing economy (Curtis and Lehner 2019).	Lower prices for public parking, and subsidies towards the purchase of electric vehicles providers of electric vehicle (EV) sharing services were given subsidies towards the purchase of electric vehicles (Jung and Koo 2018).

5.6.2.2 Shift policies

As indicated in Table 5.6, 'Shift' policies have various forms such as the demand for low carbon materials for buildings and infrastructure in manufacturing and services and shift from meat-based protein, mainly beef, to plant-based diets of other protein sources (Willett et al. 2019; Ritchie et al. 2018; Springmann et al. 2016a) (*high evidence, high agreement*). Governments also play a direct role beyond nudging citizens with information about health and wellbeing. While the effectiveness of these policies on behaviour change overall may be limited (Pearson-Stuttard et al. 2017; Shangguan et al. 2019), there is some room for policy to influence actors upstream, i.e. industry and supermarkets which may give rise to longer-term, structural change.

Table 5.6 Examples of policies to enable "shift" options

Mitigation Option	Perceived struggles to overcome	Policy to overcome struggles (Incentives)
More walking, less car use, train rather air travel	Adequate infrastructure may be absent, speed a part of modern life.	Congestion charges (Pearson-Stuttard et al. 2017; Shangguan et al. 2019); deliberate urban design including cycling lanes, shared micromobility, and extensive cycling infrastructure; synchronised/integrated transport system & timetable . Fair street space allocation (Creutzig et al. 2020).

Multifamily housing,	Zonings that favour single family homes have been dominant in planning (Hagen 2016).	Taxation, relaxation of single-family zoning policies and land use regulation (Geffner 2017).
Shifting from meat to other protein	Minimal meat required for protein intake, especially in developing countries for population suffering from malnutrition and when plant-based protein is lacking(Garnett 2011; Sunguya et al. 2014; Behrens et al. 2017; Godfray et al. 2018); Dominance of market-based instruments limits governments' role to nudging citizens with information about health and wellbeing, and point-of-purchase labelling (Pearson-Stuttard et al. 2017; Shangguan et al. 2019).	Tax on meat/beef in wealthier countries and/or households (Edjabou and Smed 2013; Säll and Gren 2015). Nationally recommended diets (NRDs) (Behrens et al. 2017; Garnett 2011; Sunguya et al. 2014; Godfray et al. 2018).
Material-efficient product design, packaging	Resistance by architects and builders who might perceive risks with lean designs. Cultural/ social norms. Policy measures not keeping up with changes on the ground such as increased consumption of packaging.	Embodied carbon standards for buildings (IEA 2019c).
Architectural design with shading and ventilation	Lack of education, awareness and capacity for new thinking, local air pollution.	Incentives for increased urban density and incentives to encourage architectural forms with lower surface-to-volume ratios and increased shading support (Creutzig et al. 2016a).

Mobility services is one of the key areas where a combination of market-based and command-and-control measures have been implemented to persuade large numbers of people to get out of their automobiles and take up public transport and cycling alternatives (Gehl et al. 2011). Congestion charges are often complemented by other measures such as company subsidies for bicycles to incentivise the shift to public mobility services. Attracting people to public transport requires sufficient spatial coverage of transport with adequate level of provision, and good quality service at affordable fares (Sims et al. 2014; Moberg et al. 2019) (*high evidence, high agreement*). Cities such as Bogota, Buenos Aires and Santiago have seen rapid growth of cycling, resulting in an 6-fold of cyclists (Pucher and Buehler 2017). Broadly, the history and type of city determines how quickly the transition to public modes of transport can be achieved. For example, cities in developed countries enjoy an advantage in that network of high-quality public transport predating the advent of automobiles, whereas cities in less developed countries are latecomers in large-scale network infrastructure (Gota et al. 2019; UN-Habitat 2013).

5.6.2.3 Improve policies

'Improve' policies focus on the efficiency and enhancement of technological performance of services (Table). In mobility services, *'improve'* policies aim at improving vehicles, comfort, fuels, transport operations and management technologies; and in building, they include policies for improving efficiency of heating systems and retrofitting existing buildings. Efficiency *improvements* in electric cooking appliances, together with the ongoing decrease in prices of renewable energy technologies, is opening policy opportunities to support households to adopt electrical cooking at mass scale (IEA 2017c; Puzzolo et al. 2019) (*medium evidence, medium agreement*). These actions towards cleaner energy for cooking often come with cooking-related reduction of GHG emissions, even though the extent of the reductions is highly dependent on context and technology and fuel pathways (Martínez et al. 2017; Mondal et al. 2018; Rosenthal et al. 2018; Serrano-Medrano et al. 2018; Hof et al. 2019) (*high evidence, high agreement*) (see Box 5.6).

Table 5.7 Examples of policies to enable "improve" options

Mitigation Option	Perceived struggles to overcome	Policy to overcome struggles (Incentives)
Lightweight vehicle, hydrogen car, electric vehicles, ecodriving	Adequate infrastructure may be absent, speed a part of modern life.	Monetary incentives and traffic regulations favouring EVs; investment in public charging infrastructure; car purchase tax calculated by a combination of weight, CO_2 and NOx emissions (Haugneland and Kvisle 2015; Globisch et al. 2018; Gnann et al. 2018; Lieven and Rietmann 2018; Rietmann and Lieven 2019).
Use low carbon materials in dwelling design	Manufacturing and R&D costs, recycling processes and aesthetic performance (Orsini and Marrone 2019). Access to secondary materials in the building sector (Nußholz et al. 2019).	Increasing recycling of construction and demolition waste; Incentives must be available to companies in the waste collection and recovery markets to offer recovered material at higher value (Nußholz et al. 2019).
Better insulation and retrofitting	Policies to advance retrofitting and GHG emission reductions in buildings are laden with high expectations since they are core components of politically ambitious city climate targets (Haug et al. 2010). Bringing building owners to implement measures identified in auditing results Lack of incentive for building owners to invest in higher efficiency than required norms (Trencher et al. 2016).	Grants and loans through Development Banks, building and heating system labels, and technical renovation requirements to continuously raise standards (Ortiz et al. 2019; Sebi et al. 2019); disclosure of energy use, financing and technical assistance (Sebi et al. 2019).
Widen low carbon energy access	Access to finance, capacity, robust policies, affordability for poor households for off-grid solutions until recently (Rolffs et al. 2015; Fuso Nerini et al. 2018; Mulugetta et al. 2019).	Feed-in-tariffs and auctions to stimulate investment. Pay-as-you-go (PAYG) end-user financing scheme where customers pay a small up-front fee for the equipment, followed by monthly payments, using mobile payment system (Yadav et al. 2019; Rolffs et al. 2015).
Improve illumination related emission	Supply side solution for low carbon electricity provision.	Building energy codes that set building standards; grants and other incentives for R&D.
Improve efficiency of cooking appliances	Reliability of power in many countries is not guaranteed; electricity tariff is high in many countries; cooking appliances are mostly imported using scarce foreign currency.	Driven by a combination of government support for appliance purchases, shifting subsidies from kerosene or LPG to electricity; community-level consultation and awareness campaigns about the hazards associated with indoor air pollution from the use of fuelwood, coal and kerosene, as well as education on the

		multiple benefits of electric cooking (Yangka and Diesendorf 2016; Martínez-Gómez et al. 2016; Gould and Urpelainen 2018; Dendup and Arimura 2019; Pattanayak et al. 2019; Martínez et al. 2017).
Shift to LED lamp	People spend increasing amounts of time indoors, with heavy dependence on and demand for artificial lighting environment (Ding et al. 2020).	Government Incentive, utility incentive (Bertoldi et al. 2021). EU bans on directional and non-directional halogen bulbs (Franceschini et al. 2018).
Solar water heating	Dominance of incumbent energy source i.e. electricity; cheap conventional energy; high initial investment costs and long payback (Joubert et al. 2016).	Subsidy for solar heaters (Li et al. 2013; Bessa and Prado 2015; Sgouridis et al. 2016).

Table 5.7 highlights the significant progress made in the uptake of the Electrical Vehicle (EV) in Europe, driven by a suite of incentives and policies. Increased activity in widening Electric Vehicle (EV) use is also occurring in developing countries. The Indian Government's proposal to reach the target of a 100% electric vehicle fleet by 2030 has stimulated investment in charging infrastructure that can facilitate diffusion of larger EVs (Dhar et al. 2017). Although the proposal was not converted into a policy, India's large and growing two-wheeler market has benefitted from the policy attention on EVs , showing a significant potential for increasing the share of electric two-and three-wheelers in the short-term (Ahmad and Creutzig 2019). Similar opportunities exist for China where e-bikes have replaced car trips and are reported to act as intermediate links in multimodal mobility (Cherry et al. 2016).

In recent years, policy interest has arisen to address the energy access challenge in Africa using low-carbon energy technologies to meet energy for poverty reduction and climate action simultaneously (Rolffs et al. 2015; Fuso Nerini et al. 2018; Mulugetta et al. 2019). This aspiration has been bolstered on the technical front by significant advances in appliance efficiency such as light-emitting diode (LED) technology, complemented by the sharp reduction in the cost of renewable energy technologies, and largely driven by market stimulating policies and public R&D to mitigate risks (Alstone et al. 2015; Zubi et al. 2019) (*high evidence, high agreement*).

5.6.3 Policies in transition phases

Demand-side policies tend to vary for different transition phases (*high evidence, high agreement*) (Sandin et al. 2019; Roberts and Geels 2019). In the first phase, which is characterised by the emergence or introduction of radical innovations in small niches, policies focus on: a) supporting R&D and demonstration projects to enable learning and capability developments, b) nurturing the building of networks and multi-stakeholder interactions, and c) providing future orientation through visions or targets (Brown et al. 2003; López-García et al. 2019; Roesler and Hassler 2019). In the second phase, the policy emphasis shifts towards upscaling of experiments, standardisation, cost reduction, and the creation of early market niches (Ruggiero et al. 2018; Borghei and Magnusson 2018). In the third and later phases, comprehensive policy mixes are used to stimulate mass adoption, infrastructure creation, social acceptance and business investment (Fichter and Clausen 2016; Strauch 2020; Geels et al. 2018). In the fourth phases, transitions can also be stimulated through policies that weaken or phase-out existing regimes such as removing inefficient subsidies (for cheap petrol or fuel oil) that encourage wasteful consumption, increasing taxes on carbon-intensive products and practices (Box 5.11), or substantially tightening regulations and standards (Kivimaa and Kern 2016; David 2017; Rogge and Johnstone 2017).

START BOX 5.11 HERE

Box 5.11: Carbon pricing and fairness

Whether the public supports specific policy instruments for reducing greenhouse gas emissions is determined by cultural and political world views (Alberini et al. 2018; Cherry et al. 2017; Kotchen et al. 2017) and national position in international climate negotiations with major implications for policy design. For example, policy proposals need to circumvent "solution aversion": that is, individuals are more doubtful about the urgency of climate change mitigation if the proposed policy contradicts their political worldviews (Campbell and Kay 2014). While there are reasons to believe that carbon pricing is the most efficient way to reduce emissions, a recent literature – focusing on populations in Western Europe and North America and carbon taxes – documents that efficiency feature alone is not what makes citizens like or dislike carbon pricing schemes (Kallbekken et al. 2011; Carattini et al. 2017; Klenert et al. 2018).

Citizens tend to ignore or doubt the idea that pricing carbon emissions reduces GHG emissions (Kallbekken et al. 2011; Douenne and Fabre 2019; Maestre-Andrés et al. 2019). Further, citizens have fairness concerns about carbon pricing (Büchs and Schnepf 2013; Douenne and Fabre 2019; Maestre-Andrés et al. 2019), even if higher carbon prices can be made progressive by suitable use of revenues (Rausch et al. 2011; Williams et al. 2015; Klenert and Mattauch 2016). There are also non-economic properties of policy instruments that matter for public support: Calling a carbon price a "CO_2 levy" alleviates solution aversion (Kallbekken et al. 2011; Carattini et al. 2017). It may be that the word "tax" evokes a feeling of distrust in government and may have high costs, low benefits and distributional effects (Strand 2020). Trust in politicians is negatively correlated with higher carbon prices (Hammar and Jagers 2006; Rafaty 2018) and political campaigns for a carbon tax can lower public support for them (Anderson et al. 2019). Few developing countries have adopted carbon taxes, probably due to high costs, relatively low benefits, and distributional effects (Strand 2020).

To address these realities regarding support for carbon pricing, some studies have examined whether specific uses of the revenue can increase public support for higher carbon prices (Carattini et al. 2017; Beiser-McGrath and Bernauer 2019). Doubt about the environmental effectiveness of carbon pricing may be alleviated if revenue from carbon pricing is earmarked for specific uses (Kallbekken et al. 2011; Carattini et al. 2017) and higher carbon prices may then be supported (Beiser-McGrath and Bernauer 2019). This is especially the case for using the proceeds on "green investment" in infrastructure or energy efficiency programmes (Kotchen et al. 2017). Further, returning the revenues to individuals in a salient manner may increase public support and alleviate fairness proposals, given sufficient information (Carattini et al. 2017; Klenert et al. 2018). Perceived fairness is one of the strongest predictors of policy support (Jagers et al. 2010; Whittle et al. 2019).

END BOX 5.11 HERE

5.6.4 Policy sequencing and packaging to strengthen enabling conditions

Policy coordination is critical to manage infrastructure interdependence across sectors, and to avoid trade-off effects (Raven and Verbong 2007; Hiteva and Watson 2019), specifically requiring the consideration of interactions among supply-side and demand-side measures (Kivimaa and Virkamäki 2014; Rogge and Reichardt 2016; de Coninck et al. 2018; Edmondson et al. 2019) (*high evidence, high*

agreement). For example, the amount of electricity required for cooking can overwhelm the grid which can lead to failure, causing end-users to shift back to traditional biomass or fossil fuels (Ateba et al. 2018; Israel-Akinbo et al. 2018); thus grid stability policies need to be undertaken in conjunction.
Policy makers operate in a politically dynamic national and international environment, and their policies often reflect their contextual situations and constraints with regards to climate-related reforms (Levin et al. 2012; Copland 2019), including differentiation between developed and developing countries (Beer and Beer 2014; Roy et al. 2018c) *(high evidence, high agreement).* Variables such as internal political stability, equity, informality (Box 5.10), macro-economic conditions, public debt, governance of policies, global oil prices, quality of public services, and the maturity of green technologies play important roles in determining policy directions.

Sequencing policies appropriately is a success factor for climate policy regimes (*high evidence, high agreement*). In most situations policy measures require a preparatory phase that prepares the ground by lowering the costs of policies, communicating the costs and benefits to citizens, and building coalitions for policies, thus reducing political resistance (Meckling et al. 2017). This policy sequencing aims to incrementally relax or remove barriers over time to enable significant cumulative increases in policy stringency and create coalitions that support future policy development (Pahle et al. 2018). German policies into renewables began with funding for RD&D, then subsidies for demonstration projects during the 1970s and 1980s, and continued to larger-scale projects such as 'Solar Roofs' programmes in the 1990s, including the scaled-up FITs for solar power (Jacobsson and Lauber 2006). These policies led to industrial expansion in wind and solar energy systems, giving rise to powerful renewables interest coalitions that defend existing measures and lend political support for further action. Policy sequencing has also been deployed to introduce technology bans and strict performance standards with a view to eliminate emissions as the end goal, and may the involve simultaneous support low carbon options while deliberately phasing out established technological regime (Rogge and Johnstone 2017).

As a key contending policy instrument, carbon pricing also requires embedding into policy packages *(high evidence, medium agreement).* Pricing may be regressive and perceived as additional costs by households and industry, making investments into green infrastructure politically unfeasible, as examples from France and Australia show (Copland 2019; Douenne and Fabre 2020). Reforms that would push up household energy expenses are often left aside for fear of how citizens, especially the poor, would react or cope with higher bills (Martinez and Viegas 2017; Tesfamichael et al. 2021) (*high evidence, medium agreement*). This makes it important to precede carbon pricing with investments into renewable energy and low carbon transport modes (Biber et al. 2017; Tvinnereim and Mehling 2018), and especially support developing countries by building up low-carbon energy and mobility infrastructures and technologies, thus reducing resistance to carbon pricing (Creutzig 2019). Additionally, carbon pricing receives higher acceptance if fairness and distributive consideration are made explicit in revenue distribution (see Box 5.11).

The effectiveness of a policy package is determined by design decisions as well as the wider governance context that include the political environment, institutions for coordination across scales, bureaucratic traditions, and judicial functioning (Howlett and Rayner 2013; Rogge and Reichardt 2013; Rosenow et al. 2016) (*high evidence, high agreement*). Policy packages often emerge through interactions between different policy instruments as they operate in either complementary or contradictory ways, resulting from conflicting policy goals (Cunningham et al. 2013; Givoni et al. 2013). An example includes the acceleration in shift from traditional biomass to the adoption of modern cooking fuel for 80 million households in rural India over a very short period of 4 years (2016-2020), which employed a comprehensive 'policy package' including financial incentives, infrastructural support and strengthening of the supply chain to induce households to shift towards a clean cooking fuel from the use of biomass (Kumar 2019). This was operationalised by creating a LPG supply chain by linking oil and gas companies with distributors to assure availability, create infrastructure for local storage along with an improvement of the rural road network, especially in the rural context (Sankhyayan and Dasgupta 2019). State governments initiated separate policies to increase the distributorship of LPG in their states (Kumar et al. 2016). Similarly, policy actions for scaling up electric vehicles need to be well designed and coordinated where EV policy, transport policy and climate policy are used together, working on different decision points and different aspects of human behaviour (Barton and Schütte 2017). The coordination of the multiple policy actions enables co-evolution of multiple outcomes that involve shifting towards renewable energy production, improving access to charging infrastructure, carbon pricing and other GHG measures (Wolbertus et al. 2018).

Design of policy packages should consider not only policies that support low carbon transitions but also those that challenge existing carbon-intensive regimes, generating not just policy "winners" but also "losers" (Carley and Konisky 2020) (*high evidence, high agreement*). The winners include low carbon innovators and entrepreneurs, while the potential losers include incumbents with vested interests in sustaining the status quo (Mundaca et al. 2018; Monasterolo and Raberto 2019). Low carbon policy packages would benefit from looking beyond climate benefits to include non-climate benefits such as health benefits, fuel poverty reductions and environmental co-benefits (Ürge-Vorsatz et al. 2014; Sovacool et al. 2020b). The uptake of decentralised energy services using solar PV in rural areas in developing countries is one such example where successful initiatives are linked to the convergence of multiple policies that include import tariffs, research incentives for R&D, job creation programmes, policies to widen health and education services, and strategies for increased safety for women and children (Kattumuri and Kruse 2019; Gebreslassie 2020).

The energy efficient lighting transition in Europe represents a good case of the formation of policy coalitions that led to the development of policy packages. As attention for energy efficiency in Europe increased in the 1990s, policymakers attempted to stimulate energy-saving lamp diffusion through voluntary measures. But policies stimulated only limited adoption. Consumers perceived CFLs as giving 'cold' light, being unattractively shaped, taking too long to achieve full brightness, unsuitable for many fixtures, and unreliable (Wall and Crosbie 2009). Still, innovations by major CFL and LED multinationals continued. Increasing political attention to climate change and criticisms from environmental NGOs (e.g. WWF, Greenpeace) strengthened awareness about the inefficiency of incandescent light bulbs (ILBs), which led to negative socio-cultural framings that associated ILBs with energy waste (Franceschini and Alkemade 2016). The combined pressures from the lighting industry, NGOs and member states led the European Commission to introduce the 2009 ban of ILBs of more than 80W, progressing to lower-wattage bans in successive years. While the ILB ban initially mainly boosted CFL diffusion, it also stimulated LED uptake. LED prices decreased quickly by more than 85% between 2008 and 2012 (Sanderson and Simons 2014), because of scale economies, standardisation and commoditisation of LED chip technology, and improved manufacturing techniques. Because of further rapid developments to meet consumer tastes, LEDs came to be seen as the future of domestic lighting (Franceschini et al. 2018). Acknowledging these changing views, the 2016 and 2018 European bans on directional and non-directional halogen bulbs explicitly intended to further accelerate the LED transition and reduce energy consumption for residential lighting.

In summary, more equitable societies are associated with high levels of social trust and enables action that reduce GHG emissions. To this end, people play an important role in the delivery of demand-side mitigation options within which efficiency and 'improve' options dominate. Policies that are aimed at behaviour and lifestyle changes come with political risks for policy makers. However, the potential exists for broadening demand-side interventions to include 'avoid' and 'shift' policies. Longer term thinking and implementation that involves careful sequencing of policies as well as designing policy packages that address multiple co-benefits would be critical to manage interactions among supply-side and demand-side options to accelerate mitigation.

5.7 Knowledge gaps

Knowledge gap 1: Better metric to measure actual human well-being

Knowledge on climate action that starts with the social practices and how people live in various environments, cultures, contexts and attempts to improve their well-being, is still in its infancy. In models, climate solutions remain supply-side oriented, and evaluated against GDP, without acknowledging the reduction in well-being due to climate impacts. GDP is a poor metric of human well-being, and climate policy evaluation requires better grounding in relation to decent living standards and or similar benchmarks. Actual solutions will invariably include demand, service provisioning and end use. Literature on how gender, informal economies mostly in developing countries, and solidarity and care frameworks translate into climate action, but also how climate action can improve the life of marginalised groups remains scarce. The working of economic systems under a well-being driven rather than GDP driven paradigm requires better understanding.

Knowledge gap 2: Evaluation of climate implication of the digital economy

The digital economy, as well as shared and circular economy, is emerging as template for great narratives, hopes and fears. Yet, there is few systematic evaluations of what is already happening and what can govern it towards a better narrative. Research needs to better gauge energy trends for rapidly evolving systems like data centres, increased use of social media and influence of consumption and choices, AI, blockchain, implication of digital divide among social groups and countries on well-being. Governance decisions on AI, indirectly fostering either climate harming or climate mitigating activities remain unexplored. Better integration of mitigation models and consequential life cycle analysis is needed for assessing how digitalisation, shared economy and circular economy change material and energy demand.

Knowledge gap 3: Scenario modelling of services

Scenarios start within parameter-rich models carrying more than a decade-long legacy of supply side technologies that are not always gauged in recent technological developments. Service provisioning systems are not explicitly modelled, and diversity in concepts and patterns of lifestyles rarely considered. A new class of flexible and modular models with focus on services and activities, based on variety of data sources including big data collected and compiled is needed. There is scope for more sensitivity analysis on two aspects to better guide further detailed studies on societal response to policy. These aspects need to explore which socio-behavioural aspects/ organisation changes has biggest impact on energy/emissions reductions, and on the scale for take-back effects, due to interdependence on inclusion or exclusion of groups of people. Models mostly consider behavioural change free, and don't account for how savings due to "avoid" measures may be re-spent. Most quantitatively measurable service indicators e.g. pkm or tkm are also inadequate to measure services in the sense of well-being contributions. More research is needed on how to measure e.g. accessibility, social inclusion etc. Otherwise services will also be poorly represented in scenarios.

Knowledge gap 4: Dynamic interaction between individual, social, and structural drivers of change

Better understanding is required on: (1) More detailed causal mechanisms in the mutual interactions between individual, social, and structural drivers of change and how these vary over time, i.e. what is their relative importance in different transition phases; (2) how narratives associated with specific technologies, group identities, and climate change influence each other and interact over time to enable and constrain mitigation outcomes; (3) how social media influences the development and impacts of narratives about low carbon transitions; (4) the effects of social movements (for climate justice, youth climate activism, fossil fuel divestment, and climate action more generally) on social norms and political change, especially in less developed countries; (5) how existing provisioning systems and social practices destabilise through the weakening of various lock-in mechanisms, and resulting deliberate strategies for accelerating demand-side transitions; (6) a dynamic understanding of feasibility, which addresses the dynamic mechanisms that lower barriers or drive mitigation options over the barriers. (7) how shocks like prolonged pandemic impacts willingness and capacity to change and their permanency for various social actors and country contexts. The debate on the most powerful leverage point/s and policies for speeding up change in social and technological systems need to be resolved with more evidence. Discussion on the policy interdependence and implications of end-user and efficiency focused strategies have only just started suggesting an important area for future research.

Frequently Asked Questions (FAQs)

FAQ 5.1 What can every person do to limit warming to 1.5°C?

People can be educated through knowledge transfer so they can act in different roles, and in each role everyone can contribute to limit global warming to 1.5°C. As citizens, with enough knowledge can organise and put political pressure on the system. Role models can set examples to others. Professionals (e.g., engineers, urban planners, teachers, researchers) can change professional standards in consistency with decarbonisation; e.g., urban planners and architects can design physical infrastructures to facilitate low-carbon mobility and energy use by making walking and cycling safe for children. Rich investors can make strategic plan to divest from fossils and invest in carbon-neutral technologies. As consumers, especially if one belongs to the top 10% of the world population in terms of income, can limit consumption, especially in mobility, and explore the good life consistent with sustainable consumption. Policy makers support individual actions in certain contexts not only by economic incentives, such as carbon pricing, but also by interventions that understand complex decision making processes, habits, and routines. Examples of such interventions include but are not limited to choice architectures and nudges that set green options as default, shift away from cheap petrol or gasoline, increasing taxes on carbon-intensive products, or substantially tightening regulations and standards support shifts in social norms, and thus can be effective beyond the direct economic incentive.

FAQ 5.2 How does society perceive transformative change?

Human induced global warming, together with other global trends and events, such as digitalisation and automation, and the COVID-19 pandemic, induces changes in labour markets, and bring large uncertainty and ambiguity. History and psychology reveal that societies can thrive in these circumstances if they openly embrace uncertainty on the future and try out ways to improve life. Tolerating ambiguity can be learned, e.g., by interacting with history, poetry and the arts. Sometimes religion and philosophy also help.

As a key enabler, novel narratives created in a variety of ways e.g., by advertising, images, entertainment industry, help to break away from the established meanings, values and discourses and the status quo. For example, discourses that frame comfortable public transport service to avoid stress from driving cars on busy, congested roads help avoid car driving as a status symbol and create a new social norm to shift to public transport. Discourses that portray plant based protein and as healthy and natural promote and stabilise particular diets. Novel narratives and inclusive processes help strategies to overcome multiple barriers. Case studies demonstrate that citizens support transformative changes if participatory processes enable a design that meets local interests and culture. Promising narratives specify that even as speed and capabilities differ humanity embarks on a joint journey towards well-being for all and a healthy planet.

FAQ 5.3 Is demand reduction compatible with growth of human well-being?

There is a growing realisation that mere monetary value of income growth is insufficient to measure national welfare and individual well-being. Hence, any action towards climate change mitigation is best evaluated against a set of indicators that represent a broader variety of needs to define individual well-being, macroeconomic stability, and planetary health. Many solutions that reduce primary material and fossil energy demand, and thus reduce GHG emissions, provide better services to help achieve well-being for all.

Economic growth measured by total or individual income growth is a main driver of GHG emissions. Only a few countries with low economic growth rates have reduced both territorial and consumption-based GHG emissions from, typically by switching from fossil fuels to renewable energy and by reduction in energy low/zero carbon fuels, but until now at insufficient rates and levels for stabilising global warming at 1.5°C. High deployment of low/zero carbon fuels and associated rapid reduction in demand and use of coal, gas, and oil can further reduce the interdependence between economic growth and GHG emissions.

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Chapter 6: Energy Systems

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Date of Draft: 27/11/2021

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Executive Summary

Warming cannot be limited to well below 2°C without rapid and deep reductions in energy system CO_2 and GHG emissions. In scenarios limiting likely warming to 1.5°C with limited overshoot (likely below 2°C), net energy system CO_2 emissions (interquartile range) fall by 87% to 97%% (60% to 79%) in 2050. In 2030, in scenarios limiting warming to 1.5°C with no or limited overshoot, net CO2 and GHG emissions fall by 35-51% and 38-52% respectively. In scenarios limiting warming to 1.5°C with no or limited overshoot (likely below 2°C), net electricity sector CO_2 emissions reach zero globally between 2045 and 2055 (2050 and 2080) *(high confidence)* {6.7}

Limiting warming to well below 2°C will require substantial energy system changes over the next 30 years. This includes reduced fossil fuel consumption, increased production from low- and zero-carbon energy sources, and increased use of electricity and alternative energy carriers. Coal consumption without CCS falls by 67% to 82% (interquartile range) in 2030 in scenarios limiting warming to 1.5°C with no or limited overshoot. Oil and gas consumption fall more slowly. Low-carbon sources produce 93% to 97% of global electricity by 2050 in scenarios that limit likely warming to 2°C or below. In scenarios limiting warming to 1.5°C with no or limited overshoot (likely below 2°C), electricity supplies 48% to 58% (36% to 47%) of final energy in 2050, up from 20% in 2019. *(high confidence)* {6.7}

Net Zero energy systems will share common characteristics, but the approach in every country will depend on national circumstances. Common characteristics of net zero energy systems will include: (1) electricity systems that produce no net CO_2 or remove CO_2 from the atmosphere; (2) widespread electrification of end uses, including light-duty transport, space heating, and cooking; (3) substantially lower use of fossil fuels than today (4) use of alternative energy carriers such as hydrogen, bioenergy, and ammonia to substitute for fossil fuels in sectors less amenable to electrification; (5) more efficient use of energy than today; (6) greater energy system integration across regions and across components of the energy system; and (7) use of CO_2 removal (e.g., DACCS, BECCS) to offset any residual emissions. (*high confidence*) {6.6}

Energy demands and energy sector emissions have continued to rise. From 2015 to 2019, global final energy consumption grew by 6.6%, CO_2 emissions from the global energy system grew by 4.6%, and total GHG emissions from energy supply rose by 2.7%. Methane emissions, mainly fugitive emissions from oil, gas, and coal, accounted for 18% of GHG emissions in 2019. Coal electricity capacity grew by 7.6% between 2015 and 2019, as new builds in some countries offset declines in others. Total consumption of oil and oil products increased by 5%, and natural gas consumption grew by 15%. Declining energy intensity in almost all regions has been balanced by increased energy consumption. (*high confidence*) {6.3}

Prices have dropped rapidly over the last five years for several key energy system mitigation options, notably solar PV, wind power, and batteries. From 2015 to 2020, the prices of electricity from PV and wind dropped 56% and 45%, respectively, and battery prices dropped by 64%. Electricity from PV and wind is now cheaper than electricity from fossil sources in many regions, electric vehicles are increasingly competitive with internal combustion engines, and large-scale battery storage on electricity grids is increasingly viable. (*high confidence*) {6.3, 6.4}

Global wind and solar PV capacity and generation have increased rapidly. Solar PV grew by 170% (to 680 TWh); wind grew by 70% (to 1420 TWh) from 2015 to 2019. Policy, societal pressure to limit fossil generation, low interest rates, and cost reductions have all driven wind and solar PV deployment. Solar PV and wind together accounted for 21% of total low-carbon electricity generation and 8% of total electricity generation in 2019. Nuclear generation grew 9% between 2015 and 2019 and accounted for 10% of total generation in 2019 (2790 TWh); hydroelectric power grew by 10% and accounted for

16% (4290 TWh) of total generation. In total, low- and zero-carbon electricity generation technologies produced 37% of global electricity in 2019. (*high confidence*) {6.3, 6.4}

If investments in coal and other fossil infrastructure continue, energy systems will be locked-in to higher emissions, making it harder to limit warming to well below 2°C. Many aspects of the energy system – physical infrastructure; institutions, laws, and regulations; and behaviour – are resistant to change or take many years to change. New investments in coal-fired electricity without CCS are inconsistent with limiting warming to well below 2°C. (*high confidence*) {6.3, 6.7}

Limiting warming to well below 2°C will strand fossil-related assets, including fossil infrastructure and unburned fossil fuel resources. The economic impacts of stranded assets could amount to trillions of dollars. Coal assets are most vulnerable over the coming decade; oil and gas assets are more vulnerable toward mid-century. CCS can allow fossil fuels to be used longer, reducing potential stranded assets. *(high confidence)* {6.7}

A low-carbon energy transition will shift investment patterns and create new economic opportunities. Total energy investment needs will rise, relative to today, over the next decades, if likely warming is limited to 2°C or below. These increases will be far less pronounced, however, than the reallocations of investment flows that are likely to be seen across sub-sectors, namely from fossil fuels (extraction, conversion, and electricity generation) without CCS and toward renewables, nuclear power, CCS, electricity networks and storage, and end-use energy efficiency. A significant and growing share of investments between now and 2050 will be made in emerging economies, particularly in Asia. (*high confidence*) {6.7}

Climate change will affect many future local and national low-carbon energy systems. The impacts, however, are uncertain, particularly at the regional scale. Climate change will alter hydropower production, bioenergy and agricultural yields, thermal power plant efficiencies, and demands for heating and cooling, and it will directly impact power system infrastructure. Climate change will not affect wind and solar resources to the extent that it would compromise their ability to reduce emissions. (*high confidence*) {6.5}

Electricity systems powered predominantly by renewables will be increasingly viable over the coming decades, but it will be challenging to supply the entire energy system with renewable energy. Large shares of variable solar PV and wind power can be incorporated in electricity grids through batteries, hydrogen, and other forms of storage; transmission; flexible non-renewable generation; advanced controls; and greater demand-side responses. Because some applications (e.g., air travel) are not currently amenable to electrification, 100% renewable energy systems would likely need to include alternative fuels such as hydrogen or biofuels. Economic, regulatory, social, and operational challenges increase with higher shares of renewable electricity and energy. The ability to overcome these challenges in practice is not fully understood. *{high confidence}* {6.6}

Multiple energy supply options are available to reduce emissions over the next decade. Nuclear power and hydropower are already established technologies. Solar PV and wind are now cheaper than fossil-generated electricity in many locations. Bioenergy accounts for about a tenth of global primary energy. Carbon capture is widely used in the oil and gas industry, with early applications in electricity production and biofuels. It will not be possible to widely deploy all of these and other options without efforts to address the geophysical, environmental-ecological, economic, technological, socio-cultural, and institutional factors that can facilitate or hinder their implementation. (*high confidence*) {6.4}

Some mitigation options can provide more immediate and cost-effective emissions reductions than others, but a comprehensive approach will be required over the next ten years to limit warming to well below 2°C. There are substantial, cost-effective opportunities to reduce emissions rapidly in several sectors, including electricity generation and light-duty transportation. But near-term reductions in these sectors will not be sufficient to limit warming to well below 2°C. A broad-based approach across the energy sector will be necessary to reduce emissions over the next ten years and to set the stage for still deeper reductions beyond 2030. (*high confidence*) {6.4, 6.6, 6.7}

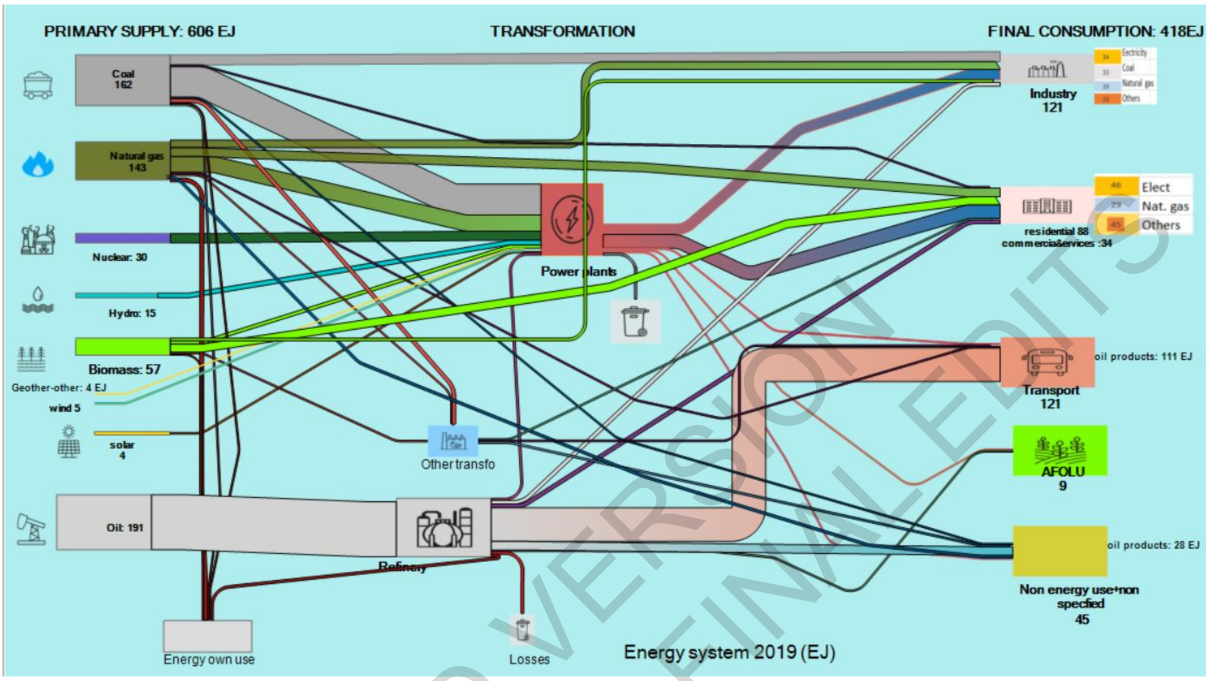
Enhanced integration across energy system sectors and across scales will lower costs and facilitate low-carbon energy system transitions. Greater integration between the electricity sector and end use sectors can facilitate integration of Variable Renewable Energy (VRE) options. Energy systems can be integrated across district, regional, national, and international scales. *(high confidence)* {6.4, 6.6}

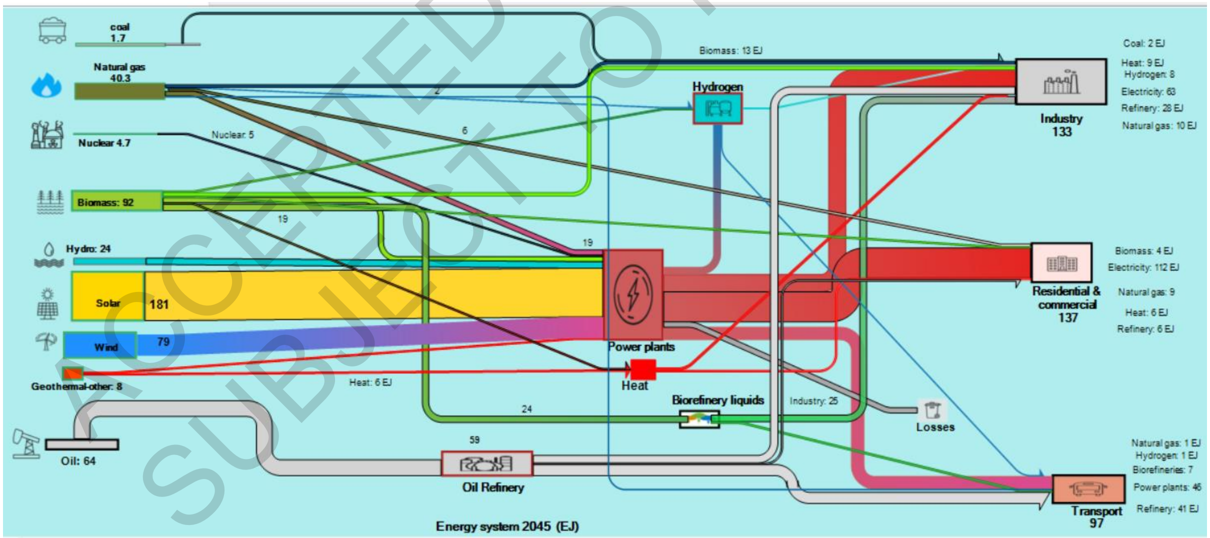
The viable speed and scope of a low-carbon energy system transition will depend on how well it can support sustainable development goals (SDGs) and other societal objectives. Energy systems are linked to a range of societal objectives, including energy access, air and water pollution, health, energy security, water security, food security, economic prosperity, international competitiveness, employment. These linkages and their importance vary among regions. Energy sector mitigation and efforts to achieve SDGs generally support one another, though there are important region-specific exceptions. *(high confidence)* {6.1, 6.7}

The economic outcomes of low-carbon transitions in some sectors and regions may be on par with, or superior to those of an emissions-intensive future. Cost reductions in key technologies, particularly in electricity and light-duty transport, have increased the economic attractiveness of near-term low-carbon transitions. Long-term mitigation costs are not well understood and depend on policy design and implementation, and the future costs and availability of technologies. Advances in low-carbon energy resources and carriers such as next-generation biofuels, hydrogen produced from electrolysis, synthetic fuels, and carbon-neutral ammonia would substantially improve the economics of net zero energy systems. (*medium confidence*) {6.4, 6.7}

6.1 Introduction

The global energy system is the largest source of CO_2 emissions (Chapter 2). Reducing energy sector emissions is therefore essential to limit warming. The energy systems of the future will be very different from those of today if the world successfully limits warming to well below 2°C. Energy will be provided, converted, and used in different ways than it is today (Figure 6.1). Achieving and responding to these changes presents an impressive range of challenges and opportunities.





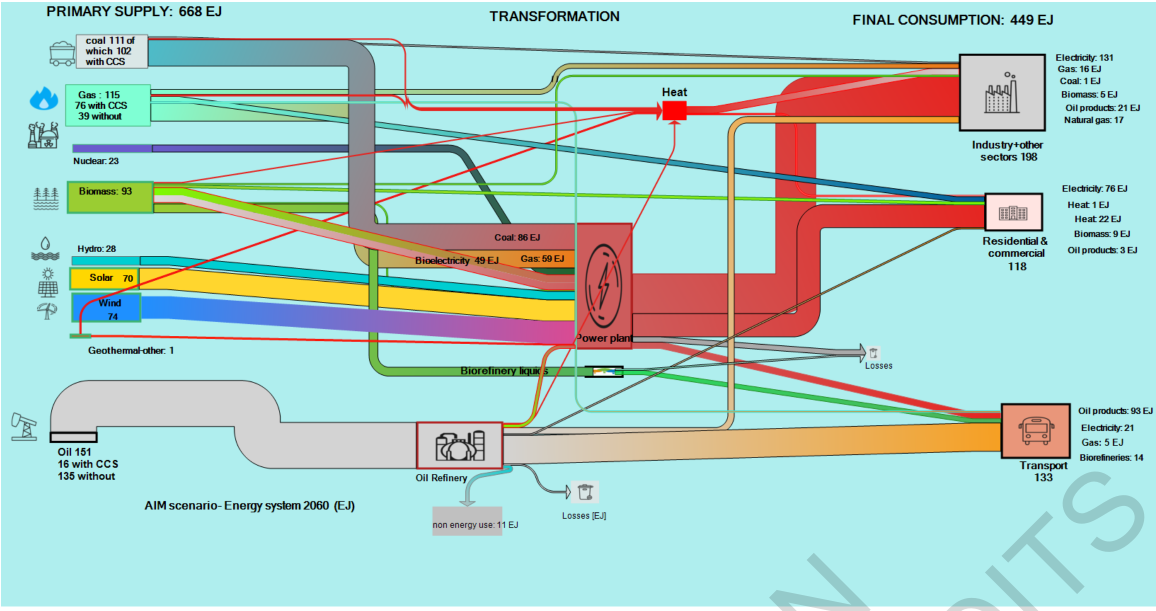


Figure 6.1 Global energy flows within the 2019 global energy system (top panel) and within two illustrative future, net zero CO2 emissions global energy system (bottom panels). Source: IEA, IPCC Database. Flows below 1 EJ are not represented, rounded figures. The illustrative net zero scenarios correspond to the years in which net energy system CO_2 emissions reach zero – 2045 in IP1 and 2060 in IP2. Source: IP1: Luderer et al.(2021); IP2: Riahi, K. et al., 2021;IP2

Within this context, this chapter has two main objectives. First, it aims to assess specific, individual mitigation options in energy supply, energy transformation, and energy transportation and transmission. This assessment is complementary to a set of chapters that explore mitigation options in agriculture, forestry, and other land uses (Chapter 7), urban systems and other settlements (Chapter 8), buildings (Chapter 9), transport (Chapter 10), industry (Chapter 11), and cross-sectoral perspectives (Chapter 12). Second, this chapter aims to assess system-level mitigation opportunities and challenges across the entirety of energy systems. These systems include energy supply, transformation, transmission, storage, transportation, and end-uses. They also include the societal systems that interact with the physical energy system. As energy systems become increasingly integrated and interconnected, a system-wide perspective is necessary for understanding mitigation opportunities and challenges.

Within this context, this chapter addresses six topics, each of which is addressed in a separate section. First, Section 6.2 defines the scope of the energy system. Section 6.3 then discusses the recent trends in energy systems that might exert the most significant influence on energy system evolution and options for reducing emissions. Section 6.4 assesses the status and potential of individual energy supply, transformation, storage, transportation and transmission, and integration mitigation options in the energy sector. Section 6.5 explores how climate change might affect energy systems and alter potential energy system mitigation options and strategies. Section 6.6 identifies key characteristics of net zero energy systems – those that emit very little or no CO_2. Section 6.7 explores transition pathways toward and through net zero energy systems. Across all of these sections, the chapter aims to explore the ways that energy sector mitigation options and strategies interact with SDGs and other societal and environmental goals.

6.2 The Scope of the Energy System and its Possible Evolution

For this chapter, energy systems are defined broadly to include both physical and societal elements. The physical infrastructure includes all the infrastructure and equipment used to extract, transform, transport, transmit, and convert energy to provide energy services. In addition to the physical system, a broad range of societal systems and dynamics are relevant to the energy system. Human societies use energy to transport themselves and the goods that they use and consume, to heat, cool, and light their homes, to cook their food, and to produce goods and services. Energy systems are therefore tied to the systems involved in the provision of these various goods and services. All energy users engage in the operation of energy systems by demanding energy at particular times and in particular forms. They can adjust their behaviour and demands, for example, by using less energy or by changing when they use energy. Consumers can invest in equipment that reduces their energy needs, and they can invest in technologies that transform energy (e.g., rooftop solar) or store energy (e.g., batteries). Firms and governments invest in equipment to produce, transform, and transport energy such as power plants, refineries, electric transmission lines, and oil tankers. All aspects of energy systems are governed by laws, regulations, and actual institutions that reside within businesses and governments at all levels. This includes, for example, rules for trading emissions permits, deciding when particular electricity generation technologies might come online, water management and related environmental rules that define the availability of hydropower or influence water availability for cooling power plants, regulations for injecting CO_2 into underground reservoirs or disposing of nuclear waste, and even company policies regarding work hours or teleworking, which can have important implications for energy demand profiles. Many people are employed in the energy sector, and energy system mitigation will eliminate some jobs while creating others.

This broader view of energy systems is essential for understanding energy system mitigation, as these broader societal and institutional factors can have an important influence on energy system transformations and the potential to rapidly reduce energy CO_2 emissions. Energy system mitigation is as much about the challenges of societal change as it is about the challenges of changes in physical infrastructure, technologies, and operations. While this chapter does not attempt to draw a specific boundary around all the different systems that interact with the energy system, it frequently explores these broader system interactions when assessing different mitigation options and strategies.

There is no single spatial scale at which energy systems might be defined and assessed. They can be assessed at the scales of homes, cities, states or provinces, countries, regions, or the entire world. These different scales are frequently both distinct with their own internal dynamics yet also connected to one another. This chapter most frequently assesses energy systems from the country and global perspective.

Because the energy system is so complex, it can be hard to define particular parts of it precisely, and there may be competing definitions in the literature. For the purposes of this chapter, "energy supply" encompasses all primary energy, conversion, and transmission processes with the exception of those that use final energy to provide energy services in the end-use sectors (transport, buildings, industry and agriculture). The "energy system" includes energy end uses sectors along with energy supply. "Low-emissions" is used for energy technologies that produce little CO_2 or no CO_2 or that remove CO_2 from the atmosphere. Similarly, "low-carbon" transitions is used to describe transitions that limit likely warming to 2°C or below. "Net-zero" energy systems refer to those that produce very little or no CO_2 or may even sequester CO_2 from the atmosphere.

6.3 Recent Energy System Trends and Developments

Global energy sector emissions continue to grow but at a decreasing rate

Current energy sector emissions trends, if continued, will not limit global temperature change to well below 2°C *(high confidence)*. Global energy system fossil fuel CO_2 emissions grew by 4.6% between 2015 and 2019 (1.1% yr^{-1}), reaching 38 $GtCO_2$ yr^{-1} and accounting for approximately two-thirds of annual global anthropogenic GHG emissions. In 2020, with the worldwide COVID pandemic, energy sector CO_2 emissions dropped by roughly 2 $GtCO_2$ yr^{-1} (Figure 6.2). However global energy-related CO_2 emissions are projected to rebound by nearly 5% in 2021, approaching the 2018-19 peak (IEA 2021d)

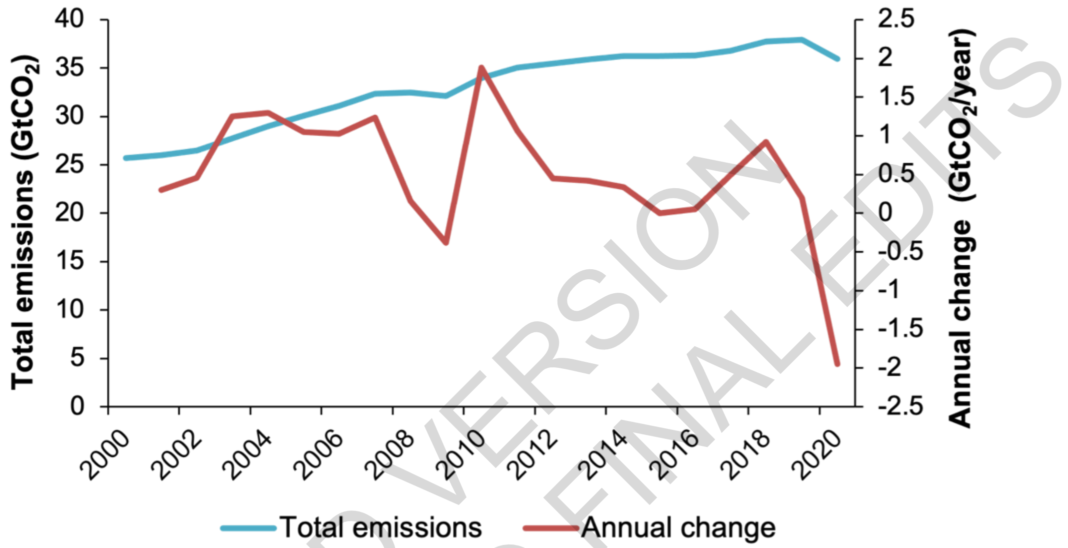


Figure 6.2 Global energy sector fossil fuel CO_2 emissions and annual change 2000-2019 ($MtCO_2$ yr^{-1}). (Source: adapted from (Minx et al. 2021a; Crippa et al. 2021)

Coal was the single largest contributor to energy sector CO_2 emissions between 2015 and 2019, accounting for about 44% of energy sector CO_2 emissions in 2019. Oil accounted for about 34% and natural gas accounted for about 22% of energy sector CO_2 emissions. Coal, oil and natural gas CO_2 emissions grew respectively by 1.2%, 2% and 12.7% (annual rates of 0.31%, 0.5% and 3%) (Figure 6.3). The electricity sector remains the single largest source of energy sector CO_2 emissions, accounting for about 36% in 2019, followed by industry at 22% and transport (excluding international shipping and aviation transport) at about 18% (Figure 6.3). Shipping and aviation accounted for a little over 3%. These proportions have remained relatively unchanged over the last decade. Recent trends reinforce the near-term challenges facing energy sector mitigation - electricity sector emissions continue to rise despite rapid deployment of wind and solar power (see below); transportation emissions continue to rise, and petroleum remains the dominant fuel, despite advances in batteries and electric cars (see below). Some specific sectors, such as shipping and aviation, may present longer-term challenges.

Energy supply GHG emissions, including CO_2 and non-CO_2 greenhouse gases, reached 20 $GtCO_2$-eq yr^{-1} in 2019, rising by 2.7% between 2015 and 2019 (0.66% yr^{-1}). Approximately 18% of energy supply emissions were non-CO_2 emissions. Electricity and heat contributed approximately 69% of total energy supply GHG emissions in 2019 (Figure 6.3). This growth has occurred despite the high penetration of solar PV and wind power, particularly in Asia and developed countries.

Fugitive emissions from fossil fuel production, primarily methane, accounted for about 18% of sector supply emissions in 2019, with 2.6 Gt CO_2eq yr^{-1} linked to oil and gas production and 1.3 Gt CO_2eq yr^{-}

[1] to coal mining (Crippa et al. 2021). Oil and gas operations produced 2.9 $GtCO_2eq\ yr^{-1}$ in 2019 (82 Mt yr^{-1} as methane), split roughly equally between the two (IEA 2020a). There remains a high degree of uncertainty in methane emissions estimates from oil and gas operations despite the emergence of new data from satellites and other measurement campaigns. According to a recent study (Hmiel et al. 2020), methane emissions are underestimated by about 25 to 40%.

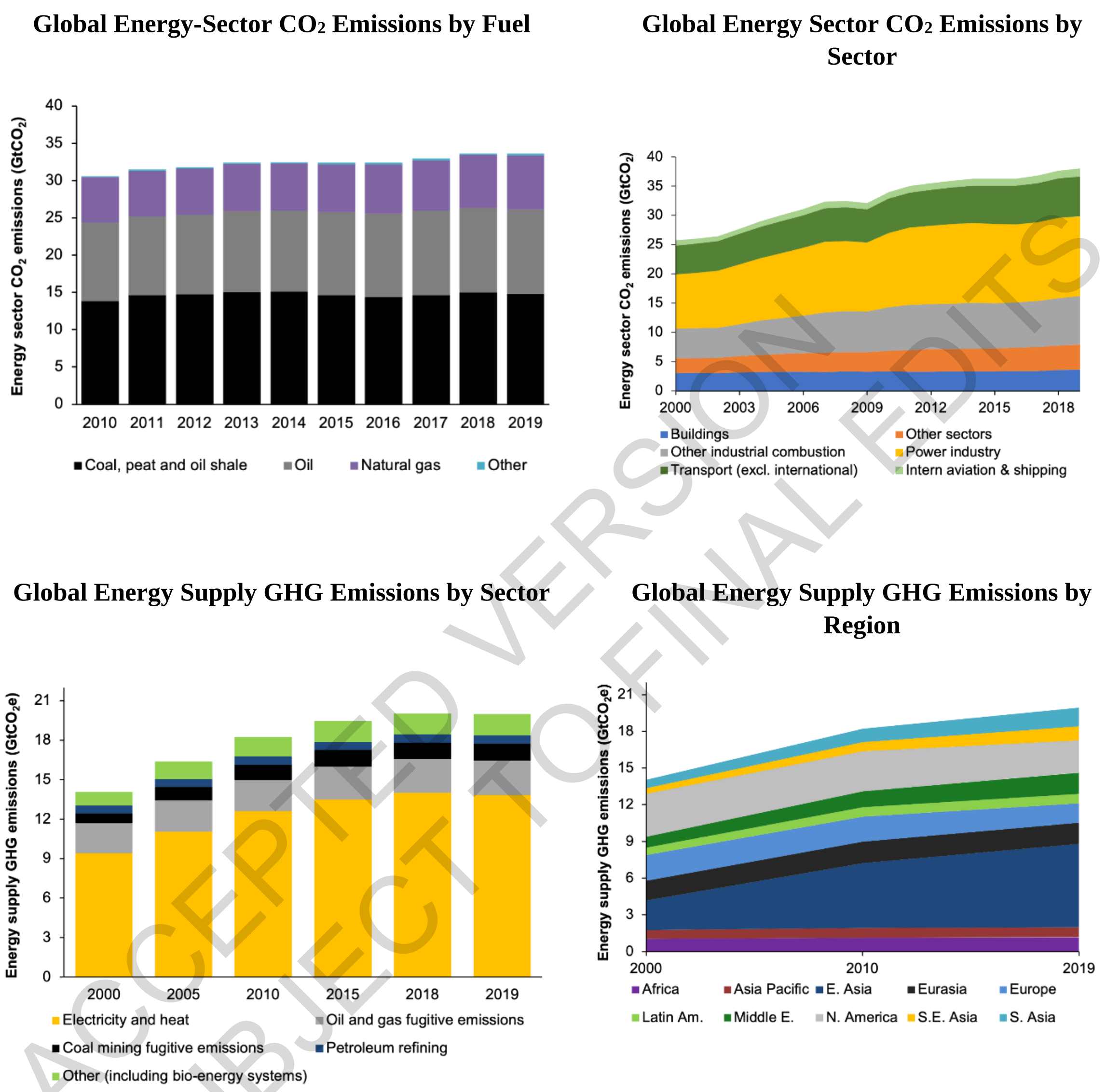


Figure 6.3 Global energy sector CO_2 emissions and global energy supply GHG emission. Panel a: (IEA 2020a)**, other panels** (Crippa et al. 2021)

Increasing global energy sector GHG emissions have been driven by rising emissions in some large developing and emerging countries; however, per capita emissions in these countries remain well below those in developed countries (Yu et al. 2019). From 2015 to 2019, Eastern Asia, Southern Asia, and South-East Asia energy sector CO_2 emissions grew by 2.4% yr^{-1}, 2.6% yr^{-1}, and 5.1% yr^{-1}, respectively. The relative and absolute shares of Europe and North America have continued to decline, partly due to the growth in other countries (Figure 6.3).

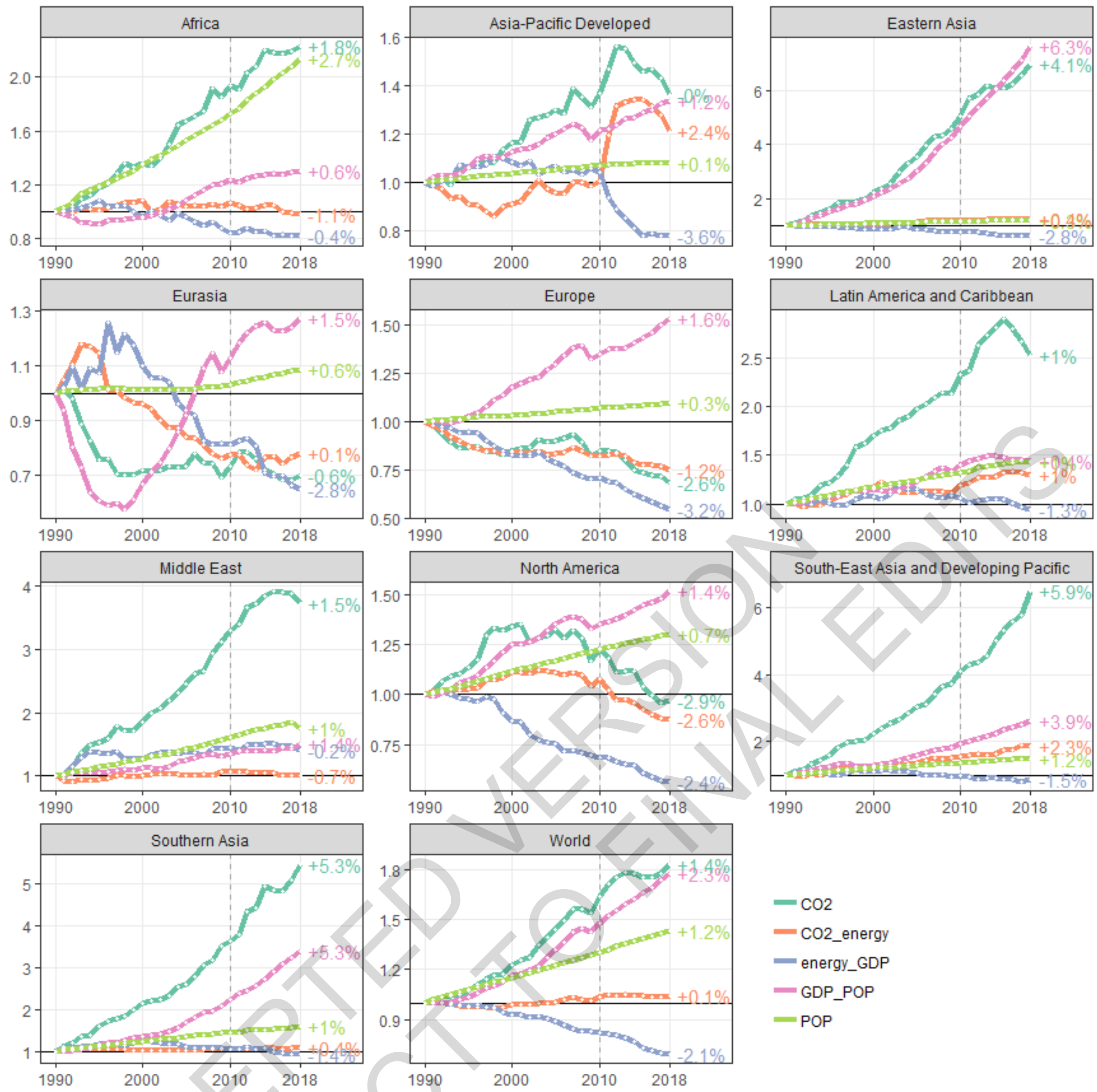


Figure 6.4 Drivers of greenhouse gas emissions across selected regions (Lamb et al. 2021).

Despite the declining energy intensity, global energy system CO2 emissions have closely tracked GDP per capita (Figure 6.4). This is especially true in the Asian economies, which have experienced rapid GDP per capita growth in the past decades and a massive rise in energy demand. Similarly, emissions have declined in times of economic downturns – for example, in Eurasia in the 1990s and globally in 2009 and 2020. Population growth has also contributed to emissions growth globally and in most regions, particularly Africa, but the effect of population growth has been less than that of economic growth. Since 2015, energy intensity has been declining (IEA 2020b), limiting the impact of economic and population growth. However, there is no region where this factor alone would have been sufficient to decrease CO_2 emissions from the energy system. In Europe and North America, the only two regions where emissions decreased meaningfully since 2010, a steady decrease in the carbon intensity of energy was a significant downward driver. The reduction in carbon intensity in the EU is due primarily to the increase of renewable electricity production coupled with the low levels of fossil fuel-based production in the energy mix (Dyrstad et al. 2019).

Global energy production and demand continue to grow, but at a declining rate

Recent changes in the energy system can be viewed within the context of longer-term trends in energy supply and use. Over the last decade, there has been a significant increase in the total primary energy supply (TPES) and major changes in energy sources. From 2015 to 2019, TPES grew by 6.6% (1.6% yr^{-1}) from 569 EJ yr^{-1} to 606 EJ yr^{-1}. Natural gas consumption grew most quickly during this period, at 3.5% yr^{-1}. Coal, oil and oil products grew at annual rates of 0.23% yr^{-1} and 0.83% yr^{-1}, respectively. In 2019, the shares of coal, oil, and natural gas in global TPES were 27%, 31% and 23%, representing only a modest shift from 2015, when the shares were 28%, 32% and 22%, respectively. Renewables, excluding hydropower, grew at an annual rate of 12% yr^{-1} during this period; however, their share remains marginal in 2019 with just 2.2% of the TPES compared to 1.5% in 2015 (Figure 6.5). Bioenergy (including traditional bioenergy) accounted for 9.4% of the TPES, a similar share compared with 2015.

The total final energy consumption (TFC) grew by 6.6% (1.6% yr^{-1}) from 2015 to 2019, rising from 392 EJ yr^{-1} to 418 EJ yr^{-1}. This is a slower growth rate than the previous decade (2.8 % yr^{-1}) (Figure 6.5). In 2019, oil products used for transportation accounted for 41% of TFC. The penetration of non-fossil fuels is still marginal despite the significant growth of electric vehicles in recent years. Coal still accounted for 9.5% of TFC in 2019, dropping from 11.7% in 2015. Coal is mainly used as a primary energy source in industry and to a lesser extent in the residential sector. The share of electricity increased modestly, from 18.6% in 2015 to 20.2% in 2019, reflecting increasing access in developing countries and increasing use of electricity for a wide variety of end uses in the residential sector (see Box 6.1). Heat accounts for approximately 3% of TFC, used mainly in industry and the residential sector. Biofuels and waste accounted for 10.4% of TFC in 2019, only modestly changed compared with 2015.

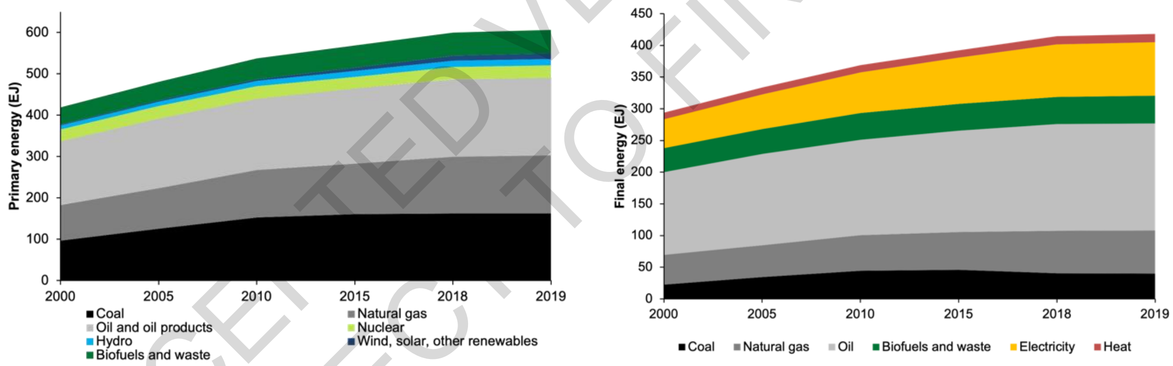


Figure 6.5 World Total Primary Energy Supply (TPES) (EJ) and total final energy consumption (TFC) 2000-2019 (adapted from IEA world energy balances (Minx et al. 2021b)**database for IPCC)**

There are important differences in fuel use across countries. While developed countries almost exclusively use modern fuels, many countries still obtain a significant fraction of their energy from traditional bioenergy (fuelwood and charcoal). Traditional bioenergy (fuelwood and charcoal) is particularly important in sub-Saharan countries and some Asian countries such as India, particularly in the residential sector for cooking. Africa is still characterized by a high share of traditional bioenergy in TPES and TFC. In 2019, biomass and waste in Africa accounted for 44% of the TPES. The global average was 9.4%.

Asia has been particularly important in TFC growth since 2015. In 2019, Eastern Asia accounted for more 24% of TFC (1.52% annual growth from 2015). In contrast, TFC has increased by only 0.58% in Europe and 1.24% in North America. Despite an increase of 2.05% over the same period, Africa's TFC remains relatively low (6.1% of global TFC), particularly in sub-Saharan countries. Approximately 860 million people, mostly in sub-Saharan Africa and some Asian countries, lacked access to electricity and about 2.65 billion to clean-cooking facilities in 2018 (IEA 2019a). Achieving universal energy access (SDG-7) will require energy transitions in the domestic sector, including new developments in off-grid energy technologies, emphasis on rationalizing energy subsidies, and increasing efforts to address health concerns related to the use of traditional fuels (Box 6.1).

Non-climate factors continue to drive energy systems changes

While energy system changes are vital to climate mitigation, recent energy system changes have arisen in response to a much broader set of factors. Important factors include economic growth, energy access, energy justice, energy security, air pollution, technological progress in low-emissions technologies, local job creation. Several of these are discussed here.

Energy Access. Between 2000 and 2019, the proportion of the population with access to electricity increased from 73% to 90% (IEA 2020c). Although most of those people gaining access to energy have gained access to fossil fuel-based electricity, an increasing number are gaining access to electricity from renewable sources. Low-emissions, decentralised systems are proving a cost-effective way to provide electricity in rural areas (Scott et al. 2016; IEA 2019b; Muchunku et al. 2018), although the use of diesel generators continues in some remote areas. Between 2000 and 2019 the proportion of the population with access to clean cooking (modern fuels and/or improved biomass cookstoves) rose from 52% to 66%.

Energy Security. The ability of countries to maintain access to reliable and affordable energy resources continues to shape energy policy. Energy security is perceived as a national security issue and often prioritized over climate concerns (Nyman 2018). The linkage between climate and energy security is now widely recognized (Toke and Vezirgiannidou 2013, Fu et al. 2021; La Viña et al. 2018; Blarke and Lund 2007; World Energy Council 2020; United Nations 2021). Approaches to energy security are frequently driven by the scope of domestic energy resources. For example, energy security concerns have led to continued reliance on domestic coal production and consumption (Jakob et al. 2020) and increased investment in domestic renewable generation (Konstantinos & Ioannidis, 2017). LNG Importers have diversified their sources as reliance on LNG has increased (Vivoda 2019).

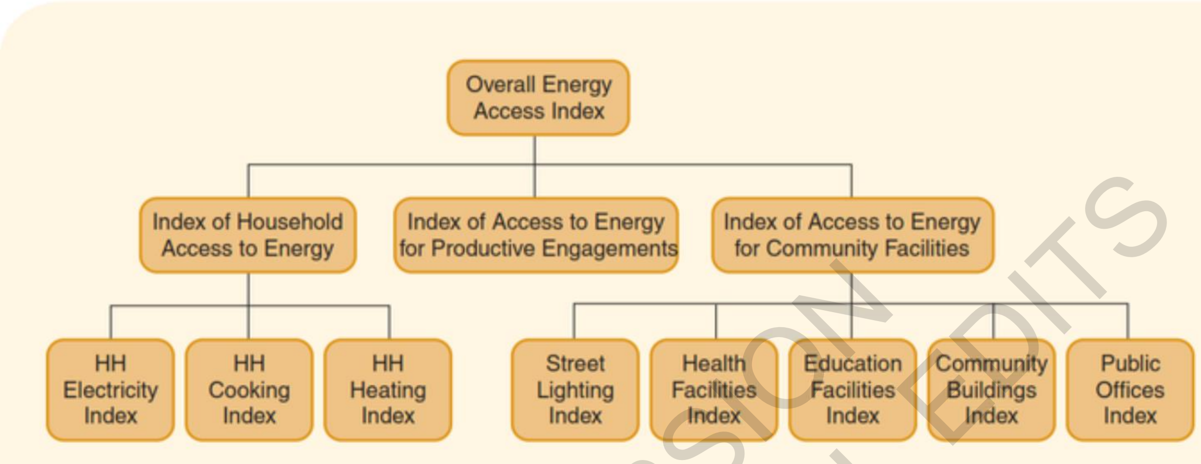
Air Pollution. The energy system is an important source of air pollution, including both indoor and outdoor air pollution. Efforts to address air pollution in several countries and regions (the U. S., Mexico, China, India, European Union, Africa, Southeast Asia, among others) have had an importance influence on energy system changes (Bollen and Brink 2014, Fang et al. 2019). Policies aimed at controlling NO_X and SO_2 emissions have driven emissions abatement efforts and coal fleet retirements (Drake & York, 2021) (Singh and Rao 2015). In some places, the prospect of reducing local air pollution remains more salient to policymakers and the public than climate mitigation when deciding to tighten regulations on coal use (Brauers & Oei, 2020).

Technology and costs. Costs for renewable technologies have fallen significantly in recent years, driving significant changes in electricity production and transportation (see below). These advances are not divorced from climate and other environmental concerns (Kuik, Branger, & Quirion, 2019; Timilsina & Shah, 2020). Recent advances in PV cells, for example, can be traced in part to aggressive deployment policies spurred by energy security, climate, and other environmental concerns (Kreuz and Müsgens 2017, 6.3.5, 6.4.2). The falling costs of batteries, manly Li-ion batteries, has boosted the competitiveness of electric vehicles (6.3.7. Nykvist et al. 2015).

START BOX 6.1 HERE

Box 6.1 Energy access, energy systems, and sustainability

Successful mitigation must work in tandem with fundamental development goals such as access to modern forms of energy. In many developing countries, access to electricity, clean cooking fuels, and modern and efficient energy remain an essential societal priority. This is particularly true in sub-Saharan Africa and several Asian countries. SDG7 on universal access to modern energy includes targets on modern energy services, renewable energy, and energy efficiency, which implies a profound transformation of the current energy systems. Although there are different definitions of energy access, the ultimate goal is universal access to clean and modern fuels.



BOX 6.1 Figure 1 Measuring access to energy (ESMAP-World Bank, 2015)

Despite progress in some countries such as India, Bangladesh and Kenya, 860 million people were without access to electricity in 2018, compared with 1.2 billion in 2010. About 2.65 billion households were cooking with solid fuels, distributed across Asia and Africa (IEA et al. 2020). Around 850 million people in sub-Saharan Africa relied on traditional biomass (firewood and charcoal) for cooking, and 60 million relied on kerosene and coal to meet their energy needs (IEA 2018a). Air pollution was likely responsible for 1.1 million deaths across Africa in 2019 (Fisher et al. 2021). It has been estimated that 2.2 billion people will still be dependent on inefficient and polluting energy sources for cooking by 2030, mainly in Asia and Sub-Saharan Africa, and 650 million people are likely to remain without access to electricity in 2030, 90% of whom will reside in Sub-Saharan Africa (IEA et al. 2020).

Research indicates that decentralised and on-grid renewables are likely the least cost options to provide universal access to electricity by 2030 (Section 6.4.2). Natural gas, LPG, and improved biomass cookstoves are the most important options for cooking. Universal access to electricity and clean cooking requires a rapid shift from traditional biomass to cleaner fuels and/or clean cooking technologies (IEA et al. 2020). It has been estimated that the provision of electricity and clean cooking for all would require USD 786 billion in cumulative investment to 2030, equal to 3.4% of total energy sector investment over the period (IEA 2017).

Even without universal access to modern energy, increased access will substantially affect energy systems, particularly electricity systems through the deployment of renewable energy, LPG, and biomass supply chains. Universal access for households, however, will have a minimal impact on global energy demand; it has been estimated that universal access for household will increase energy demand by 0.2% in 2030 (37 Mtoe yr^{-1}) relative to a future without any change in access to modern energy (citation)

[END BOX 6.1 HERE]

There have been initial efforts to phase out coal but only modest declines in use

Global coal consumption has been declining, with small fluctuations, since it peaked in 2013 (IEA 2020d). Coal is faring differently across regions. Coal use has been decreasing in the OECD regions, particularly in the U.S. and the European Union, while remaining mostly flat in China after a period of growth, and it is continuing to increase in other major developing Asian economies (IEA 2020d). Trends in the electricity sector, where most coal is being consumed, are similar. Growth in coal-fired electricity generation capacity in the Asia Pacific region has offset retirements in North America and Europe (Jakob et al. 2020).

Reductions in coal consumption have been driven in large part by non-climate factors, most notably environmental regulations to address air pollution, rapidly declining costs of renewables, and lower natural gas prices, especially inexpensive unconventional gas in the U.S. (Diluiso et al 2021; Vinichenko et al., 2021; Culver and Hong 2016). Older coal-fired power plants that cannot meet new environmental regulations or have become unprofitable or uncompetitive have been closed in many regions. Moreover, coal power expansion has slowed down in Asia, as countries have suspended and cancelled new projects for reasons such as overcapacity, environmental constraints, and the development of renewables (see Box 6.2).

Different regions have replaced retired coal with different energy sources. Old coal fleets have been replaced approximately half by gas and half by renewables in the U.S., mainly by renewables in the European Union, and by advanced coal plants and renewables in Asia (EMBER 2020). Replacing old coal with new coal facilities is inconsistent with limiting warming to 2ºC or below *{high confidence}* (Pfeiffer et al. 2016, 2018; Smith et al. 2019; Tong et al. 2019, Section 6.7.4).

Major coal consuming countries with abundant coal reserves remain far from phasing out coal (Spencer et al. 2018; Edenhofer et al. 2018). In most developing countries with large coal reserves, coal use has been increasing to support energy security and because it is perceived to have lower costs than alternatives (Steckel et al. 2015; Kalkuhl et al 2019). However, coal faces increasing business risks from the decreasing costs of alternative, low-emissions energy sources and increasing focus on air pollution and other environmental impacts from coal mining and use (Garg et al. 2017; Sovacool et al 2021). Continued coal builds, mostly in developing countries, will increase the risks of stranded assets (see Box 6.13) (Farfan Orozco 2017; Saygin et al. 2019; Cui et al. 2019).

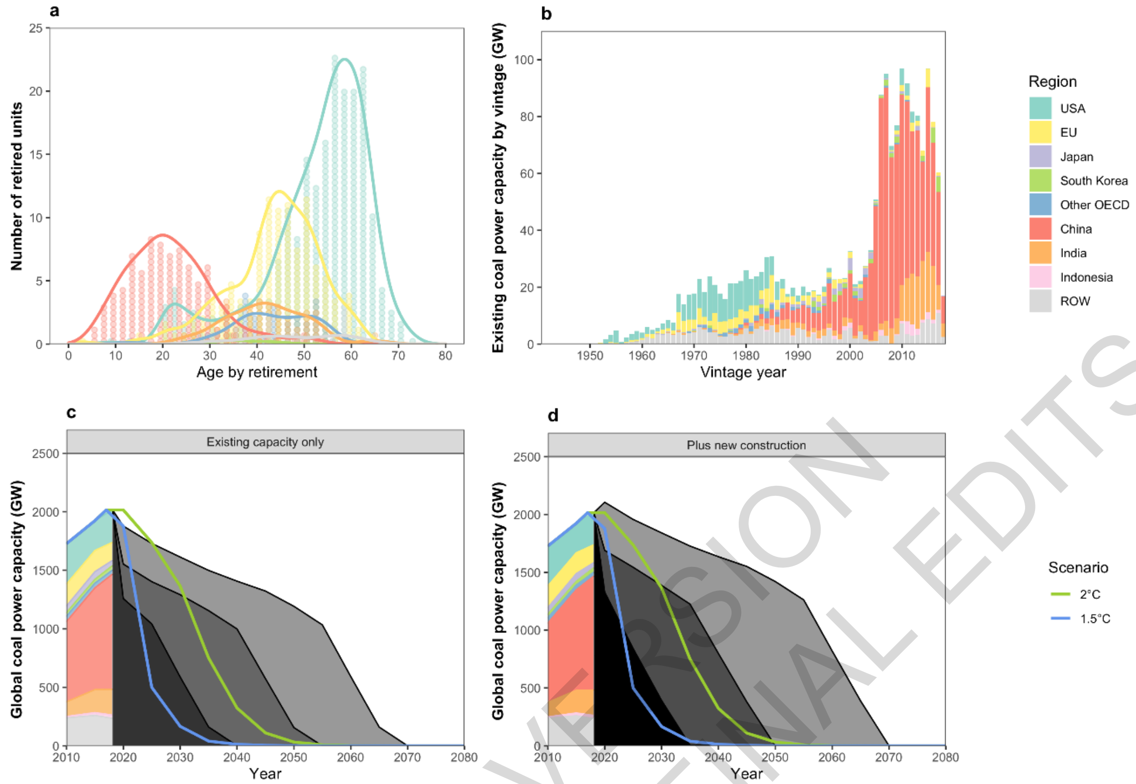
Economic, social, and employment impacts of accelerated coal phaseouts tend to be significant in coal-dependent regions. Tailored reemployment has been used to support coal transitions in some regions. Although some estimates show higher employment opportunities from low-carbon energy (Garrett-Peltier 2017), results vary across regions. Moreover, even with a net increase in total employment, in the long run, renewable jobs are often located outside of coal regions and require different skill sets from the coal industry (Spencer et al. 2018). In a broader sense, achieving a "just transition" also requires managing the impacts on regional economic development for coal-dependent communities and the effects of higher energy prices for consumers and energy-intensive industries through a comprehensive policy package (see Box6.2) (Jakob et al. 2020; Green and Gambhir 2020).

[START BOX 6.2 HERE]

Box 6.2 Status and Challenges of a Coal Phase-Out

Limiting global warming to 2ºC or below requires a rapid shift away from unabated coal consumption (coal without CCS) in the energy system by 2050 (IPCC 2018a Section 6.7, Chapter 3). This will require cancellation of new coal power projects and accelerated retirement of existing coal plants (Pfeiffer et al. 2018; Edenhofer et al. 2018; Tong et al. 2019, Kriegler et al. 2018Smith et al. 2019). To limit warming to 2ºC or below, and without new builds, existing coal plants will need to retire 10 to 25 years earlier than the historical average operating lifetime. Completing all planned projects will further reduce the viable lifetime of all plants by 5 to 10 years if warming is to be limited to 2ºC or below (Cui et al.

2019). Phasing-out coal in the next few decades will present economic, social, and security challenges. These will vary across regions based on the characteristics of existing coal infrastructure, the availability of alternatives, economic development, and technological and institutional lock-in (Jakob et al. 2020).



Box 6.2 Figure 1 Retirement of coal-fired power plants to limit warming to 1.5°C and likely 2°C. (a) Historical facility age at retirement (b) the vintage year of existing units, (c) global coal capacity under different plant lifetimes, compared to capacity levels consistent with a well-below 2°C (green) and 1.5°C (blue) pathway assuming no new coal plants, and (d) and assuming plants currently under construction come online as scheduled, but those in planning or permitting stages are not built. (Source: (Cui et al. 2019)).

Between 2015 and 2019, global coal power capacity grew by 146 GW, or 7.6%, as new builds offset retirements in some countries (Global Energy Monitor et al. 2021). Meanwhile, an increasing number of countries and regions have committed to or operationalised coal phase-outs (Jewell et al. 2019; Watts et al. 2019; Littlecott et al. 2021). Actions are being taken by various international and subnational actors, including national and subnational governments, public and private power companies, and financial institutions and pension funds that have committed not to fund new coal or coal-based infrastructure (yan Nie et al. 2016; Buckley 2019; Auger et al. 2021). Although these initial efforts are not yet sufficient in limiting warming to 1.5°C, and most have occurred in regions with older coal fleets, these examples provide insight into possible coal phaseout strategies (Spencer et al. 2018) and help identify the mechanisms driving the move away from coal, such as market, technology, policy, or other societal objectives. They also enable better understanding of the possible character of oil and gas phase-downs that would ultimately be needed to limit warming two well below 2°C (Section 6.7.4; (Raimi et al. 2019).

Europe: Several European countries are part of the Powering Past Coal Alliance (PPCA) and have committed to phase-out unabated coal on or before 2030 (Jewell et al. 2019). Because these countries represent a small share of global coal generation capacity and have mostly ageing coal plants, they tend to face fewer changes in phasing out coal. The effectiveness of PPCA in countries with younger coal fleets has thus been questioned (Jewell et al. 2019; Blondeel et al. 2020). Germany recently joined the PPCA and has committed to phaseout unabated coal by 2038. As part of its commitment to phase out coal, Germany is implementing a set of measures that include compensation for power plant closures, labour market measures for coal workers, and substantial support of structural change in coal-mining regions. Poland, another coal-heavy country in Europe, has not indicated a coal phaseout target and faces substantial challenges (Whitley et al. 2017; Antosiewicz et al. 2020). European efforts to phase out coal indicate that appropriate financial instruments are needed (Rentier et al. 2019), and a just transition for workers are important to gain broad public support and help those most affected by the phaseout (Johnstone and Hielscher 2017; Osička et al. 2020).

North America: Coal use has been declining in North America. In the U.S., the primary driver has been the availability of cheap shale gas and ageing coal fleets. Coal use in the US has dropped by over 50% since 2008 (EIA 2019). The recently announced NDC by the Biden Administration sets a 100% carbon-free electricity goal by 2035 (The White House 2021), indicating a phaseout not only of unabated coal electricity generation, but also of natural gas generation. As one of the two founding countries of the PPCA, Canada has committed to phasing out unabated coal power by 2030 (Government of Canada 2018). Declining coal use in both the U.S. and Canada has decreased GHG emissions, local air pollutants, and cooling water use (Harris et al. 2015; Kondash et al. 2019). However, there have been concerns about social and economic consequences, particularly at the local level. For instance, the U.S. has lost about 50,000 coal mining jobs between 2011 and 2021 (U.S. Bureau of Labor Statistics, 2021), with significant regional and economic inequities (Bodenhamer 2016; Abraham 2017; Greenberg 2018). Comprehensive social programs, such as retirement compensation, training for reemployment, and business support for economic diversification, have been suggested as means to support a just transition (Patrizio et al. 2018; Homagain et al. 2015; Grubert 2020).

Asia: After a period of rapid growth, coal expansion has slowed in Asia, but it still the primary driver of the global increase in coal demand (IEA 2020e). China's coal consumption reached a plateau under policy efforts during the 13th Five-Year Plan (2016-2020), and new coal plants are being built at a slower rate than previously. Both China and India have suspended and cancelled many new coal power projects and retired a small set of old, dirty, inefficient coal plants (Global Energy Monitor et al. 2021; CEA 2019). These efforts are largely due to non-climate reasons, such air pollution and health (Singh and Rao 2015; Gass et al. 2016; Peng et al. 2018; Malik et al. 2020), overcapacity (Blondeel and Van de Graaf 2018), and rural electrification and renewable investments (Aklin et al. 2017; Thapar et al. 2018). However, as new builds offset retirements, coal generation capacity has continued to grow in both countries since 2015 (Global Energy Monitor et al. 2021). Other fast-growing Southeast Asian countries, such as Indonesia, Vietnam, and Philippines have experienced strong growth in coal use (IEA 2020b), but an increasing number of new coal power projects are being cancelled (Littlecott et al. 2021). Coal projects in these countries are decreasingly likely to proceed because they rely on international financing, and China, Japan, United States, and other G7 countries have pledged to end overseas coal financing (Schiermeier 2021).

Africa: New coal power projects in Africa have been declining since 2016, with only South Africa and Zimbabwe currently building new coal plants and several others has planned projects (Littlecott et al. 2021). However, these projects also largely depend on international financing and are thus less likely to be implemented (see above). In South Africa, employment in the coal mining sector has dropped by almost half since the 1980s and is has been estimated to fall from 77,00 today to 22,000 to 42,000 by 2050 (Strambo et al. 2019; Cock 2019). Policy and financial support are essential to ensure a sustainable transition for these workers (Swilling et al. 2016).

[END BOX 6.2 HERE]

Solar and wind energy have grown dramatically, but global shares remain low relative to other sources

Global PV and wind electric capacities grew 170% and 70%, respectively, between 2015 and 2019. Total solar and wind capacities in 2019 were 609 GW and 623 GW (Figure 6.6) and generation was 680 TWh yr^{-1} and 1420 TWh yr^{-1}. The combined share of solar and wind in the total global electricity generation in 2019 was around 8% (5.5% wind, 2.5% solar), up from around 5% in 2015 (IEA 2021a). Since 2015, the cost of solar PVs has declined by over 60%. Offshore wind costs have fallen by 32%, and onshore wind costs have fallen by 23% (Section 6.4). PV was around 99% of total solar capacity in 2019; onshore wind was about 95% of total wind capacity. Concentrating solar power (CSP) deployment has also continued to grow, but it remains far below PV. Prior to 2010, 50% of all wind capacity was in Europe, but, since then, capacity growth in Asia, led by China, has surpassed the growth in Europe. As a consequence, Europe's share in global solar capacity has declined from 74% in 2010 to 24% in 2019. Asia's share in wind and solar capacity in 2019 was 41% and 56%, followed by Europe (31% and 24%) and North America (20% and 12%) (IRENA 2021a, 2020a).

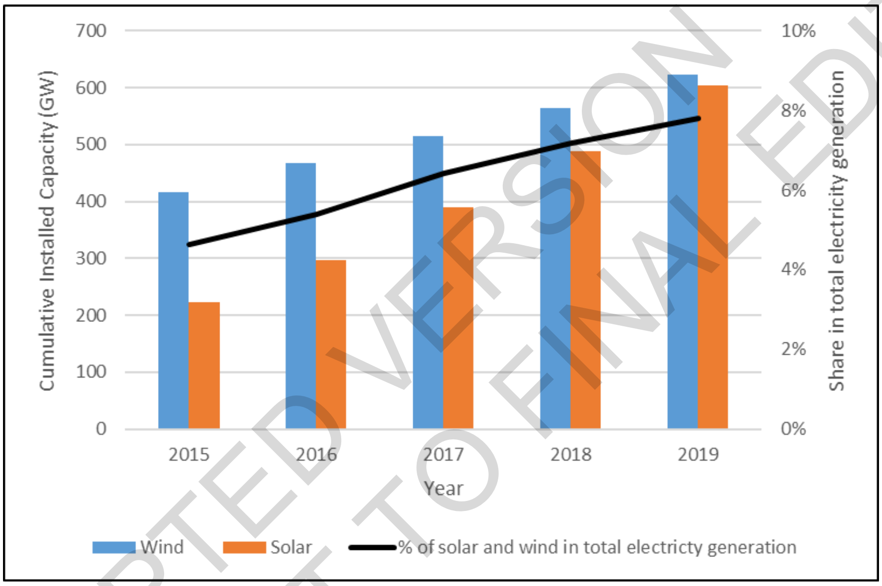


Figure 6.6 Global solar and wind electricity installed capacities (GW) from 2015–2019 and their combined share in total electricity generation Source: data from (IEA 2021a) IRENA, 2021).

Although the shares of wind and solar remains low in the global total electricity generation, recent growth rates signal the potential for these technologies to support substantial mitigation. The prospects for a continuation of recent growth rates will depend on meeting key challenges such as rapidly integrating wind and solar into electricity grids (Section 6.6.2, Box 6.8) and retiring fossil power plants (see above).

Low-carbon energy sources beyond wind and solar have continued to grow

Low-carbon energy sources such as nuclear, hydropower, bioenergy, geothermal, marine, and fossil or bioenergy with CCUS have continued to grow since 2015 (IEA, 2017; IEA, 2021a). Hydroelectric power grew from 3890 TWh yr^{-1} (14.0 EJ yr^{-1}) in 2015 to 4290 TWh yr^{-1} (15.5 EJ yr^{-1}) in 2019, or 10.3%; nuclear power grew from 2570 TWh yr^{-1} (9.3 EJ yr^{-1}) to 2790 TWh yr^{-1} (10.1 EJ yr^{-1}), or 8.6%. Hydroelectric and nuclear shares in global total electricity generation remained around 16% and 10%, respectively (IEA, 2017; IEA 2021a). Global biofuels production grew from 3.2 EJ yr^{-1} to 4.0 EJ yr^{-1} from 2015 to 2019 (IEA, 2017; IEA 2021a). Bioenergy accounted for 2.4% of electricity generation in 2019. Geothermal energy sources produced 92 TWh yr^{-1} (0.33 EJ yr^{-1}) of electricity in 2019, up from 80 TWh yr^{-1} (0.28 EJ yr^{-1}) in 2015 (IEA, 2017; IEA 2021a). At present, there are 28 commercially operating CCUS facilities with a CO_2 removal capacity of around 40 million tonnes yr^{-1} (Mtpa). Only two of these are associated with electricity production; the majority are in industrial applications. 37 commercial projects, accounting for about 75 Mtpa, are in various stages of development and construction (Global CCS Institute 2020). The share of marine energy in the global electricity generation has remained at approximately 1 TWh yr^{-1} since 2015. In total, low- and zero-carbon electricity generation technologies produced 37% of global electricity in 2019.

Battery prices have dropped substantially, spurring deployment in electricity and transportation

Recent years have seen a rapid decline in the cost of energy storage, particularly batteries (see Section 6.4.4). The price of lithium-ion batteries (LIBs) has declined by 97% in the past three decades and by 90% in the past decade alone (IEA 2021a; Ziegler and Trancik 2021)These declines have important implications for the energy systems, most notably in supporting increased deployment of variable renewable electricity (VRE) generation and electrification of the vehicle fleet.

Battery electricity storage has emerged as an important for supporting the flexibility of electricity systems as they accommodate rising shares of VRE. Although pumped-storage hydropower systems accounted for 160 GW, or over 90%, of total energy storage capacity in 2019 (IEA 2020c), battery energy storage systems, led by Li-ion technology, have accounted for over 90% of new capacity addition since 2015 (IRENA 2019a). In 2019, 10 GW of batteries were connected at the grid and consumer level, rising from 0.6 GW in 2015 (IEA 2020c; IEA WEO 2019).

In California, in the U.S., legislation was passed to procure around 1.3 GW energy storage (excluding pumped storage) by 2020. One of the largest utility-scale battery storage facilities (300 MW) recently went online in California (Vistra Corp. 2021). Other major projects are in Florida in the US (409 MW), London in the UK (320 MW), Lithuania (200 MW), Australia (150 MW), Chile (112 MW) and Germany (90 MW), (Katz 2020; ARENA 2020; IRENA 2019a).

The drop in battery prices has also had important implications in the transportation sector. Automotive LIB production rose from around 40 GWh in 2015 to 160 GWh in 2020 (32%). The stock of battery electric vehicles (BEVs) grew from around 0.7 million in 2015 to 4.8 million in 2019 (IEA 2020d). The number of publicly accessible vehicle chargers reached 1.3 million in 2020, 30% of which were fast chargers. The average battery size of BEVs reached 67 kWh in 2019 due to consumer preferences and government incentives for long-range vehicles (Agency 2020; IEA 2021b).

The energy policy landscape continues to evolve

The current energy sector policy landscape consists of policy mixes or policy packages, including regulatory, market-based and other approaches. These mixes have evolved over time and include many sectoral but also some economy-wide policy instruments, such as carbon pricing, subsidies.

Governments have chosen a mix of policies and institutional mechanisms that consists of regulatory instruments, like efficiency and technology standards, economic instruments (e.g. carbon pricing, subsidies) (Bertram et al. 2015; Martin and Saikawa 2017) and other policies, such as government interventions to provide infrastructure, information policies, and voluntary actions by non-government actors (Somanathan et al. 2014). In recent years, regulatory instruments to promote low-carbon infrastructure have gained traction in developing countries (Finon 2019). The choice of policies has depended on institutional capacities, technological maturity and other developmental priorities of governments. For example, governments have favoured regulatory instruments over economic instruments when there has been sufficient institutional capacity to implement and monitor the regulations and standards (Hughes and Urpelainen 2015). Furthermore, institutional capacity has also determined the extent of implemented measures (Adenle et al. 2017). Market conditions and technological maturity are other important determinants of policy mixes being deployed in the energy sector. For example, subsidies for mitigation like feed-in-tariffs (FIT) have worked best when the technologies are in nascent stages of development (Gupta et al. 2019a).

On the other hand, market-based instruments like emission trading schemes (ETS) and auctions coupled with a regulatory framework have been a favourable strategy for more mature technologies (Polzin et al. 2015; Kitzing et al. 2018). FIT, tax incentives, and renewable portfolio standards - despite potentially substantial program costs (Andor and Voss 2016; Abrell et al. 2019) - have played a significant role in attracting foreign direct investments in the renewable sector (Wall et al. 2019). Subsidies and carbon pricing have also played an important role in mainstreaming these renewable energy sources (Best and Burke 2018). Recently, subsidy-free investments in renewables, e.g. wind offshore (Jansen et al. 2020), backed by power purchase agreements, have gained momentum (Frankfurt School-UNEP Centre and BNEF 2020). Similar considerations apply for policy mixes targeted to other sectors, for example transport and buildings.

The role of carbon pricing is still limited though increasing. Different measures have been suggested to improve the performance of the ETS, such as "price floors and caps" and other carbon pricing schemes (Bataille et al. 2018; Campiglio 2016; Goulder and Morgenstern 2018). In 2020, 61 regional, national and sub-national carbon pricing instruments, representing 22% of the global GHG emissions, were in action or scheduled for implementation (World Bank 2019). Over 51% of emissions covered are priced at less than USD 10 per tCO_2-e.. At present, however, only 5% of the global emissions covered under carbon pricing initiatives are consistent with the range of carbon prices that have been suggested as needed to limit warming to well below 2°C (Stiglitz and Stern 2017). Most of the carbon pricing schemes have taken place in the OECD countries. The limited application of carbon pricing instruments in developing, and emerging economies may be due to political economy constraints (Campiglio 2016; Finon 2019). Carbon pricing had a sizeable impact on emissions , e.g. the EU ETS impacts emissions from electricity in Germany (Schäfer 2019) and manufacturing in France (Colmer et al.), respectively. Emission reductions could be increased with higher carbon prices and without free allocation of allowances.

In the absence of a global comprehensive carbon price, regional regulatory policies for fossil fuels supply and key demand sectors like transport, industry and buildings (Chapters 9-11), coupled with regional carbon pricing instruments, were implemented to help initiating the climate actions consistent with the Paris agreement (Kriegler et al. 2018). However, differences in the stringency of climate regulation has triggered fear that regulation reduces the competitiveness of industries in regulated countries and lead to industry re-location and "carbon leakage" (Schenker et al. 2018). In recent years, however, there is little evidence of carbon leakage (Schäfer 2019; Naegele and Zaklan 2019), and even positive effects of carbon pricing on efficiency have been observed (e.g., Löschel et al. 2019, for German manufacturing firms, and (Germeshausen 2020) for German power plants). However, with asymmetric rising carbon prices, discussions about specific policy mechanisms to address carbon leakage like carbon border adjustments (Cosbey et al. 2019) were amplified. Furthermore, multiple policies - often implemented by different governmental levels (national vs subnational) - interacted with each other and thereby affected their environmental and economic effectiveness. Recent examples include interactions of ETS with renewable support policies (e.g. Boehringer and Behrens 2015; Del Rio 2017), energy efficiency policies (e.g. Wiese et al. 2018) or electricity market reform (e.g. Teng et al. 2017), respectively.

Apart from explicit carbon pricing, various implicit carbon pricing mechanisms such as fossil fuel taxes and removal of fossil fuel subsidies (see Box 6.3) and regulatory instruments are used by many countries as part of their climate policies. In addition, public provision and procurement of low-carbon infrastructure and technologies such as energy-efficient devices, renewable energy, and upgrades in electricity grids through state-sponsored institutions and public-private partnerships have played an important role in low-carbon development (e.g., (Baron 2016)).

[START BOX 6.3 HERE]

Box 6.3 Energy Subsidies

Energy subsidies continue to be widely applied. Global fossil fuel subsidies represent more than half of total energy subsidies with predominantly adverse environmental, economic, and social effects (*high confidence*).

Energy subsidies can be defined as policy measures in the energy sector to lower the prices for consumers, raise the prices for producers, or reduce energy production costs (IEA 1999). There are subsidies for fossil fuels, renewables, and energy efficiency measures. The majority of the renewable subsidies are generation-based incentives for solar, wind or biomass in the form of feed-in-tariffs (FIT) (Chapter 13), with total annual renewable subsidy estimates of about USD 150 billion yr^{-1} globally (IEA 2018b). Estimates of fossil fuel subsidies can vary by an order of magnitude. For the year 2017, the IEA estimated fossil fuel subsidies of USD 300 billion using IEA's pre-tax, price-gap method (IEA 2018b), while the IMF included unpriced externalities in calculating subsidies of USD 5.2 trillion or 6.5% of global GDP (World Bank 2019; Coady et al. 2017, 2019). It has been estimated that the amount spent on fossil fuel subsidies was around double the amount of subsidies spent on renewables (IEA 2018b). There are adverse environmental, economic and social consequences of fossil fuel subsidies (Rentschler and Bazilian 2017). More than 75% of the distortions created by fossil fuel subsidies are domestic, and studies indicate that reforming them can have substantial in-country benefits (Coady et al. 2019, 2017). Some of the G-20 countries have implemented subsidy reforms based on low oil prices (Jewell et al. 2018).

Fossil fuel subsidies most commonly pursue non-climate objectives, for example, enhanced access to energy sources (*high confidence*). In some cases, these energy access subsidies have helped extend modern energy sources to the poor (Kimemia and Annegarn 2016) and thereby contribute to SDG-7. However, the subsidies have proven to be regressive in most cases, with little benefit reaching the poor (Lockwood 2015). For example, Indonesia has introduced liquefied petroleum gas (LPG) subsidies for cooking. The kerosene to LPG conversion program ("Zero Kero") was launched in 2007 and provided mainly households with free initial LPG equipment and LPG at a low subsidized price (Thoday et al. 2018; Imelda et al. 2018b). Besides the national government, provincial governments and industry played a crucial role in implementation. Overall, the LPG conversion program in Indonesia reduced cooking kerosene use (Andadari et al. 2014; Imelda et al. 2018b) and GHG emissions (Permadi et al. 2017) with positive health effects (Thoday et al. 2018; Imelda et al. 2018b). However, the program is generally viewed as regressive and has failed to reduce traditional solid fuel use (Andadari et al. 2014; Toft 2016; Thoday et al. 2018). Furthermore, even if the program decreased greenhouse gas emissions relative to continued kerosene use, these subsidies are still targeted at fossil fuels and contribute to GHG emissions.

India started a large LPG program in 2015 that provided a capital cost subsidy to poor households (e.g. Kar et al. 2019; Jose et al. 2018; Gould 2018). While the program has increased adoption of LPG in India (e.g. Sharma et al. 2019), it has not yet achieved a sustained use of LPG and replacement of solid fuels for cooking, amplifying the need for complementary policy measures (Gould 2018; Kar et al. 2019; Mani et al. 2020). The climate impacts of switching from biomass to LPG depend on the degree of biomass combustion in stoves and the extent to which biomass originates from non-renewable sources (Jose et al. 2018; Singh and Rao 2015). Barriers to increasing LPG use for cooking further included abundance of solid fuels at zero (monetary) costs (Mani et al. 2020) as well as benefits of solid fuels, such as maintaining the traditional taste of food and space heating in colder seasons (Gould 2018; Sharma et al. 2020).

[END BOX 6.3 HERE]

6.4 Mitigation Options

6.4.1 Elements of Characterization

This section characterizes energy system mitigation options and discusses which factors enable and inhibit their implementation. We touch on a broad range of factors that may enable and inhibit the implementation of mitigation options by considering six dimensions that affect their feasibility (Table 6.1, Annex II.11). The assessment aims to identify which mitigation options can be readily implemented and which face barriers that would need to be overcome before they can be deployed at scale.

Table 6.1 Dimensions and indicators to assess the barriers and enablers of implementing mitigation options in low carbon energy systems.

Metric	Indicators
Geophysical: Are the required resources available?	Physical potential: physical constraints to implementation Geophysical resources (including geological storage capacity): availability of resources needed for implementation Land use: claims on land where an option would be implemented
Environmental-ecological: What are the wider environmental and ecological impacts of the option?	Air pollution: increase or decrease in air pollutants, such as NH_4, CH_4 and fine dust Toxic waste, mining, ecotoxicity and eutrophication Water quantity and quality: changes in the amount of water available for other uses Biodiversity: changes in conserved primary forest or grassland that affect biodiversity, and management to conserve and maintain land carbon stocks
Technological: Can the required option be upscaled soon?	Simplicity: is the option technically simple to operate, maintain and integrate Technology scalability: can the option be scaled up, technically Maturity and technology readiness: R&D and time needed to implement the option
Economic: What economic conditions can support or inhibit the implementation of the option?	Costs in 2030 and in the long term: investment costs, costs in USD tCO_2-eq^{-1} Employment effects and economic growth: decrease or increase in jobs and economic welfare
Socio-cultural: What social conditions could support or inhibit acceptance, adoption, and use of the option?	Public acceptance: the extent to which the public supports the option and will change their behaviour accordingly Effects on health and wellbeing Distributional effects: equity and justice across groups, regions, and generations, including energy, water, and food security and poverty
Institutional: What institutional conditions could support or inhibit the implementation of the option?	Political acceptance: the extent to which politicians support the option Institutional capacity and governance, cross-sectoral coordination: capability of institutions to implement and handle the option Legal and administrative capacity

6.4.2 Energy Sources and Energy Conversion

6.4.2.1 Solar Energy

Solar PV is increasingly competitive with other forms of electricity generation and is the low-cost option in many applications (*high confidence*). Costs have declined by 62% since 2015 (*high confidence*) and are anticipated to decline by an additional 16% by 2030 if current trends continue (*low confidence, medium evidence*). Key areas for continued improvement are grid integration and non-module costs for rooftop systems (*high confidence*). Most deployment is now utility-scale (*high confidence*). Global future potential is not limited by solar irradiation, but by grid integration needed to address its variability, as well as access to finance, particularly in developing countries (*high confidence*).

The global technical potential of direct solar energy far exceeds that of any other renewable energy resource and is well beyond the total amount of energy needed to support ambitious mitigation over the current century (*high confidence*). Estimates of global solar resources have not changed since AR5 (Lewis 2007; Besharat et al. 2013) even as precision and near-term forecasting have improved (Abreu et al. 2018; Diagne et al. 2013). Approximately 120,000 TW of sunlight reaches the Earth's surface continuously, almost 10,000 times average world energy consumption; factoring in competition for land-use leaves a technical potential of about 300 PWh yr^{-1} (1080 EJ yr^{-1}) for solar PV, roughly double current consumption (Dupont et al. 2020). The technical potential for concentrating solar power (CSP) is estimated to be 45–82 PWh yr^{-1} (162–295 EJ yr^{-1}) (Dupont et al. 2020). Areas with the highest solar irradiation are western South America; northern, eastern and southwestern Africa; and the Middle East and Australia (Figure 6.7) (Prăvălie et al. 2019).

In many parts of the world, the cost of electricity from PV is below the cost of electricity generated from fossil fuels, and in some, it is below the operating costs of electricity generated from fossil fuels (*high confidence*). The weighted average cost of PV in 2019 was USD 68 MWh^{-1}, near the bottom of the range of fossil fuel prices (IRENA 2019b). The cost of electricity from PV has fallen by 89% since 2000 and 69% since AR5, at a rate of –16% per year. The 5:95 percentile range for PV in 2019 was USD 52–190 MWh^{-1} (IRENA 2021b). Differences in solar insolation, financing costs, equipment acquisition, installation labour, and other sources of price dispersion explain this range (Nemet et al. 2016; Vartiainen et al. 2020) and scale. For example, in India, rooftop installations cost 41% more than utility-scale installations, and commercial-scale costs are 39% higher than utility-scale. Significant differences in regional cost persist (Kazhamiaka et al. 2017; Vartiainen et al. 2020), with particularly low prices in China, India, and parts of Europe. Globally, the range of global PV costs is quite similar to the range of coal and natural gas prices.

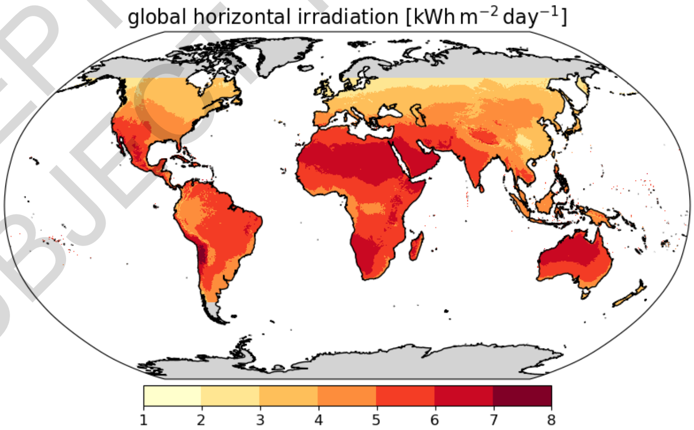


Figure 6.7 Distribution of the daily mean global horizontal irradiation (GHI, kWh m^{-2} day^{-1}).

Source: Global Solar Atlas (ESMAP 2019)

PV costs (Figure 6.8) have fallen for various reasons: lower silicon costs, automation, lower margins, automation, higher efficiency, and a variety of incremental improvements (Fu et al. 2018; Green 2019) (Chapter 16). Increasingly, the costs of PV electricity are concentrated in the installation and related "soft costs" (marketing, permitting) associated with the technology rather than in the modules themselves, which now account for only 30% of installed costs of rooftop systems (O'Shaughnessy et al. 2019; IRENA 2021b). Financing costs are a significant barrier in developing countries (Ondraczek et al. 2015) and growth there depends on access to low-cost finance (Creutzig et al. 2017).

CSP costs have also fallen, albeit at about half the rate of PV: –9% yr^{-1} since AR5. The lowest prices for CSP are now competitive with more expensive fossil fuels, although the average CSP cost is above the fossil range. Other data sources put recent CSP costs at USD 120 MWh^{-1}, in the middle of the fossil range (Lilliestam et al. 2020). Continuing the pace of change since AR5 will make CSP competitive with fossil fuels in sunny locations, although it will be difficult for CSP to compete with PV and even hybrid PV-battery systems. CSP electricity can be more valuable, however, because CSP systems can store heat longer than PV battery systems.

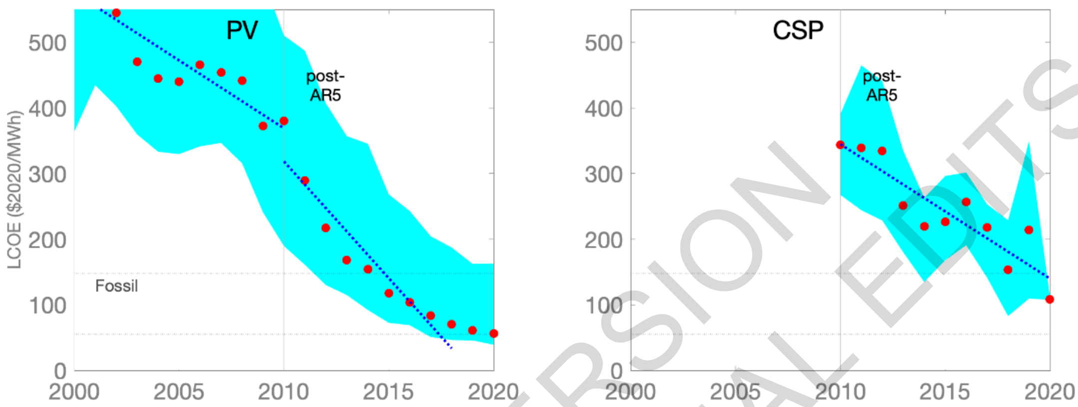


Figure 6.8 Levelized costs of electricity (LCOE) of solar energy technologies 2000–2020. Range of fossil fuel LCOE indicated as dashed lines USD 50–177 MWh^{-1}. Linear fit lines were applied to data for AR4–AR5 and post-AR5 (2012). Red dots are capacity-weighted global averages for utility-scale installations. The blue area shows the range between the 5th and 95th percentile in each year. Data: (IRENA 2021b).

The share of total costs of PV-intensive electricity systems attributed to integration costs has been increasing but can be reduced by enhancing grid flexibility (Section 6.4.3, 6.6, Box 6.8) (*high confidence*). The total costs of PV include grid integration, which varies tremendously depending on PV's share of electricity, other supply sources like wind, availability of storage, transmission capacity, and demand flexibility (Heptonstall and Gross 2020). Transmission costs can add USD 1–10 MWh^{-1} or 3–33% to the cost of utility-scale PV (Gorman et al. 2019). Distributed (rooftop) PV involves a broader set of grid integration costs - including grid reinforcement, voltage balancing and control, and impacts on other generations - and has a larger range of integration costs from USD 2–25 MWh^{-1}, which is –3% to +37% (Hirth et al. 2015; Wu et al. 2015; Gorman et al. 2019). Other meta-analyses put the range at USD 1–7 MWh^{-1} in the USA (Luckow et al.; Wiser et al. 2017), while a comprehensive study put the range at USD 12–18 MWh^{-1} for up to 35% renewables and USD 25–46 MWh^{-1} above 35% renewables (Heptonstall and Gross 2020). Increased system flexibility can reduce integration costs of solar energy (Wu et al. 2015) including storage, demand response, sector-coupling (Bogdanov et al. 2019; Brown et al. 2018), and increase complementarity between wind and solar (Heide et al. 2010) (Sections 6.4.3 and 6.4.4).

Since solar PV panels have very low-operating costs, they can, at high penetrations and in the absence of adequate incentives to shift demand, depress prices in wholesale electricity markets, making it difficult to recoup investment and potentially reducing incentives for new installations (Hirth 2013; Millstein et al. 2021). Continued cost reductions help address this issue of value deflation, but only partially. Comprehensive solutions depend on adding transmission and storage (Das et al. 2020) and, more fundamentally, adjustments to electricity market design (Bistline and Young 2019; Roques and Finon 2017).

The most important ways to minimize PVs impact on the environment lie in recycling materials at end of life and making smart land-use decisions (*medium confidence*). A comprehensive assessment of PVs environmental impacts requires life-cycle analysis (LCA) of resource depletion, land-use, ecotoxicity, eutrophication, acidification, ozone, and particulates, among other things (Mahmud et al. 2018). LCA studies show that solar PVs produce far less CO_2 per unit of electricity than fossil generation, but PV CO_2 emissions vary due to the carbon intensity of manufacturing energy and offset electricity (Grant and Hicks 2020). Concerns about systemic impacts, such as reducing the Earth's albedo by covering surfaces with dark panels, have shown to be trivial compared to the mitigation benefits (Nemet 2009) (Box 6.7). Even though GHG LCA estimates span a considerable range of 9–250 $gCO_2\ kWh^{-1}$ (de Wild-Scholten 2013; Kommalapati et al. 2017), recent studies that reflect higher efficiencies and manufacturing improvements find lower life-cycle emissions, including a range of 18–60 $gCO_2\ kWh^{-1}$ (Wetzel and Borchers 2015) and central estimates of 80 $gCO_2\ kWh^{-1}$ (Hou et al. 2016), 50 $gCO_2\ kWh^{-1}$ (Nugent and Sovacool 2014), and 20 $gCO_2\ kWh^{-1}$ (Louwen et al. 2016). These recent values are an order of magnitude lower than coal and natural gas and further decarbonization of the energy system will make them lower still. Thin films and organics produce half the life-cycle emissions of silicon wafer PV, mainly because they use less material (Lizin et al. 2013; Hou et al. 2016). Novel materials promise even lower environmental impacts, especially with improvements to their performance ratios and reliability (Gong et al. 2015; Muteri et al. 2020). Higher efficiencies, longer lifetimes, sunny locations, less carbon intensive manufacturing inputs, and shifting to thin films could reduce future life-cycle impacts.

Another environmental concern with large PV power plants is the conversion of land to collect solar energy (Hernandez et al. 2015). Approximately 2 hectares of land are needed for 1 MW of solar electricity capacity (Kabir et al. 2018; Perpiña Castillo et al. 2016); at 20% efficiency, a square of PV panels of 550 km by 550 km, comprising 0.2% of Earth's land area, could meet global energy demand. Land conversion can have local impacts, especially near cities and where land used for solar competes with alternative uses, such as agriculture. Large installations can also adversely impact biodiversity (Hernandez et al. 2014), especially where the above ground vegetation is cleared and soils are typically graded. Landscape fragmentation creates barriers to the movement of species. However, a variety of means have emerged to mitigate land use issues. Substitution among renewables can reduce land conversion (Tröndle and Trondle 2020). Solar can be integrated with other uses through 'agrivoltaics' (the use of land for both agriculture and solar production) (Dupraz et al. 2011) by, for example, using shade-tolerant crops (Dinesh and Pearce 2016). Combining solar and agriculture can also create income diversification, reduced drought stress, higher solar output due to radiative cooling, and other benefits (Elamri et al. 2018; Hassanpour Adeh et al. 2018; Barron-Gafford et al. 2019). PV installations floating on water also avoid land-use conflicts (Sahu et al. 2016; Lee et al. 2020), as does dual-use infrastructure, such as landfills (Jäger-Waldau 2020) and reservoirs where evaporation can also be reduced (Farfan and Breyer 2018).

Material demand for PV will likely increase substantially to limit warming to well below 2°C, but PV materials are widely available, have possible substitutes, and can be recycled (*medium confidence*) (Box 6.4). The primary materials for PV are silicon, copper, glass, aluminium, and silver, the costliest being silicon and glass being the most essential by mass, at 70%. None of these materials is considered to be either critical or potentially scarce (IEA 2020e). Thin-film cells, such as amorphous silicon, cadmium telluride and copper indium gallium diselenide (CIGS), use far less material (though they use more glass), but account for less than 10% of the global solar market. Other thin-films, such as those based on perovskites, organic solar cells, or earth-abundant, non-toxic materials such as kesterites, either on their own, or layered on silicon, could further reduce material use per energy produced. (Box 6.4)

After a typical lifetime of 30 years of use, PV modules can be recycled to prevent environmental contamination from the toxic materials within them, reusing valuable materials and avoiding waste accumulation. Recycling allows the reuse of nearly all - 83% in one study - of the components of PV modules, other than plastics (Ardente et al. 2019) and would add less than 1% to lifecycle GHG emissions (Latunussa et al. 2016). Glass accounts for 70% of the mass of a solar cell and is relatively easy to recycle. Recycling technology is advancing, but the scale and share of recycling is still small (Li et al. 2020d). By 2050, however, end-of-life PV could total 80 MT and comprise 10% of global electronic waste (Stolz and Frischknecht 2017), although most of it is glass. IEA runs a program to enable PV recycling by sharing best practices to minimise recycling life cycle impacts. Ensuring that a substantial amount of panels are recycled at end of life will likely require policy incentives, as the market value of the recovered materials, aside from aluminium and copper, is likely to be too low to justify recycling on its own (Deng et al. 2019). A near-term priority is maximizing the recovery of silver, silicon, and aluminium, the most valuable PV material components (Heath et al. 2020).

Many alternative PV materials are improving in efficiency and stability, providing longer-term pathways for continued PV costs reductions and better performance (*high confidence*). While solar PV based on semi-conductors constructed from wafers of silicon still captures 90% of the market, new designs and materials have the potential to reduce costs further, increase efficiency, reduce resource use, and open new applications. The most significant technological advance within silicon PV in the past ten years has been the widespread adoption of the passivated emitter and rear cell (PERC) design (Green 2015), which now accounts for the majority of production. This advance boosts efficiency over traditional aluminium backing by increasing reflectivity within the cell and reducing electron hole recombination (Blakers 2019). Bifacial modules increase efficiency by using reflected light from the ground or roof on the backside of modules (Guerrero-Lemus et al. 2016). Integrating PV into buildings can reduce overall costs and improve building energy performance (Shukla et al. 2016). Concentrating PV uses lenses or mirrors that collect and concentrate light onto high efficiency PV cells (Li et al. 2020a). Beyond crystalline silicon, thin films of amorphous silicon, cadmium telluride, and copper indium gallium selenide (among others) have the potential for much lower costs while their efficiencies have increased (Green et al. 2019). Perovskites, inexpensive and easy to produce crystalline structures, have increased in efficiency by a factor of six in the past decade; the biggest challenge is light-induced degradation as well as finding lead-free efficient compounds or establish lead recycling at the end of the life cycle of the device (Petrus et al. 2017; Chang et al. 2018; Wang et al. 2019b; Zhu et al. 2020). Organic solar cells are made of carbon-based semiconductors like the ones found in the displays made from organic light emitting diodes (OLEDs) and can be processed in thin films on large areas with scalable and fast coating processes on plastic substrates. The main challenges are raising the efficiency and improving their lifetime (Ma et al. 2020; Riede et al. 2021). Quantum dots, spherical semi-conductor nano-crystals, can be tuned to absorb specific wavelengths of sunlight giving them the potential for high efficiency with very little material use (Kramer et al. 2015). A common challenge for all emerging solar cell technologies is developing the corresponding production equipment. Hybrids of silicon with layers of quantum dots and perovskites have the potential to take advantage of the benefits of all three, although those designs require that these new technologies have stability and scale that match those of silicon (Palmstrom et al. 2019; Chang et al. 2017). This broad array of alternatives to making PV from crystalline silicon offer realistic potential for lower costs, reduced material use, and higher efficiencies in future years (Victoria et al. 2021).

Besides PV, alternative solar technologies exist, including CSP, which can provide special services in high-temperature heat and diurnal storage, even if it is more costly than PV and its potential for deployment is limited. CSP uses reflective surfaces, such as parabolic mirrors, to focus sunlight on a receiver to heat a working fluid, which is subsequently transformed into electricity (Islam et al. 2018). Solar heating and cooling are also well established technologies, and solar energy can be utilized directly for domestic or commercial applications such as drying, heating, cooling, and cooking (Ge et al. 2018). Solar chimneys, still purely conceptual, heat air using large transparent greenhouse-like structures and channel the warm air to turbines in tall chimneys (Kasaeian et al. 2017). Solar energy can also be used to produce solar fuels, for example, hydrogen or synthetic gas (syngas) (Nocera 2017; Montoya et al. 2016; Detz et al. 2018). In addition, research proceeds on space-based solar PV, which takes advantage of high insolation and a continuous solar resource (Kelzenberg et al. 2018), but faces the formidable obstacle of developing safe, efficient, and inexpensive microwave or laser transmission to the Earth's surface (Yang et al. 2016). CSP is the most widely adopted of these alternative solar technologies.

Like PV, CSP facilities can deliver large amounts of power (up to 200 MW per unit) and maintain substantial thermal storage, which is valuable for load balancing over the diurnal cycle (McPherson et al. 2020). However, unlike PV, CSP can only use direct sunlight, constraining its cost-effectiveness to North Africa, the Middle East, Southern Africa, Australia, the Western U.S., parts of South America (Peru, Chile), the Western part of China, and Australia (Deng et al. 2015; Dupont et al. 2020). Parabolic troughs, central towers and parabolic dishes are the three leading solar thermal technologies (Wang et al. 2017d). Parabolic troughs represented approximately 70% of new capacity in 2018 with the balance made up by central tower plants (Islam et al. 2018). Especially promising research directions are on tower-based designs that can achieve high temperatures, useful for industrial heat and energy storage (Mehos et al. 2017), and direct steam generation designs (Islam et al. 2018). Costs of CSP have fallen by nearly half since AR5 (Figure 6.8) albeit at a slower rate than PV. Since AR5, almost all new CSP plants have storage (Figure 6.9)(Thonig 2020).

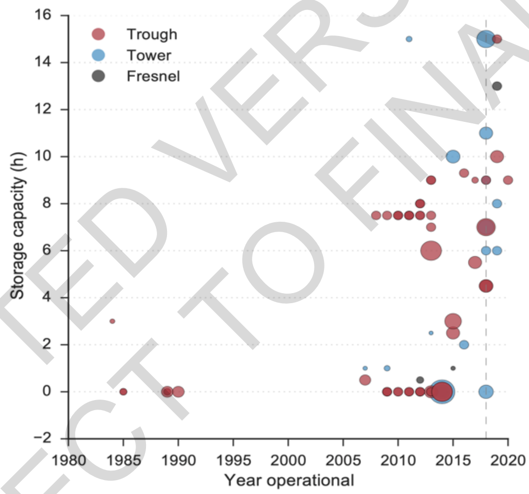


Figure 6.9 CSP plants by storage capacity in hours (vertical), year of installation (horizontal), and size of plant in MW (circle size). Since AR5, almost all new CSP plants have storage (Thonig 2020). Data source: https://csp.guru/metadata.html.

Solar energy elicits favourable public responses in most countries (*high confidence*) (Bessette and Arvai 2018; Hanger et al. 2016; Jobin and Siegrist 2018; Ma et al. 2015; Mcgowan and Sauter 2005; Hazboun and Boudet 2020; Roddis et al. 2019). Solar energy is perceived as clean and environmentally friendly with few downsides (Faiers and Neame 2006; Whitmarsh et al. 2011b). Key motivations for homeowners to adopt photovoltaic systems are expected financial gains, environmental benefits, the desire to become more self-sufficient, and peer expectations (Korcaj et al. 2015; Palm 2017; Vasseur and Kemp 2015). Hence, the observability of photovoltaic systems can facilitate adoption (Boudet 2019). The main barriers to the adoption of solar PV by households are its high upfront costs, aesthetics, landlord-tenant incentives, and concerns about performance and reliability (Whitmarsh et al. 2011b; Vasseur and Kemp 2015; Faiers and Neame 2006).

6.4.2.2 Wind Energy

Wind power is increasingly competitive with other forms of electricity generation and is the low-cost option in many applications (*high confidence*). Costs have declined by 18% and 40% on land and offshore since 2015 (*high confidence*), and further reductions can be expected by 2030 (*medium confidence*). Critical areas for continued improvement are technology advancements and economies of scale (*high confidence*). Global future potential is primarily limited by onshore land availability in wind power-rich areas, lack of supporting infrastructure, grid integration, and access to finance (especially in developing countries) (*high confidence*).

Energy from wind is abundant, and the estimated technical potentials surpass the total amount of energy needed to limit warming to well below 2°C (*high confidence*). Recent global estimates of potentially exploitable wind energy resource are in the range of 557–717 PWh yr^{-1} (2005–2580 EJ yr^{-1}) (Eurek et al. 2017; Bosch et al. 2017, 2018; McKenna et al. 2022), or 20–30 times the 2017 global electricity demand. Studies have suggested that 'bottom-up' approaches may overestimate technical potentials (Miller et al. 2015; Kleidon and Miller 2020). But even in the most conservative 'top-down' approaches, the technical wind potential surpasses the amount needed to limit warming to well below 2°C (Bosch et al. 2017; Eurek et al. 2017; Volker et al. 2017). The projected climate change mitigation from wind energy by 2100 ranges from 0.3°C–0.8°C depending on the precise socio-economic pathway and wind energy expansion scenario followed (Barthelmie and Pryor 2021). Wind resources are unevenly distributed over the globe and by time of the year (Petersen and Troen 2012), but potential hotspots exist on every continent (Figure 6.10) as expressed by the wind power density (a quantitative measure of wind energy available at any location). Technical potentials for onshore wind power vary considerably, often because of inconsistent assessments of suitability factors (McKenna et al. 2020). The potential for offshore wind power is larger than for onshore because offshore wind is stronger and less variable (Bosch et al. 2018). Offshore wind is more expensive, however, because of higher costs for construction, maintenance, and transmission. Wind power varies at a range of time scales, from annual to sub-seconds; the effects of local short-term variability can be offset by power plant control, flexible grid integration, and storage (Barra et al. 2021) (section 6.4.3). In some regions, interannual variations in wind energy resources could be important for optimal power system design (Wohland et al. 2019a; Coker et al. 2020).

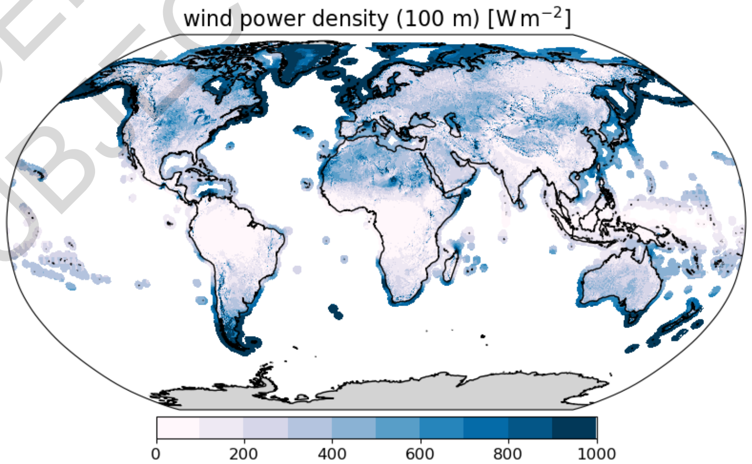


Figure 6.10 Mean wind power density [W m^{-2}] at 100 m above ground level over land and within 100 km of the coastline. Source: Global Wind Atlas https://globalwindatlas.info/

Wind power cost reductions (Figure 6.11) are driven mainly by larger capacity turbines, larger rotor diameters and taller hub heights - larger swept areas increase the energy captured and the capacity factors for a given wind speed; taller towers provide access to higher wind speeds (Beiter et al. 2021). All major onshore wind markets have experienced rapid growth in both rotor diameter (from 81.2 m in 2010 to 120 m in 2020) (IRENA 2021b), and average power ratings (from 1.9 MW in 2010 to 3 MW in 2020). The generation capacity of offshore wind turbines grew by a factor of 3.7 in less than two decades, from 1.6 MW in 2000 to 6 MW in 2020 (Wiser et al. 2021). Floating foundations could revolutionize offshore wind power by tapping into the abundant wind potential in deeper waters. This technology is particularly important for regions where coastal waters are too deep for fixed-bottom wind turbines. Floating wind farms potentially offer economic and environmental benefits compared with fixed-bottom designs due to less-invasive activity on the seabed during installation, but the long-term ecological effects are unknown and meteorological conditions further offshore and in deeper waters are harsher on wind turbine components (IRENA 2019c). A radical new class of wind energy converters has also been conceived under the name of Airborne Wind Energy Systems that can harvest strong, high-altitude winds (typically between 200–800m), which are inaccessible by traditional wind turbines (Cherubini et al. 2015). This technology has seen development and testing of small devices (Watson et al. 2019).

Wind capacity factors have increased over the last decade (Figure 6.11). The capacity factor for onshore wind farms increased from 27% in 2010 to 36% in 2020 (IRENA 2021a). The global average offshore capacity factor has decreased from a peak of 45% in 2017. This has been driven by the increased share of offshore development in China, where projects are often near-shore and use smaller wind turbines than in Europe (IRENA 2021b). Improvements in capacity factors also come from increased functionality of wind turbines and wind farms. Manufactures can adapt the wind turbine generator to the wind conditions. Turbines for windy sites have smaller generators and smaller specific capacity per rotor area, and therefore operate more efficiently and reach full capacity for a longer time period (Rohrig et al. 2019).

Electricity from onshore wind is less expensive than electricity generated from fossil fuels in a growing number of markets (*high confidence*). The global average LCOE onshore declined by 38% from 2010 to 2020 (Figure 6.11), reaching USD 0.039 kWh^{-1}. However, the decrease in cost varies substantially by region. Since 2014, wind costs have declined more rapidly than the majority of experts predicted (Wiser et al. 2021). New modelling projects onshore wind LCOE of USD .037 kWh^{-1} by 2030 (Junginger et al. 2020a), and additional reductions of 37–39% have been predicted by 2050 (Wiser et al. 2021). The future cost of offshore wind is more uncertain because other aspects besides increases in capacity factors influence the cost (Junginger et al. 2020b).

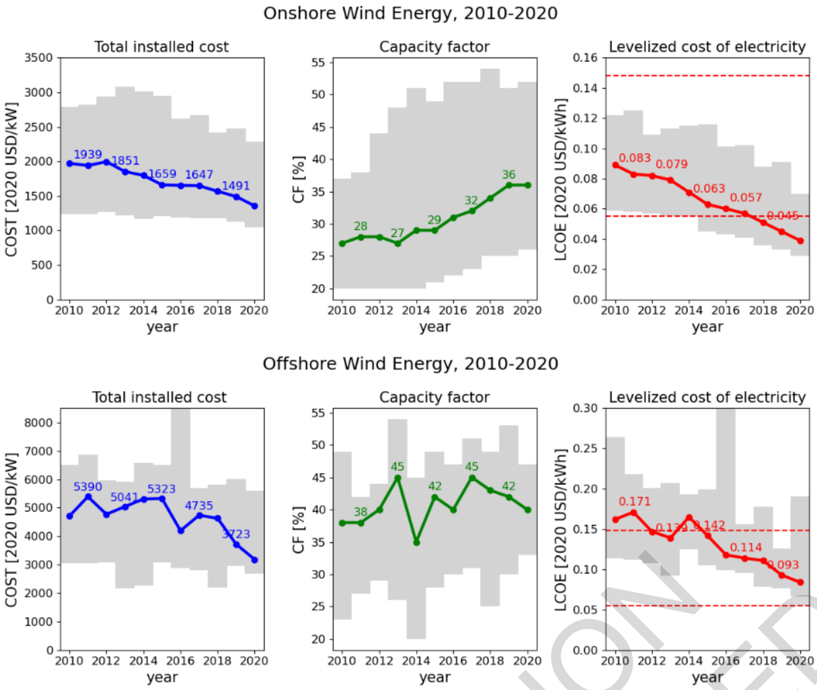


Figure 6.11 Global weighted average total installed costs, capacity factors, and LCOE for onshore (top) and offshore (bottom) wind power of existing power plants per year (2010-2020). The shaded area represents the 5th and 95th percentiles and the red dashed line represents the fossil fuel cost range. Source: (IRENA 2021a)

The cost of the turbine (including the towers) makes up the largest component of wind's LCOE. Total installed costs for both onshore and offshore wind farms have decreased since 2015 (Figure 6.11), but the total installed costs for onshore wind projects are very site- and market-specific, as reflected in the range of LCOEs. China, India, and the U.S. have experienced the largest declines in total installed costs. In 2020, typical country-average total installed costs were around USD 1150 kW^{-1} in China and India, and between USD 1403–2472 kW^{-1} elsewhere (IRENA 2021b). Total installed costs of offshore wind farms declined by 12% between 2010 and 2020. But, because some of the new offshore wind projects have moved to deeper waters and further offshore, there are considerable year-to-year variations in their price (IRENA 2021b). Projects outside China in recent years have typically been built in deeper waters (10–55 m) and up to 120 km offshore, compared to around 10 m in 2001–2006, when distances rarely exceeded 20 km. With the shift to deeper waters and sites further from ports, the total installed costs of offshore wind farms rose, from an average of around USD 2500 kW^{-1} in 2000 to around USD 5127 kW^{-1} by 2011–2014, before falling to around USD 3185 kW^{-1} in 2020 (IRENA 2020a). The full cost of wind power includes the transmission and system integration costs (Sections 6.4.3, 6.4.6. A new technology in development is the co-location of wind and solar PV power farms, also known as hybrid power plants. Co-locating wind, solar PV, and batteries can lead to synergies in electricity generation, infrastructure, and land usage, which may lower the overall plant cost compared to single technology systems (Lindberg et al. 2021).

Wind power plants pose relatively low environmental impact, but sometimes locally significant ecological effects (*high confidence*). The environmental impact of wind technologies, including CO_2 emissions, is concentrated in the manufacturing, transport, and building stage and in disposal as the end-of-life of wind turbines is reached (Liu and Barlow 2017; Mishnaevsky 2021). The operation of wind turbines produces no waste or pollutants. The LCA for wind turbines is strongly influenced by the operating lifetime, quality of wind resources, conversion efficiency, and size of the wind turbines

(Laurent et al. 2018; Kaldellis and Apostolou 2017). But, all wind power technologies repay their carbon footprint in less than a year (Bonou et al. 2016).

Wind farms can cause local ecological impacts, including impacts on animal habitat and movements, biological concerns, bird and bat fatalities from collisions with rotating blades, and health concerns (Morrison and Sinclair 2004). The impacts on animal habitats and collisions can be resolved or reduced by selectively stopping some wind turbines in high risk locations, often without affecting the productivity of the wind farm (de Lucas et al. 2012). Many countries now require environmental studies of impacts of wind turbines on wildlife prior to project development, and, in some regions, shutdowns are required during active bird migration (de Lucas et al. 2012). Offshore wind farms can also impact migratory birds and other sea species (Hooper et al. 2017). Floating foundations pose lower environmental impacts at build stage (IRENA 2019c), but their cumulative long-term impacts are unclear (Goodale and Milman 2016). Recent studies find weak associations between wind farm noise and measures of long-term human health (Poulsen et al. 2018a,b, 2019a,b).

Public support for onshore and particularly offshore wind energy is generally high, although people may oppose specific wind farm projects (*high confidence*) (e.g., Rand and Hoen 2017; Steg 2018; Bell et al. 2005; Batel and Devine-Wright 2015). People generally believe that wind energy is associated with environmental benefits and that it is relatively cheap. Yet, some people believe wind turbines can cause noise and visual aesthetic pollution, threaten places of symbolic value (Russell et al. 2020; Devine-Wright and Wiersma 2020), and have adverse effects on wildlife (Bates and Firestone 2015), which challenges public acceptability (Rand and Hoen 2017). Support for local wind projects is higher when people believe fair decision-making procedures have been implemented (Aitken 2010a; Dietz and Stern 2008). Evidence is mixed whether distance from wind turbines or financial compensation increases public acceptability of wind turbines (Hoen et al. 2019; Rand and Hoen 2017; Cass et al. 2010; Rudolph et al. 2018). Offshore wind farms projects have higher public support, but can also face resistance (Rudolph et al. 2018; Bidwell 2017).

Common economic barriers to wind development are high initial cost of capital, long payback periods, and inadequate access to capital. Optimal wind energy expansion is most likely to occur in the presence of a political commitment to establish, maintain, and improve financial support instruments, technological efforts to support a local supply chains, and grid investments integrate VRE electricity (Diógenes et al. 2020).

[START BOX 6.4 HERE]

Box 6.4 Critical strategic minerals and a low-carbon energy system transition

The secure supply of many metals and minerals (e.g., cobalt, copper, lithium, and rare earth elements, REEs) is critical to supporting a low-emissions energy system transition (Sovacool et al. 2020). A low-carbon energy system transition will increase the demand for these minerals to be used in technologies like wind turbines, PV cells, and batteries (World Bank 2020). Reliance on these minerals has raised questions about possible constraints to a low-carbon energy system transition, including supply chain disruptions (Chapter 10.6). Concerns have also been raised about mining for these materials, which frequently results in severe environmental impacts (Sonter et al. 2020), and metal production itself is energy-intensive and difficult to decarbonize (Sovacool et al. 2020).

Wind energy depends on two critical REEs - neodymium and dysprosium - used in magnets in high-performance generators (Pavel et al. 2017; Li et al. 2020b). Silicon-wafer-based solar PV, which accounted for 95% of PV production in 2020, does not use REEs but utilizes aluminium, copper, and silver (IEA 2021a). Lithium, nickel, cobalt, and phosphorous are used in batteries. Many critical minerals are used in EVs, including aluminium and copper in manufacturing the necessary EV charging infrastructure, and neodymium in permanent magnet motors.

These strategic minerals are found in a limited number of countries, and concerns have been raised that geopolitical factors could disrupt the supply chain necessary for a low-carbon energy system transition. However, excluding cobalt and lithium, no single country holds more than a third of the world reserves. The known supply of some strategic minerals is still close to 600 years at current levels of demand (BP 2020), but increased demand would cut more quickly into supplies.

There are alternatives to the strategic minerals currently used to support a low-carbon transition. Wind turbines can be manufactured without permanent magnets to reduce the need for strategic minerals, but the production costs are higher, and their efficiency is reduced (Månberger and Stenqvist 2018). Alternatives to silicon, such as thin films, could be used to produce PVs. Thin-films use much less material than silicon-based PV, but they contain other potentially critical metals like tellurium, cadmium, and gallium. Alternatives to lithium-ion batteries, such as sodium-ion batteries, are becoming more practical and feasible (Sovacool et al. 2020).

[END BOX 6.4HERE]

6.4.2.3 Hydroelectric Power

Hydropower is technically mature, proved worldwide as a primary source of renewable electricity, and may be used to balance electricity supply by providing flexibility and storage. The LCOE of hydropower is lower than the cheapest new fossil fuel-fired option. However, the future mitigation potential of hydropower depends on minimizing environmental and social impacts during the planning stages, reducing the risks of dam failures, and modernising the aging hydropower fleet to increase generation capacity and flexibility (*high confidence*).

Estimates of global gross theoretical available hydropower potential varies from 31–128 PWh yr^{-1} (112–460 EJ yr^{-1}), exceeding total electricity production in 2018 (Banerjee et al. 2017; IEA 2021d; BP 2020). This potential is distributed over 11.8 million locations (Figure 6.12), but many of the locations cannot be developed for (current) technical, economic, or political reasons. The estimated technical potential of hydropower is 8–30 PWh yr^{-1} (29–108 EJ yr^{-1}), and its estimated economic potential is 8–15 PWh yr^{-1} (29–54 EJ yr^{-1}) (van Vliet et al. 2016c; Zhou et al. 2015). Actual hydropower generation in 2019 was 4.2 PWh (15.3 EJ), providing about 16% of global electricity and 43% of global electricity from renewables (BP 2020; Killingtveit 2020; IEA 2020f). Asia holds the largest hydropower potential (48%), followed by S. America (19%) (Hoes et al. 2017).

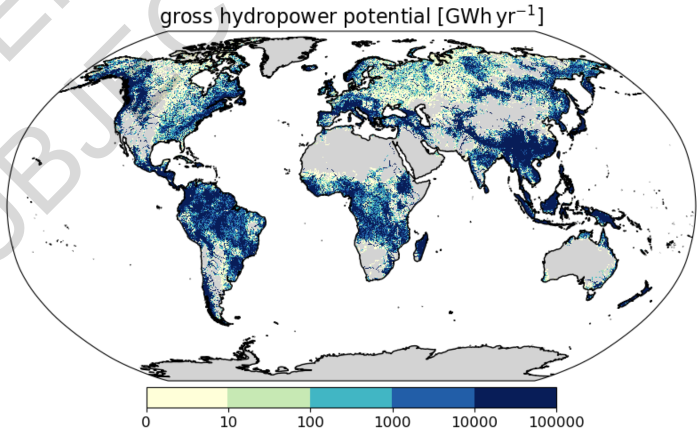


Figure 6.12 Global map of gross hydropower potential distribution [GWh yr^{-1}], Data: (Hoes et al. 2017)

Hydropower is a mature technology with locally adapted solutions (*high confidence*) (Zhou et al. 2015; Killingtveit 2020). The peak efficiency of hydroelectric plants is greater than 85%. Hydropower plants without storage or with small storage typically produce a few kWs to 10 MWs (examples of such plants producing higher amounts do exist), and are useful for providing electricity at a scale from households to small communities (El Bassam et al. 2013; Towler 2014). However, hydropower plants without or with small storage may be susceptible to climate variability, especially droughts, when the amount of water may not be sufficient to generate electricity (see Section 6.5, Premalatha et al. 2014).

Hydropower plants with storage may produce 10 GW, reaching over 100 TWh yr^{-1} (0.36 EJ yr^{-1}), but generally require large areas. Pumped storage hydropower stores energy by pumping water to higher reservoirs during low-demand periods (Killingtveit 2020). The storage in hydropower systems provides flexibility to compensate for rapid variations in electricity loads and supplies. The regulating characteristics of the storage play an important role in assuring continuity of energy supply from renewable sources (Yang et al. 2018b).

Hydropower is one of the lowest-cost electricity technologies (Mukheibir 2013; IRENA 2021b). Its operation and maintenance costs are typically 2–2.5% of the investment costs per kW yr^{-1} for a lifetime of 40–80 years (Killingtveit 2020). Construction costs are site specific. The total cost for an installed large hydropower project varies from USD 10,600–804,500 kW^{-1} if the site is located far away from transmission lines, roads, and infrastructure. Investment costs increase for small hydropower plants and may be as high as USD 100,000 kW^{-1} or more for the installation of plants of less than 1 MW - 20% to 80% more than for large hydropower plants (IRENA 2015). During the past 100 years, total installed costs and LCOE have risen by a few percent, but the LCOE of hydropower remains lower than the cheapest new fossil fuel-fired option (IRENA 2019b, 2021).

Hydroelectric power plants may pose serious environmental and societal impacts (*high confidence*) (Mccartney 2009). Dams may lead to fragmentation of ecological habitats because they act as barriers for migration of fish and other land and water-borne fauna, sediments, and water flow. These barriers can be mitigated by sediment passes and fish migration aids, and with provision of environmental flows. Below dams, there can be considerable alterations to vegetation, natural river flows, retention of sediments and nutrients, and water quality and temperature. Construction of large reservoirs leads to loss of land, which may result in social and environmental consequences. Minimizing societal and environmental impacts requires taking into account local physical, environmental, climatological, social, economic, and political aspects during the planning stage (Killingtveit 2020). Moreover, when large areas of land are flooded by dam construction, they generate GHGs (Phyoe and Wang 2019; Maavara et al. 2020; Prairie et al. 2018). On the other hand, hydropower provides flexible, competitive low-emission electricity, local economic benefits (e.g., by increasing irrigation and electricity production in developing countries), and ancillary services such as municipal water supply, irrigation and drought management, navigation and recreation, and flood control (IRENA 2021b). However, the long term economic benefits to communities affected by reservoirs are a subject of debate (de Faria et al. 2017; Catolico et al. 2021).

Public support for hydroelectric energy is generally high (Steg 2018), and higher than support for coal, gas, and nuclear. Yet, public support for hydro seems to differ for existing and new projects (*high confidence*). Public support is generally high for small and medium scale hydropower in regions where hydropower was historically used (Gormally et al. 2014). Additionally, there is high support for existing large hydropower projects in Switzerland (Plum et al. 2019; Rudolf et al. 2014), Canada (Boyd et al. 2019), and Norway (Karlstrøm and Ryghaug 2014), where it is a trusted and common energy source. Public support seems lower for new hydropower projects (Hazboun and Boudet 2020), and the construction of new large hydropower plants has been met with strong resistance in some areas (Bronfman et al., 2015; Vince, 2010). People generally perceive hydroelectric energy as clean and a non-contributor to climate change and environmental pollution (Kaldellis et al. 2013). For example, in Sweden, people believed that existing hydropower projects have as few negative environmental impacts as solar, and even less than wind (Ek 2005). However, in areas where the construction of new large-scale hydroelectric energy is met with resistance, people believe that electricity generation from hydro can cause environmental, social, and personal risks (Bronfman et al., 2012; Kaldellis et al., 2013).

The construction time of hydroelectric power plants is longer than many other renewable technologies, and that construction time may be extended by the additional time it takes to fill the reservoir. This extended timeline can create uncertainty in the completion of the project. The uncertainty is due to insecurity in year-to-year variations in precipitation and the water inflows required to fill reservoirs. This is especially critical in the case of trans-boundary hydroelectric power plants, where filling up the reservoirs can have large implications on downstream users in other nations. As a result of social and environmental constraints, only a small fraction of potential economic hydropower projects can be developed, especially in developed countries. Many developing countries have major undeveloped hydropower potential, and there are opportunities to develop hydropower combined with other economic activities such as irrigation (Lacombe et al. 2014). Competition for hydropower across country borders can lead to conflict, which could be exacerbated if climate alters rainfall and streamflow (Ito et al. 2016).

6.4.2.4 Nuclear Energy

Nuclear power can deliver low-carbon energy at scale (*high confidence*). Doing so will require improvements in managing construction of reactor designs that hold the promise of lower costs and broader use (*medium confidence*). At the same time, nuclear power continues to be affected by cost overruns, high up-front investment needs, challenges with final disposal of radioactive waste, and varying public acceptance and political support levels (*high confidence*).

There are sufficient resources for substantially increasing nuclear deployment (*medium confidence*). Estimates for identified uranium resources have been increasing steadily over the years. Conventional uranium resources have been estimated to be sufficient for over 130 years of supply at current levels of use; 100 years were estimated in 2009 (Hahn 1983; NEA/IAEA 2021). In the case of future uranium resource scarcity, thorium or recycling of spent fuel might be used as alternatives. Interest in these alternatives has waned with better understanding of uranium deposits, their availability, and low prices (OECD NEA 2015; IAEA 2005).

There are several possible nuclear technology options for the period from 2030 to 2050 (*medium confidence*). In addition to electricity, nuclear can also be used to produce low-carbon hydrogen and freshwater (Kayfeci et al. 2019; Kavvadias and Khamis 2014)

- **Large reactors**. The nuclear industry has entered a new phase of reactor construction, based on evolutionary designs. These reactors achieve improvements over previous designs through small to moderate modifications, including improved redundancy, increased application of passive safety features, and significant improvements to containment design to reduce the risk of a major accident (MIT 2018). Examples include European - EPR, Korean - APR1400, U.S. - AP1000, Chinese - HPR1000 or Russian - VVER-1200.
- **Long-term operation (LTO) of the current fleet**. Continued production from nuclear power will depend in part on life extensions of the existing fleet. By the end of 2020, two-thirds of nuclear power reactors will have been operational for over 30 years. The design lifetime of most of existing reactors is 30–40 years. Engineering assessments have established that reactors can operate safely for longer if key replaceable components (e.g., steam generator, mechanical and electrical equipment, instrumentation and control parts) are changed or refurbished (IAEA 2018). The first lifetime extension considered in most of the countries typically is 10–20 years (OECD IEA NEA 2020).
- **Small Modular Reactors**. There are more than 70 SMR designs at different stages of consideration and development, from the conceptual phase to licensing and construction of first-of-a-kind facilities (IAEA 2020). Due to smaller unit sizes, the SMRs are expected to have lower total investment costs, although the cost per unit of generation might be higher than conventional large reactors (Mignacca and Locatelli 2020). Modularity and off-site pre-production may allow greater efficiency in construction, shorter delivery times, and overall cost optimization (IEA 2019c). SMR

designs aim to offer an increased load-following capability that makes them suitable to operate in smaller systems and in systems with increasing shares of VRE sources. Their market development by the early 2030s will strongly depend on the successful deployment of prototypes during the 2020s.

Nuclear power costs vary substantially across countries (*high confidence*). First-of-a-kind projects under construction in Northern America and Europe have been marked by delays and costs overruns (Berthelemy and Rangel 2015). Construction times have exceeded 13–15 years and cost has surpassed 3–4 times initial budget estimates (OECD IEA NEA 2020). In contrast, most of the recent projects in Eastern Asia (with construction starts from 2012) were implemented within 5–6 years (IAEA PRIS 2021). In addition to region-specific factors, future nuclear costs will depend on the ability to benefit from the accumulated experience in controlling the main drivers of cost. These cost drivers fall into four categories: design maturity, project management, regulatory stability and predictability, and multi-unit and series effects (NEA 2020). With lessons learned from first-of-a-kind projects, the cost of electricity for new builds are expected to be in the range of USD 42–102 MWh^{-1} depending on the region (OECD IEA NEA 2020).

Lifetime extensions are significantly cheaper than new builds and cost competitive with other low-carbon technologies. The overnight cost of lifetime extensions is estimated in the range of USD 390–630 kWe^{-1} for Europe and North America, and the LCOE in the range of USD 30–36 MWh^{-1} for extensions of 10–20 years (OECD IEA NEA 2020).

Cost-cutting opportunities, such as design standardization and innovations in construction approaches, are expected to make SMRs competitive against large reactors by 2040 (Rubio and Tricot 2016) (*medium confidence*). As SMRs are under development, there is substantial uncertainty regarding the construction costs. Vendors have estimated first-of-a-kind LCOEs at USD 131–190 MWh^{-1}. Effects of learning for nth-of-a-kind SMR are anticipated to reduce the first-of-a-kind LCOE by 19–32%.

Despite low probabilities, the potential for major nuclear accidents exists, and the radiation exposure impacts could be large and long-lasting (Steinhauser et al. 2014). However, new reactor designs with passive and enhanced safety systems reduce the risk of such accidents significantly (*high confidence*). The (normal) activity of a nuclear reactor results in low volumes of radioactive waste, which requires strictly controlled and regulated disposal. On a global scale, roughly 421 ktons of spent nuclear fuel have been produced since 1971 (IEA 2014). Out of this volume, 2–3% is high-level radioactive waste, which presents challenges in terms of radiotoxicity and decay longevity, and ultimately entails permanent disposal.

Nuclear energy is found to be favourable regarding land occupation (Cheng and Hammond 2017; Luderer et al. 2019) and ecological impacts (Brook and Bradshaw 2015; Gibon et al. 2017). Similarly, bulk material requirements per unit of energy produced are low (e.g. aluminum, copper, iron, rare earth metals) (Vidal et al. 2013; Luderer et al. 2019). Water-intensive inland nuclear power plants may contribute to localized water stress and competition for water uses. The choice of cooling systems (closed-loop instead of once-through) can significantly moderate withdrawal rates of the freshwater (Jin et al. 2019; Fricko et al. 2016; Mouratiadou et al. 2016; Meldrum et al. 2013). Reactors situated on the seashore are not affected by water scarcity issues (JRC EU 2021). Life cycle assessment (LCA) studies suggest that the overall impacts on human health (in terms of disability adjusted life years (DALYs) from the normal operation of nuclear power plants are substantially lower than those caused by fossil fuel technologies and are comparable to renewable energy sources (Treyer et al. 2014; Gibon et al. 2017).

Nuclear power continues to suffer from limited public and political support in some countries (*high confidence*). Public support for nuclear energy is consistently lower than for renewable energy and natural gas, and in many countries as low as support for energy from coal and oil (Hobman and

Ashworth 2013; Corner et al. 2011; Pampel 2011). The major nuclear accidents (i.e. Three Mile Island, Chernobyl, and Fukushima) decreased public support (Poortinga et al. 2013; Bird et al. 2014). The public remains concerned about the safety risks of nuclear power plants and radioactive materials (Tsujikawa et al. 2016; Bird et al. 2014; Pampel 2011). At the same time, some groups see nuclear energy as a reliable energy source, beneficial for the economy and helpful in climate change mitigation. Public support for nuclear energy is higher when people are concerned about energy security, including concerns about the availability of energy and high energy prices (Gupta et al. 2019b; Groot et al. 2013), and when they expect local benefit (Wang et al. 2020c). Public support also increases when trust in managing bodies is higher (de Groot and Steg 2011). Similarly, transparent and participative decision-making processes enhance perceived procedural fairness and public support (Sjoberg 2004).

Because of the sheer scale of the investment required (individual projects can exceed USD 10 billion in value), nearly 90% of nuclear power plants under construction are run by state-owned or controlled companies with governments assuming significant part of the risks and costs. For countries that choose nuclear power in their energy portfolio, stable political conditions and support, clear regulatory regimes, and adequate financial framework are crucial for successful and efficient implementation.

Many countries have adopted technology-specific policies for low-carbon energy courses, and these policies influence the competitiveness of nuclear power. For example, feed-in-tariffs and feed-in premiums for renewables widely applied in the EU (Kitzing et al. 2012) or renewable portfolio standards in the U.S. (Barbose et al. 2016) impact wholesale electricity price (leading occasionally to low or even negative prices), which affects the revenues of existing nuclear and other plants (Bruninx et al. 2013; Newbery et al. 2018; Lesser 2019).

Nuclear power's long-term viability may hinge on demonstrating to the public and investors that there is a long-term solution to spent nuclear fuel. Evidence from countries steadily progressing towards first final disposals - Finland, Sweden and France - suggests that broad political support, coherent nuclear waste policies, and a well-managed, consensus-based decision-making process are critical for accelerating this process (Metlay 2016). Proliferation concerns surrounding nuclear power are related to fuel cycle (i.e., uranium enrichment and spent fuel processing). These processes are implemented in a very limited number of countries following strict national and internationals norms and rules, such as IAEA guidelines, treaties, and conventions. Most of the countries which might introduce nuclear power in the future for their climate change mitigation benefits do not envision developing their own full fuel cycle, significantly reducing any risks that might be linked to proliferation (IAEA 2014, 2019).

6.4.2.5 Carbon Dioxide Capture, Utilization, and Storage

Since AR5, there have been increased efforts to develop novel platforms that reduce the energy penalty associated with CO_2 capture, develop CO_2 utilization pathways as a substitute to geologic storage, and establish global policies to support CCS (*high confidence*). CCS can be used within electricity and other sectors. While it increases the costs of electricity, CCS has the potential to contribute significantly to low-carbon energy system transitions (IPCC 2018).

The theoretical global geologic storage potential is about 10,000 Gt-CO_2, with more than 80% of this capacity existing in saline aquifers (*medium confidence*). Not all the storage capacity is usable because geologic and engineering factors limit the actual storage capacity to an order of magnitude below the theoretical potential, which is still more than the CO_2 storage requirement through 2100 to limit temperature change to 1.5°C (Martin-Roberts et al. 2021) (*high confidence*). One of the key limiting factors associated with geologic CO_2 storage is the global distribution of storage capacity (Table 6.2). Most of the available storage capacity exists in saline aquifers. Capacity in oil and gas reservoirs and coalbed methane fields is limited. Storage potential in the U.S. alone is >1,000 Gt-CO_2, which is more than 10% of the world total (NETL 2015). The Middle East has more than 50% of global enhanced oil recovery potential (Selosse and Ricci 2017). It is likely that oil and gas reservoirs will be developed before saline aquifers because of existing infrastructure and extensive subsurface data (Alcalde et al. 2019; Hastings and Smith 2020). Notably, not all geologic storage is utilizable. In places with limited geologic storage, international CCS chains are being considered, where sources and sinks of CO_2 are located in two or more countries (Sharma and Xu 2021). For economic long-term storage, the desirable conditions are a depth of 800-3000 m, thickness of greater than 50 m and permeability greater than 500 mD (Singh et al. 2020; Chadwick et al. 2008). Even in reservoirs with large storage potential, the rate of injection might be limited by the subsurface pressure of the reservoir (Baik et al. 2018a). It is estimated that geologic sequestration is safe with overall leakage rates at <0.001% yr^{-1} (Alcalde et al. 2018). In many cases, geological storage resources are not located close to CO_2 sources, increasing costs and reduces viability (Garg et al. 2017a).

Table 6.2 Geologic storage potential across underground formations globally. These represent order-of-magnitude estimates. Data: (Selosse and Ricci 2017)

Reservoir Type	Africa	Australia	Canada	China	CSA	EEU	FSU	India	MEA	Mexico	ODA	USA	WEU
Enhanced Oil Recovery	3	0	3	1	8	2	15	0	38	0	1	8	0
Depleted oil and gas fields	20	8	19	1	33	2	191	0	252	22	47	32	37
Enhanced Coalbed Methane Recovery	8	30	16	16	0	2	26	8	0	0	24	90	12
Deep saline aquifers	1000	500	667	500	1000	250	1000	500	500	250	1015	1000	250

CSA: Central and South America, EEU: Eastern Europe, FSU: Former Soviet Union, MEA: Middle East, ODA: Other Asia (except China and India), WEU: Western Europe.

CO_2 utilization (CCU) - instead of geologic storage - could present an alternative method of decarbonization (*high confidence*). The global CO_2 utilization potential, however, is currently limited to 1–2 $GtCO_2$ yr^{-1} for use of CO_2 as a feedstock (Hepburn et al. 2019; Kätelhön et al. 2019) but could increase to 20 $GtCO_2$ by the mid-century (*medium confidence*). CCU involves using CO_2 as a feedstock to synthesize products of economic value and as substitute to fossil feedstock. However, several CO_2 utilization avenues might be limited by energy availability. Depending on the utilization pathway, the CO_2 may be considered sequestered for centuries (e.g., cement curing, aggregates), decades (plastics), or only a few days or months (e.g. fuels) (Hepburn et al. 2019). Moreover, when carbon-rich fuel end-products are combusted, CO_2 is emitted back into the atmosphere. Because of presence of several industrial clusters (regions with high density of industrial infrastructure) globally, a number of regions demonstrate locations where CO_2 utilization potential could be matched with large point sources of CO_2 (Wei et al. 2020).

The technological development for several CO_2 utilization pathways is still in the laboratory, prototype, and pilot phases, while others have been fully commercialized (such as urea manufacturing). Technology development in some end-uses is limited by purity requirements for CO_2 as a feedstock. The efficacy of CCU processes depends on additional technological constraints such as CO_2 purity and pressure requirements. For instance, urea production requires CO_2 pressurized to 122 bar and purified to 99.9%. While most utilization pathways require purity levels of 95-99%, algae production may be carried out with atmospheric CO_2 (Ho et al. 2019; Voldsund et al. 2016).

Existing post-combustion approaches relying on absorption are technologically ready for full-scale deployment (*high confidence*). More novel approaches using membranes and chemical looping that might reduce the energy penalty associated with absorption are in different stages of development - ranging from laboratory phase to prototype phase (Abanades et al. 2015) (*high confidence*). There has been significant progress in post-combustion capture technologies that used absorption in solvents such as monoethanol amine (MEA). There are commercial-scale application of solvent-based absorption at two facilities – Boundary Dam since 2015 and Petra Nova (temporarily suspended) since 2017, with capacities of 1 and 1.6 $MtCO_2$ yr^{-1} respectively (Mantripragada et al. 2019; Giannaris et al. 2020a).

Several 2nd and 3rd generation capture technologies are being developed with the aim of not just lowering costs but also enhancing other performance characteristics such as improved ramp-up and lower water consumption. These include processes such as chemical looping, which also has the advantage of being capable of co-firing with biomass (Bhave et al. 2017; Yang et al. 2019). Another important technological development is the Allam cycle, which utilizes CO_2 as a working fluid and operates based on oxy-combustion capture. Applications using the Allam Cycle can deliver net energy efficiency greater than 50% and 100% CO_2 capture, but they are quite sensitive to oxygen and CO_2 purity needs (Scaccabarozzi et al. 2016; Ferrari et al. 2017).

CO_2 capture costs present a key challenge, remaining higher than USD 50 tCO_2^{-1} for most technologies and regions; novel technologies could help reduce some costs (*high confidence*). The capital cost of a coal or gas electricity generation facility with CCS is almost double one without CCS (Zhai and Rubin 2016; Rubin et al. 2015; Bui et al. 2018). Additionally, the energy penalty increases the fuel requirement for electricity generation by 13–44%, leading to further cost increases (Table 6.3).

Table 6.3 Costs and efficiency parameters of CCS in electric power plants. Data: (Muratori et al. 2017a)

	Capital Cost [USD kW^{-1}]	Efficiency [%]	CO_2 Capture Cost [USD ton-CO_2^{-1}]	CO_2 Avoided Cost [USD ton-CO_2^{-1}]
Coal (steam plant) + CCS	5800	28%	63	88
Coal (IGCC) + CCS	6600	32%	61	106
Natural Gas (CC) + CCS	2100	42%	91	33
Oil (CC) + CCS	2600	39%	105	95
Biomass (steam plant) + CCS	7700	18%	72	244
Biomass (IGCC) + CCS	8850	25%	66	242

In addition to reductions in capture costs, other approaches to reduce CCS costs rely on utilizing the revenues from co-products such as oil, gas, or methanol, and on clustering of large-point sources to reduce infrastructure costs. The potential for such reductions is limited in several regions due to low sink availability, but it could jumpstart initial investments (*medium confidence*). Injecting CO_2 into hydrocarbon formations for enhanced oil or gas recovery can produce revenues and lower costs (Edwards and Celia 2018). While enhanced oil recovery potential is <5% of the actual CCS needs, they can enable early pilot and demonstration projects (Núñez-López and Moskal 2019; Núñez-López et al. 2019). Substantial portions of CO_2 are effectively stored during enhanced oil recovery (Sminchak et al. 2020; Menefee and Ellis 2020). By clustering together of several CO_2 sources, overall costs may be reduced by USD 10 tCO_2^{-1} (Abotalib et al. 2016; Garg et al. 2017a), but geographical circumstances determine the prospects of these cost reductions via economies-of-scale. The major pathways for methanol, methane, liquid fuel production, and cement curing have costs greater than USD 500 tCO_2^{-1} (Hepburn et al. 2019). The success of these pathways therefore depends on the value of such fuels and on the values of other alternatives.

The public is largely unfamiliar with carbon capture, utilization, and storage technologies (Tcvetkov et al. 2019; L'Orange Seigo et al. 2014) (*high confidence*), and many people may not have formed stable attitudes and risk perceptions regarding these technologies (Daamen et al. 2006; Jones et al. 2015; Van Heek et al. 2017) *(medium confidence)*. In general, low support has been reported for CCS technologies (Allen and Chatterton 2013; Demski et al. 2017). When presented with neutral information on CCS, people favour other mitigation options such as renewable energy and energy efficiency (de Best-Waldhober et al. 2009; Scheer et al. 2013; Karlstrøm and Ryghaug 2014). Although few totally reject CCS, specific CCS projects have faced strong local resistance, which has contributed to the cancellation of CCS projects (Terwel et al. 2012; L'Orange Seigo et al. 2014). Communities may also consider CCU to be lower-risk and view it more favourably than CCS (Arning et al. 2019).

CCS requires considerable increases in some resources and chemicals, most notably water. Power plants with CCS could shutdown periodically due to water scarcity. In several cases, water withdrawals for CCS are 25–200% higher than plants without CCS (Yang et al. 2020; Rosa et al. 2020b) due to energy penalty and cooling duty. The increase is slightly lower for non-absorption technologies. In regions prone to water scarcity such as the Southwestern U.S. or Southeast Asia, this may limit deployment and result in power plant shutdowns during summer months (Liu et al. 2019b; Wang et al. 2019c). The water use could be managed by changing heat integration strategies and implementing reuse of wastewater (Magneschi et al. 2017; Giannaris et al. 2020b).

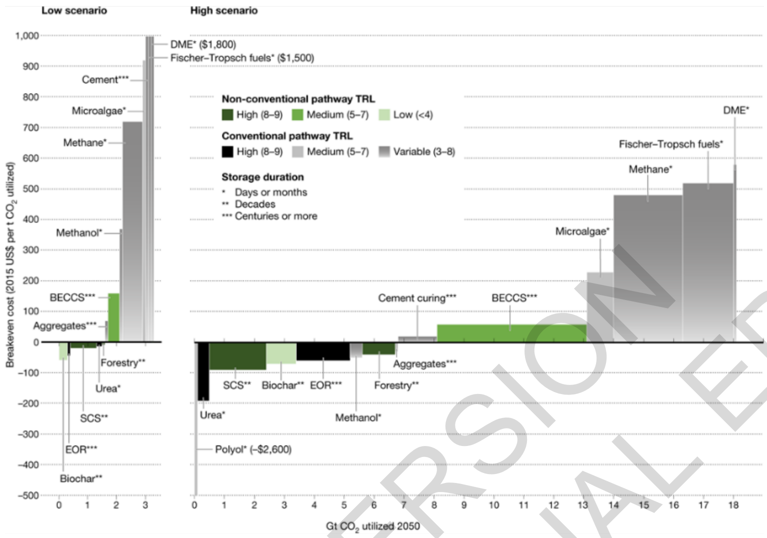


Figure 6.13 Costs and potential for different CO_2 utilization pathways (Hepburn et al. 2019)

Because CCS always adds cost, policy instruments are required for it to be widely deployed (*high confidence*). Relevant policy instruments include financial instruments such as emission certification and trading, legally enforced emission restraints, and carbon pricing (Haszeldine 2016; Kang et al. 2020). There are some recent examples of policy instruments specifically focused on promoting CCS. The recent U.S. 45Q tax credits offers nationwide tax credits for CO_2 capture projects above USD 35–50 tCO_2^{-1} which offset CO_2 capture costs at some efficient plants (Esposito et al. 2019). Similarly, California's low-carbon fuel standard offers benefits for CO_2 capture at some industrial facilities such as biorefineries and refineries (Von Wald et al. 2020).

6.4.2.6 Bioenergy

Bioenergy has the potential to be a high-value and large-scale mitigation option to support many different parts of the energy system. Bioenergy could be particularly valuable for sectors with limited alternatives to fossil fuels (e.g., aviation, heavy industry), production of chemicals and products, and, potentially, in carbon dioxide removal (CDR) via BECCS or biochar. While traditional biomass and first-generation biofuels are widely used today, the technology for large-scale production from advanced processes is not competitive, and growing dedicated bioenergy crops raises a broad set of sustainability concerns. Its long-term role in low-carbon energy systems is therefore uncertain (*high confidence*). [Note that this section focuses on the key technological developments for deployment of commercial bioenergy.]

Bioenergy is versatile: technology pathways exist to produce multiple energy carriers from biomass - electricity, liquid fuels, gaseous fuels, hydrogen, and solid fuels - as well as other value-added products *(high confidence)*. Different chemical and biological conversion pathways exist to convert diverse biomass feedstocks into multiple final energy carriers (Figure 6.14). Currently, biomass is mostly used to produce heat or for cooking purposes (traditional biomass), electricity, or first-generation sugar-based biofuels (e.g., ethanol produced via fermentation), as well as biodiesel produced from vegetable oils and animal fats. Electricity generated from biomass contributes about 3% of global generation. Tens of billions of gallons of first-generation biofuels are produced per year. The processing requirements (drying, dewatering, pelletizing) of different feedstocks for producing electricity from biomass are energy-intensive, and when utilizing current power plants, the efficiency is around 22%, with an increase up to 28% with advanced technologies (Zhang et al. 2020).

Scaling up bioenergy use will require advanced technologies such as gasification, Fischer-Tropsch processing, hydrothermal liquefaction (HTL), and pyrolysis. These pathways could deliver several final energy carriers starting from multiple feedstocks, including forest biomass, dedicated cellulosic feedstocks, crop residues, and wastes (Figure 6.14). While potentially cost-competitive in the future, pyrolysis, Fischer-Tropsch, and HTL are not currently cost-competitive (IEA 2018c; Molino et al. 2018; Prussi et al. 2019), and scaling-up these processes will require robust business strategies and optimized use of co-products (Lee and Lavoie 2013). Advanced biofuels production processes are at the pilot or demonstration stage and will require substantial breakthroughs or market changes to become competitive. Moreover, fuels produced from these processes require upgrading to reach “drop-in” conditions – that is, conditions in which they may be used directly consistent with current standards in existing technologies (van Dyk et al. 2019). Additional opportunities exist to co-optimize second generation biofuels and engines (Ostadi et al. 2019; Salman et al. 2020). In addition, gaseous wastes, or high-moisture biomass, such as dairy manure, wastewater sludge and organic MSW could be utilized to produce renewable natural gas. Technologies for producing biogas (e.g. digestion) tend to be less efficient than thermochemical approaches and often produce large amounts of CO_2, requiring the produced fuels to undergo significant upgrading (Melara et al. 2020).

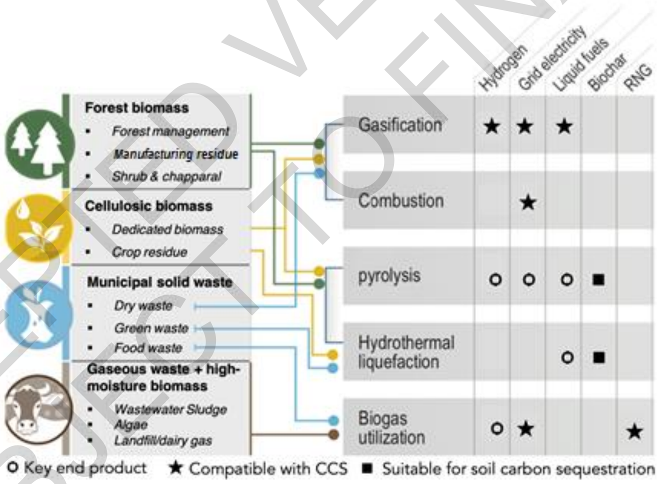


Figure 6.14 Range of advanced bioenergy conversion pathways (excluding traditional biomass, direct heat generation, first-generation biofuels, and non-energy products) based on feedstock, targeted end product, and compatibility with CDR via CCS and soil carbon sequestration (Modified from Baker et al, 2020)

A major scale-up of bioenergy production will require dedicated production of advanced biofuels. First generation biofuels produced directly from food crops or animal fats both have limited potential and lower yield per land area than advanced biofuels. Wastes and residues (e.g., from agricultural, forestry, animal manure processing) or biomass grown on degraded, surplus, and marginal land can provide opportunities for cost-effective and sustainable bioenergy at significant but limited scale (Saha and Eckelman 2018; Fajardy and Mac Dowell 2020; Spagnolo et al. 2020; Morris et al. 2013). Assessing the potential for a major scale-up of purpose-grown bioenergy is challenging due to its far-reaching linkages to issues beyond the energy sector, including competition with land for food production and forestry, water use, impacts on ecosystems, and land-use change) (IPCC 2020; Chapter 12; (Roe et al. 2021)). These factors, rather than geophysical characteristics, largely define the potential for bioenergy and explain the difference in estimates of potential in the literature. Biomass resources are not always in close proximity to energy demand, necessitating additional infrastructure or means to transport biomass or final bioenergy over larger distances and incur additional energy use (Baik et al. 2018b; Singh et al. 2020).

An important feature of bioenergy is that it can be used to remove carbon from the atmosphere by capturing CO_2 in different parts of the conversion process and then permanently storing the CO2 (BECCS or biochar) (Chapter 3, Chapter 7; Chapter 12.5; Smith et al. 2016; Fuss et al. 2018). Some early opportunities for low-cost BECCS are being utilized in the ethanol sector but these are applicable only in the near-term at the scale of $\leq$100 Mt-CO_2 yr^{-1} (Sanchez et al. 2018). Several technological and institutional barriers exist for large-scale BECCS implementation, including large energy requirements for CCS, limit and cost of biomass supply and geologic sinks for CO_2 in several regions, and cost of CO_2 capture technologies (*high confidence*). Besides BECCS, biofuels production through pyrolysis and hydrothermal liquefaction creates biochar, which could also be used to store carbon as 80% of the carbon sequestered in biochar will remain in the biochar permanently (Chapter 7). In addition to its ability to sequester carbon, biochar can be used as a soil amendment (Wang et al. 2014b).

First-generation bioenergy is currently competitive in some markets, though on average its costs are higher than other forms of final energy. Bioenergy from waste and residues from forestry and agriculture is also currently competitive, but the supply is limited (Aguilar et al. 2020). These costs are context-dependent, and regions having large waste resources are already producing low-cost bioenergy (Jin and Sutherland 2018). In the future, technology costs are anticipated to decrease, but bioenergy produced through cellulosic feedstocks may remain more expensive than fossil alternatives. Large-scale deployment of early opportunities especially in the liquid fuel sector may reduce the technological costs associated with biomass conversion (IEA 2020g). At the same time, the cost of feedstocks may rise as bioenergy requirements increase, especially in scenarios with large bioenergy deployment (Muratori et al. 2020). The costs of bioenergy production pathways are highly uncertain (Table 6.4).

Table 6.4 The costs of electricity generation, hydrogen production, and second-generation liquid fuels production from biomass in 2020. These costs are adapted from (Daioglou et al. 2020), (Bhave et al. 2017), (NREL 2020a), (Lepage et al. 2021), (Witcover and Williams 2020), (NREL 2020b)

	Unit	Low	Median	High
Bioelectricity with CCS	USD/MWh	74	86	160
Bioelectricity without CCS	USD/MWh	66	84	112
Biohydrogen with CCS*	USD/kg	1.63	2.37	2.41
Biohydrogen without CCS*	USD/kg	1.59	1.79	2.37
Liquid biofuels with CCS	USD/gge	1.34	4.20	7.85
Liquid biofuels without CCS	USD/gge	1.15	4.00	7.60

*** Using cellulosic feedstocks**

- <u>Electricity.</u> The costs of baseload electricity production with biomass are higher than corresponding fossil electricity production with and without CCS, and are likely to remain as such without carbon pricing (Bhave et al. 2017). The additional cost associated with CO_2 capture are high for conventional solvent-based technologies. However, upcoming technologies such as chemical looping are well-suited to biomass and could reduce CCS costs.
- <u>Hydrogen.</u> The costs of hydrogen production from biomass are somewhat higher than, but comparable, to that produced by natural gas reforming with CCS. Further, the incremental costs for incorporating CCS in this process are less than 5% of the levelized costs in some cases, since the

gasification route creates a high-purity stream of CO_2 (Muratori et al. 2017a; Sunny et al. 2020). While these processes have fewer ongoing prototypes/demonstrations, the costs of biomass-based hydrogen (with or without CCS) are substantially cheaper than that produced from electrolysis utilizing solar/wind resources (Kayfeci et al. 2019; Newborough and Cooley 2020), even though electrolysis costs are dropping.

- Liquid Biofuels. First-generation sugar-based biofuels (e.g., ethanol produced via fermentation) or biodiesel produced from vegetable oils and animal fats are produced in several countries at large scale and costs competitive with fossil fuels. However, supply is limited. The costs for second generation processes (Fischer-Tropsch and cellulosic ethanol) are higher in most regions (Li et al. 2019). Technological learning is projected to reduce these costs by half (IEA 2020g).

Large-scale bioenergy production will require more than wastes/residues and cultivation on marginal lands, which may raise conflicts with SDGs relevant to environmental and societal priorities (Gerten et al. 2020; Heck et al. 2018) (Chapter 12). These include competition with food crops, implications for biodiversity, potential deforestation to support bioenergy crop production, energy security implications from bioenergy trade, point-of-use emissions and associated effects on air quality, and water use and fertilizer use (Fajardy and Mac Dowell 2018; Tanzer and Ramírez 2019; Fuss et al. 2018; Brack and King 2020). Overall, the environmental impact of bioenergy production at scale remains uncertain and varies by region and application.

Alleviating these issues would require some combination of increasing crop yields, improving conversion efficiencies, and developing advanced biotechnologies for increasing the fuel yield per tonne of feedstock (Henry et al. 2018). Policy structures would be necessary to retain biodiversity, manage water use, limit deforestation and land-use change emissions, and ultimately optimally integrate bioenergy with transforming ecosystems. Large-scale international trade of biomass might be required to support a global bioeconomy, raising questions about infrastructure, logistics, financing options, and global standards for bioenergy production and trade (Box 6.10). Additional institutional and economic barriers are associated with accounting of carbon dioxide removal, including BECCS (Fuss et al. 2014; Muratori et al. 2016; Fridahl and Lehtveer 2018).

Life-cycle emissions impacts from bioenergy are subject to large uncertainties and could be incompatible with net zero emissions in some contexts. Due to the potentially large energy conversion requirements and associated GHG emissions (Chapter 7, Chapter 12), bioenergy systems may fail to deliver near-zero emissions depending on operating conditions and regional contexts (Staples et al. 2017; Lade et al. 2020; Daioglou et al. 2017; Hanssen et al. 2020; Elshout et al. 2015). As a result, bioenergy carbon neutrality is debated and depends on factors such as the source of biomass, conversion pathways and energy used for production and transport of biomass, and land use changes, as well as assumed analysis boundary and considered timescale (Fan et al. 2021; Wiloso et al. 2016; Zanchi et al. 2012; Booth 2018). Similarly, the lifecycle emissions of BECCS remain uncertain and will depend on how effectively bioenergy conversion processes are optimized (Fajardy and Mac Dowell 2017; Tanzer and Ramírez 2019).

Acceptability of bioenergy is relatively low compared to other renewable energy sources like solar and wind (Poortinga et al. 2013; EPCC 2017; Peterson et al. 2015; Ma et al. 2015) and comparable to natural gas (Scheer et al. 2013). People also know relatively little about bioenergy compared to other energy sources (Whitmarsh et al. 2011a; EPCC 2017) and tend be be more ambivalent towards bioenergy compared to other mitigation options (Allen and Chatterton 2013). People evaluate biomass from waste products (e.g., food waste) more favourably than grown-for-purpose energy crops, which are more controversial (Demski et al. 2015; Plate et al. 2010). The most pressing concerns for use of woody biomass are air pollution and loss of local forests (Plate et al. 2010). Various types of bioenergy additionally raise concerns about landscape impacts (Whitmarsh et al. 2011a) and biodiversity

(Immerzeel et al. 2014). Moreover, many people do not see biomass as a renewable energy source, possibly because it involves burning of material.

START BOX 6.5 HERE

Box 6.5 Methane mitigation options for coal, oil, and gas

Methane emissions mainly from coal, oil, and gas currently represent in 2019 about 18% of energy supply sector GHG emissions and 90% of global energy supply non-CO_2 emissions in 2019 (Minx et al. 2021b). While approximately 80% of the life-cycle methane emissions in the coal sector occur during underground mining, oil and gas emissions are spread throughout upstream, midstream, and downstream stages (IPCC, 2019) (Alvarez et al. 2018). For this reason, methane reductions from coal mining can be accomplished through coal mine methane recovery (where methane and coal are recovered simultaneously) and from the ventilation air, which can reduce methane emissions by 50–75% (Singh and Hajra 2018; Zhou et al. 2016). Governments incentivize such operations through a number of emissions trading and offset programs (Haya et al. 2020). Methane emissions in the oil and gas sector can be reduced by leak detection and repair, relevant across varying time scales (hours to decades) and regional scopes (component/facility level to continental) (Fox et al. 2019). Around 50% of the methane emitted from oil and gas infrastructure can be mitigated at net-negative costs; that is, the market price of the recovered methane is higher than the mitigation costs (IEA 2021e). As CO_2 emissions are reduced and fossil fuel consumption decreases, methane emissions associated with these supply chains are anticipated to decline (section 6.7). That said, substantial 'legacy' methane emissions – methane leaks after abandonment – will remain even if a complete fossil fuel phase-out takes place. These legacy emissions are estimated to be less than 1–4% of overall methane emissions across all fossil fuel sources (Kholod et al. 2020; Williams et al. 2021b). Even without a complete phase-out, 50-80% of methane emissions from coal, oil and gas could be avoided with currently available technologies at less than USD 50 tCO_2-eq^{-1} (Höglund-Isaksson et al. 2020; Harmsen et al. 2019). Methane recovery from abandoned coal mines could offset most project costs (Singh and Sahu 2018). For abandoned oil and gas wells, low plugging costs could be offset through methane recovery, while high plugging costs would likely require some market or policy support (Kang et al. 2019).

[END BOX 6.5 HERE]

6.4.2.7. Fossil Energy

Fossil fuels could play a role in climate change mitigation if strategically deployed with CCS *(high confidence)*. On the one hand, the primary mechanism for reducing emissions is to eliminate the unabated fossil fuel use. On the other hand, fossil energy combined with CCS provides a means of producing low-carbon energy while still utilizing the available base of fossil energy worldwide and limiting stranded assets. While Section 6.4.2.5 discusses the important aspects of CCS with fossil fuels, this section aims to elucidate the feasibility criteria around these fuels itself.

Fossil fuel reserves have continued to rise because of advanced exploration and utilization techniques (*high confidence*). A fraction of these available reserves can be used consistent with mitigation goals when paired with CCS opportunities in close geographical proximity (*high confidence*). Based on continued exploration, the fossil fuel resource base has increased significantly; for example, a 9% increase in gas reserves and 12% in oil reserves was observed in the U.S. between 2017 and 2018. This increase is a result of advanced exploration techniques, which are often subsidized (Lazarus and van Asselt 2018; MA et al. 2018). Fossil reserves are distributed unevenly throughout the globe. Coal represents the largest remaining resource (close to 500 ZJ). Conventional oil and gas resources are an order of magnitude smaller (15–20 ZJ each). Technological advances have increased the reserves of unconventional fossil in the last decade. Discovered ultimate recoverable resources of unconventional oil and gas are comparable to conventional oil and gas (Fizaine et al. 2017).

It is unlikely that resource constraints will lead to a phaseout of fossil fuels, and instead, such a phase-out would require policy action. Around 80% of coal, 50% of gas, and 20% of oil reserves are likely to remain unextractable under 2°C constraints (McGlade and Ekins 2015; Pellegrini et al. 2020). Reserves are more likely to be utilized in a low-carbon transition if they can be paired with CCS. Availability of CCS technology not only allows continued use of fossil fuels as a capital resource for countries but also paves the way for CDR through BECCS (Pye et al. 2020; Haszeldine 2016). While the theoretical geologic CO_2 sequestration potential is vast, there are limits on how much resource base could be utilized based on geologic, engineering, and source-sink mapping criteria (Budinis et al. 2017).

Technological changes have continued to drive down fossil fuel extraction costs. Significant decarbonization potential also exists via diversification of the fossil fuel uses beyond combustion (high evidence). The costs of extracting oil and gas globally have gone down by utilizing hydraulic fracturing and directional drilling for resources in unconventional reservoirs (Wachtmeister and Höök 2020). Although the extraction of these resources is still more expensive than those derived from conventional reservoirs, the large availability of unconventional resources has significantly reduced global prices. The emergence of liquefied natural gas (LNG) markets has also provided opportunities to export natural gas significant distances from the place of production (Avraam et al. 2020). The increase in availability of natural gas has been accompanied by an increase in the production of natural gas liquids as a co-product to oil and gas. Over the period from 2014 to 2019, exports of natural gas liquids increased by 160%. Natural gas liquids could potentially be a lower-carbon alternative to liquid fuels and hydrocarbons. On the demand side, natural gas can be used to produce hydrogen using steam methane reforming, which is a technologically mature process (Sections 6.4.4, 6.4.5). When combined with 90% CO_2 capture, the costs of producing hydrogen are around USD 1.5–2 $kg(H_2)^{-1}$ (Newborough and Cooley 2020; Collodi et al. 2017), considerably less than hydrogen produced via electrolysis.

Significant potential exists for gasifying deep-seated coal deposits *in situ* to produce hydrogen. Doing so reduces fugitive methane emissions from underground coal mining. The integration costs of this process with CCS are less than with natural gas reforming. The extent to which coal gasification could be compatible with low-carbon energy would depend on the rate of CO_2 capture and the ultimate use of the gas (Verma and Kumar 2015). Similarly, for ongoing underground mining projects, coal mine methane recovery can be economic for major coal producers such as China and India. Coal mine methane and ventilation air methane recovery can reduce the fugitive methane emissions by 50–75% (Zhou et al. 2016; Singh and Sahu 2018).

The cost of producing electricity from fossil sources has remained roughly the same with some regional exceptions while the costs of transport fuels has gone down significantly (*high confidence*). The cost of producing electricity from fossil fuels has remained largely static, with the exception of some regional changes, for example, a 40% cost reduction in the U.S. for natural gas (Rai et al. 2019), where the gas wellhead price has declined by almost two-thirds due to large reserves. Similarly, the global price of crude oil has declined from almost USD 100–55 bbl^{-1} in the last five years.

The energy return of investment (EROI) is a useful indicator of full fossil lifecycle costs. Fossil fuels create significantly more energy per unit energy invested – or in other words have much larger EROI – than most cleaner fuels such as biomass or electrolysis-derived hydrogen, where intensive processing reduces EROI (Hall et al. 2014). That said, recent years have seen a decrease in fossil EROI, especially as underground coal mining has continued in China. Exploitation of unconventional gas reservoirs is also energy intensive and has led to a reduction in EROI. The primary energy EROI of fossil fuels has converged at about 30, which represents a 20-point decrease from the 1995 value for coal (Brockway et al. 2019). When processing and refining stages are considered, these EROI values further decrease.

Several countries have large reserves of fossil fuels. Owing to climate constraints, these may become stranded causing considerable economic impacts (6.7.3, 6.7.4, Box 6.13) (*high confidence*). While global fossil energy resources are greater than 600 ZJ, more than half of these resources would likely be unburnable even in the presence of CCS (Pye et al. 2020; McGlade and Ekins 2015). This would entail a significant capital loss for the countries with large reserves. The total amount of stranded assets in such a case would amount to USD 1–4 trillion at present value (Box 6.13).

Apart from CO_2 emissions and air pollutants from fossil fuel combustion, other environmental impacts include fugitive methane leakages and implications to water systems**.** While the rate of methane leakage from unconventional gas systems is uncertain, their overall GHG impact is less than coal (Deetjen and Azevedo 2020; Tanaka et al. 2019). The stated rate of leakage in such systems ranges from 1-8%, and reconciling different estimates requires a combination of top-down and bottom-up approaches (Grubert and Brandt 2019; Zavala-Araiza et al. 2015). Similarly, for coal mining, fugitive methane emissions have grown despite some regulations on the degree to which emission controls must be deployed. Recent IPCC inventory guidance also notes considerable CO_2 emissions resulting from spontaneous combustion of the coal surface, and accounting for these emissions will likely increase the overall life-cycle emissions by 1–5% (Fiehn et al. 2020; Singh 2019; IPCC 2019).

Another key issue consistently noted with unconventional wells (both oil and gas, and coalbed methane) is the large water requirements (Qin et al. 2018). The overall water footprint of unconventional reservoirs is higher than conventional reservoirs because of higher lateral length and fracturing requirements (Scanlon et al. 2017; Kondash et al. 2018). Moreover, produced water from such formations is moderately to highly brackish, and treating such waters has large energy consumption (Singh and Colosi 2019; Bartholomew and Mauter 2016).

Oil and coal consistently rank among the least preferred energy sources in many countries (*high confidence*). The main perceived advantage of fossil energy is the relatively low costs, and emphasizing these costs might increase acceptability somewhat (Pohjolainen et al. 2018; Hazboun and Boudet 2020; Boyd et al. 2019). Acceptability of fossil fuels is on average similar to acceptability of nuclear energy, although evaluations are less polarized. People evaluate natural gas as somewhat more acceptable than other fossil fuels, although they generally oppose hydraulic fracturing (Clarke et al. 2016). Yet, natural gas is evaluated as less acceptable than renewable energy sources, although evaluations of natural gas and biogas are similar (Liebe and Dobers 2019; Plum et al. 2019). Acceptability of fossil energy tends to be higher in countries and regions that strongly rely on them for their energy production (Boyd et al. 2019; Pohjolainen et al. 2018). Combining fossil fuels with CCS can increase their acceptability (Van Rijnsoever et al. 2015; Bessette and Arvai 2018). Some people seem ambivalent about natural gas, as they perceive both benefits (e.g., affordability, less carbon emissions than coal) and disadvantages (e.g., finite resource, contributing to climate change) (Blumer et al. 2018).

Fossil fuel subsidies have been valued of the order of USD 0.5–5 trillion annually by various estimates which have the tendency to introduce economic inefficiency within systems (Merrill et al. 2015; Jakob et al. 2015) (*high confidence*). Subsequent reforms have been suggested by different researchers who have estimated reductions in CO_2 emissions may take place if these subsidies are removed (Mundaca 2017). Such reforms could create the necessary framework for enhanced investments in social welfare – through sanitation, water, clean energy - with differentiating impacts (Edenhofer 2015).

6.4.2.8 Geothermal Energy

Geothermal energy is heat stored in the Earth’s subsurface and is a renewable resource that can be sustainably exploited. The geophysical potential of geothermal resources is 1.3 to 13 times the global electricity demand in 2019 (*medium confidence*). Geothermal energy can be used directly for various thermal applications, including space heating and industrial heat input, or converted to electricity depending on the source temperature (Moya et al. 2018; REN21 2019; Limberger et al. 2018).

Suitable aquifers underlay 16% of the Earth's land surface and store an estimated 110,000–1,400,000 PWh (400,000–1,450,000 EJ) that could theoretically be used for direct heat applications. For electricity generation, the technical potential of geothermal energy is estimated to be between 30 PWh yr^{-1} (108

EJ yr^{-1}) (to 3 km depth) and 300 PWh yr^{-1} (1080 EJ yr^{-1}) (to 10 km depth). For direct thermal uses, the technical potential is estimated to range from 2.7–86 PWh yr^{-1} (9.7–310 EJ yr^{-1})(IPCC 2011). Despite the potential, geothermal direct heat supplies only 0.15% of the annual global final energy consumption. The technical potential for electricity generation, depending on the depth, can meet one third to almost three times the global final consumption (based on IEA database for IPCC). The mismatch between potential and developed geothermal resources is caused by high up-front costs, decentralized geothermal heat production, lack of uniformity among geothermal projects, geological uncertainties, and geotechnical risks (IRENA 2017a; Limberger et al. 2018). A limited number of countries have a long history in geothermal. At least in two countries (Iceland and New Zealand), geothermal accounts for 20–25% of electricity generation (Spittler et al. 2020; Pan et al. 2019). Furthermore, in Iceland approximately 90% of the households are heated with geothermal energy. In Kenya, as of July 2019, geothermal accounted for 734 MW effective capacity spread over 10 power plants and approximately one third of the total installed capacity (Kahlen 2019).

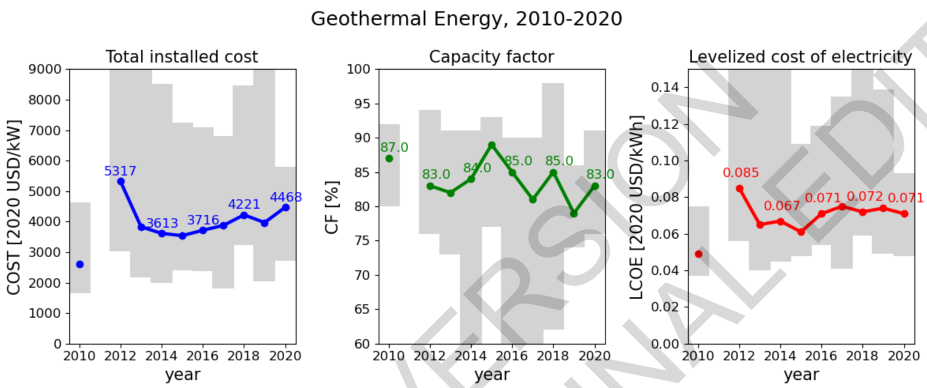


Figure 6.15 Global weighted average total installed costs, capacity factors and LCOE for geothermal power per year (2010-2020). The shaded area represents the 5% and 95% percentiles. Source: (IRENA 2021a)

There are two main types of geothermal resources: convective hydrothermal resources, in which the Earth's heat is carried by natural hot water or steam to the surface, and hot, dry rock resources, in which heat cannot be extracted using water or steam, and other methods must be developed. There are three basic types of geothermal power plants: (1) dry steam plants use steam directly from a geothermal reservoir to turn generator turbines; (2) flash steam plants take high-pressure hot water from deep inside the Earth and convert it to steam to drive generator turbines and (3) binary cycle power plants transfer the heat from geothermal hot water to another liquid. Many of the power plants in operation today are dry steam plants or flash plants (single, double and triple) harnessing temperatures of more than 180°C.

However, medium temperature fields are increasingly used for electricity generation or combined heat and power. The use of medium temperature fields has been enabled through the development of binary cycle technology, in which a geothermal fluid is used via heat exchangers. Increasing binary generation technologies are now being utilized instead of flash steam power plants. This will result in almost 100% injection and essentially zero GHG emissions, although GHG emissions from geothermal power production are generally small compared to traditional baseload thermal energy power generation facilities (Fridriksson et al. 2016).

Additionally, new technologies are being developed like Enhanced Geothermal Systems (EGS), which is in the demonstration stage (IRENA 2018), deep geothermal technology, which may increase the prospects for harnessing the geothermal potential in a large number of countries, or shallow-geothermal energy, which represents a promising supply source for heating and cooling buildings (Narsilio and Aye 2018). Successful large-scale deployment of shallow geothermal energy will depend not only on site-specific economic performance but also on developing suitable governance frameworks (Bloemendal et al. 2018; García-Gil et al. 2020). Technologies for direct uses like district heating, geothermal heat pumps, greenhouses, and other applications are widely used and considered mature. Given the limited number of plants commissioned, economic indicators (Figure 6.15) vary considerably depending on site characteristics.

Public awareness and knowledge of geothermal energy is relatively low *(high confidence)*. Geothermal energy is evaluated as less acceptable than other renewable energy sources such as solar and wind, but is preferred over fossil and nuclear energy, and in some studies, over hydroelectric energy (Karytsas et al. 2019; Pellizzone et al. 2015; Steel et al. 2015; Hazboun and Boudet 2020) (*high confidence*). Some people are concerned about the installation of geothermal facilities close to their homes, similar to solar and wind projects (Pellizzone et al. 2015). The main concerns about geothermal energy, particularly for large scale, high-temperature geothermal power generation plants, involve water usage, water scarcity, and seismic risks of drilling (Dowd et al. 2011). Moreover, noise, smell and damages to the landscape have been reasons for protests against specific projects (Walker 1995). However, with the implementation of modern technologies, geothermal presents fewer adverse environmental impacts. At the same time, people perceive geothermal energy as relatively environmentally friendly (Tampakis et al. 2013).

6.4.2.9 Marine Energy

The ocean is a vast source of energy (Hoegh-Guldberg et al. 2019). Ocean energy can be extracted from tides, waves, ocean thermal energy conversion (OTEC), currents, and salinity gradients (Bindoff et al. 2019). Their technical potentials, without considering possible exclusion zones, are explored below. Tidal energy, which uses elevation differences between high and low tides, appears in two forms: potential energy (rise and fall of the tide) and current energy (from tidal currents). The global technically harvestable tidal power from areas close to the coast is estimated as ~1.2 PWh yr^{-1} (4.3 EJ yr^{-1}) (IRENA 2020b). The potential for tidal current energy is estimated to be larger than that for tidal range or barrage (Melikoglu 2018). Ocean wave energy is abundant and predictable and can be extracted directly from surface waves or pressure fluctuations below the surface (Melikoglu 2018). Its global theoretical potential is 29.5 PWh yr^{-1} (106 EJ yr^{-1}) ,which means that wave energy alone could meet all global energy demand (Mørk et al. 2010; IRENA 2020b). The temperature gradients in the ocean can be exploited to produce energy, and its total estimated available resource could be up to 44.0 PWh yr^{-1} (158 EJ yr^{-1}) (Rajagopalan and Nihous 2013). Salinity gradient energy, also known as osmotic power, has a global theoretical potential of over 1.6 PWh yr^{-1} (6.0 EJ yr^{-1}) (IRENA 2020b). The greatest advantage of most marine energy, excluding wave energy, is that their sources are highly regular and predictable, and energy can be furthermore generated both day and night. An additional use of sea water is to develop lower-cost district cooling systems near the sea (Hunt et al. 2019). The greatest barrier to most marine technology advances is the relatively high upfront costs, uncertainty on environmental regulation and impact, need for investments and insufficient infrastructure (Kempener and Neumann 2014a,b). There are also concerns about technology maturity and performance; thus, not all have the potential to become economically viable (IRENA 2020b).

6.4.2.10 Waste-to-Energy

Waste-to-energy (WTE) is a strategy to recover energy from waste in a form of consumable heat, electricity, or fuel (Zhao et al. 2016). Thermal (incineration, gasification, and pyrolysis) and biological (anaerobic digestion and landfill gas to energy) technologies are commonly used (Ahmad et al. 2020).When WTE technologies are equipped with proper air pollution reduction facilities they can contribute to clean electricity production and reduction of GHG emissions. However, if not properly operated, they can exacerbate air quality issues.

In 2019, there were more than 1,200 WTE incineration facilities worldwide, with estimated capacity of 310 million tons per year (UNECE 2020). It is estimated that treatment of a minimum of 261 million tons/year of waste could produce 283 TWh (1 EJ) of power and heat by 2022 (Awasthi et al., 2019). Incineration plants can reduce the mass of waste by 70%-80% and the volume of waste by 80%-90% (Haraguchi et al. 2019). Incineration technology can reduce water and soil pollution (Gu et al., 2019). However, if not properly handled, dust, and gases such as SO_2, HCL, HF, NO_2, and dioxins in the flue gases can harm the environment (Mutz et al. 2017). Anaerobic digestion technology has a positive environmental impact and the ability to reduce GHG emissions (Ayodele et al. 2018; Cudjoe et al. 2020). The by-product of the anaerobic digestion process could be used as a nutrient-rich fertilizer for enhancing soil richness for agricultural purposes (Wainaina et al. 2020). Due to the potential negative impacts on domestic environment and residents' health, WTE projects such as incineration encounter substantial opposition from the local communities in which they are located (Ren et al., 2016; Baxter et al., 2016). Therefore, for WTE to be deployed more widely, policies would need to be tailored with specific guidelines focused on mitigating emissions, which may have adverse effect on the environment.

Depending on the origin of the waste used, the integration of WTE and carbon capture and storage (CCS) could enable waste to be a net zero or even net negative emissions energy source (Kearns 2019; Wienchol et al. 2020). For example, in Europe only, the integration of CCS with WTE facilities has the potential to capture about 60 to 70 million tons of carbon dioxide annually (Tota et al. 2021).

Waste-to-energy is an expensive process compared to other energy sources such as fossil fuels and natural gas (Mohammadi and Harjunkoski 2020). However, the environmental and economic benefits make its high financial costs justifiable. In 2019, the global WTE market size was valued at USD 31 billion, and it is predicted to experience 7.4% annual growth until 2027 (UNECE 2020).

6.4.3 Energy System Integration

Greenhouse gases are emitted across all economic activities. Therefore, cost-effective decarbonization requires a "system of systems" approach that considers the interaction between different energy sectors and systems. Flexibility technologies and advanced control of integrated energy systems (e.g., considering the interaction between electricity, heating/cooling, gas/hydrogen, transport sectors) could reduce energy infrastructure investments substantially in future low-carbon energy systems (Strbac et al. 2015b; Jacobson et al. 2019)

The electricity grid will serve as a backbone of future low-carbon energy systems. Integration of large amounts of VRE generation (Hansen et al. 2019), particularly wind and solar generation (Perez et al. 2019; Bistline and Young 2019), presents economic and technical challenges to electricity system management across different timescales from sub-seconds, hours, days, seasons, to multiple years. Furthermore, electrification of segments of the transport and heat sectors could disproportionately increase peak demand relative to supply (Bistline et al. 2021). Increases in peak demand may require reinforcing network infrastructures and generation in the historical passive system operation paradigm (Strbac et al. 2020).

These challenges to electricity system management can be addressed through system integration and a digitalized control paradigm involving advanced information and communication technologies. Real-time maintenance of supply-demand balance and sufficient flexibility technologies such as electricity storage, flexible demand, and grid forming converters (Strbac et al. 2015a; López Prol and Schill 2021) would be increasingly valuable for incorporating larger amounts of VRE generation. This flexibility will be particularly important to deal with sudden losses of supply, for example, due to a failure of a large generator or interconnector or a rapid increase in demand (Teng et al. 2017; Chamorro et al. 2020).

The transition to a digitalized-based electricity system control paradigm would facilitate radical changes in the security of supply, moving from the traditional approach of redundancy in assets to a smart control paradigm. Advanced control and communication systems can significantly reduce the electricity system investment and operation costs (2020; Münster et al. 2020; Harper et al. 2018).

Importance of cross-sector coupling for cost-effective energy system decarbonization

Integrated whole-system approaches can reduce the costs of low-carbon energy system transitions (*high confidence*). A lack of flexibility in the electricity system may limit the cost-effective integration of technologies as part of broader net zero energy systems. At the same time, the enormous latent flexibility hidden in heating and cooling, hydrogen, transport, gas systems, and other energy systems provides opportunities to take advantage of synergies and to coordinate operations across systems (Martinez Cesena and Mancarella 2019; Zhang et al. 2018; Bogdanov et al. 2021; Pavičević et al. 2020; Martin et al. 2017) (Figure 6.16).

Sector coupling can significantly increase system flexibility, driven by the application of advanced technologies (Bogdanov et al. 2019; Solomon et al. 2019; Clegg and Mancarella 2016; Zhang and Fujimori 2020; Zhao et al. 2021; Heinen et al. 2016; Zhang et al. 2019b). For example, district heating infrastructure can generate both heat and power. Cooling systems and electrified heating systems in buildings can provide flexibility through preheating and precooling via thermal energy storage Li, G. et al. 2017; Li, Z. et al. 2016).. System balancing services can be provided by electric vehicles (EVs) based on vehicle-to-grid concepts and deferred charging through smart control of EV batteries without compromising customers' requirements for transport (Aunedi and Strbac 2020).

Hydrogen production processes (power-to-gas and vice versa) and hydrogen storage can support short-term and long-term balancing in the energy systems and enhance resilience (Stephen and Pierluigi 2016; Strbac et al. 2020). However, the economic benefits of flexible power-to-gas plants, energy storage, and other flexibility technological and options will depend on the locations of VRE sources, storage sites, gas, hydrogen, and electricity networks (Jentsch et al. 2014; Heymann and Bessa 2015; Ameli et al. 2020). Coordinated operation of gas and electricity systems can bring significant benefits in supplying heat demands. For example, hybrid heating can eliminate investment in electricity infrastructure reinforcement by switching to heat pumps in off-peak hours and gas boilers in peak hours (Dengiz et al. 2019; Fischer et al. 2017; Bistline et al. 2021). The heat required by direct air carbon capture and storage (DACCS) could be effectively supplied by inherent heat energy in nuclear plants, enhancing overall system efficiency (Realmonte et al. 2019).

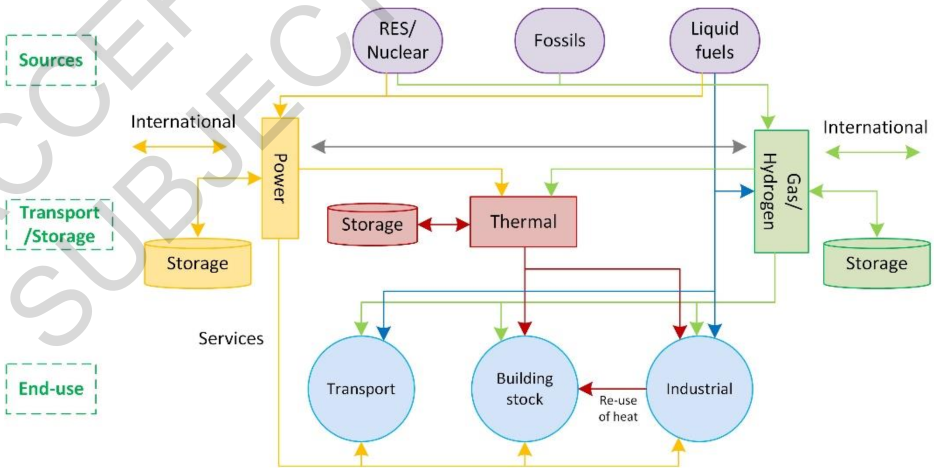


Figure 6.16 Interaction between different energy sectors (extracted from Münster et al. 2020)

Rather than incremental planning, strategic energy system planning can help minimize long-term mitigation costs (*high confidence*). With a whole-system perspective, integrated planning can consider both short-term operation and long-term investment decisions, covering infrastructure from local to national and international, while meeting security of supply requirements and incorporating the flexibility provided by different technologies and advanced control strategies (Zhang et al. 2018; O'Malley et al. 2020; Strbac et al. 2020). Management of conflicts and synergies between local district and national level energy system objectives, including strategic investment in local hydrogen and heat infrastructure, can drive significant whole-system cost savings (Fu et al. 2020; Zhang et al. 2019b). For example, long-term planning of the offshore grid infrastructure to support offshore wind development, including interconnection between different countries and regions, can provide significant savings compared to a short-term incremental approach in which every offshore wind farm is individually connected to the onshore grid (E3G 2021).

6.4.3.1 Role of flexibility technologies

Flexibility technologies - including energy storage, demand-side response, flexible/dispatchable generation, grid forming converters, and transmission interconnection - as well as advanced control systems, can facilitate cost-effective and secure low-carbon energy systems (*high confidence*). Flexibility technologies have already been implemented, but they can be enhanced and deployed more widely. Due to their interdependencies and similarities, there can be both synergies and conflicts for utilizing these flexibility options (Bistline et al. 2021). It will therefore be important to coordinate the deployment of the potential flexibility technologies and smart control strategies. Important electricity system flexibility options include the following:

- *Flexible/dispatchable generation:* Advances in generation technologies, for example, gas/hydrogen plants and nuclear plants, can enable them to provide flexibility services. These technologies would start more quickly, operate at lower power output, and make faster output changes, enabling more secure and cost-effective integration of VRE generation and end-use electrification. There are already important developments in increasing nuclear plants flexibility (e.g., in France (Office of Nuclear Energy 2021)) and the development of small modular reactors, which could support system balancing (FTI Consulting 2018).
- *Grid-forming converters (inverters):* The transition from conventional electricity generation, applying mainly synchronous machines to inverter-dominated renewable generation, creates significant operating challenges. These challenges are mainly associated with reduced synchronous inertia, system stability, and black start capability. Grid-forming converters will be a cornerstone for the control of future electricity systems dominated by VRE generation. These converters will address critical stability challenges, including the lack of system inertia, frequency and voltage regulation, and black-start services while reducing or eliminating the need to operate conventional generation (Tayyebi et al. 2019).
- *Interconnection:* Electricity interconnections between different regions can facilitate more cost-effective renewable electricity deployment. Interconnection can enable large-scale sharing of energy and provide balancing services. Back-up energy carriers beyond electricity, such as ammonia, can be shared through gas/ammonia/hydrogen-based interconnections, strengthening temporal coupling of multiple sectors in different regions (Bhagwat et al. 2017; Brown et al. 2018) (Section 6.4.5).
- *Demand-side response:* Demand-side schemes – including, for example, smart appliances, EVs, and building-based thermal energy storage (Heleno et al. 2014) – can provide flexibility services across multiple time frames and systems. Through differentiation between essential and non-essential needs during emergency conditions, smart control of demands can significantly enhance system resilience (Chaffey 2016).
- *Energy storage:* Energy storage technologies (Section 6.4.4) can act as both demand and generation sources. They can provide services such as system balancing, various ancillary services, and network management. Long-duration energy storage can significantly enhance the utilization of renewable energy sources and reduce the need for firm low-carbon generation (Sepulveda et al. 2021).

6.4.3.2 Role of digitalization and advanced control systems

A digitalized energy system can significantly reduce energy infrastructure investments while enhancing supply security and resilience (*high confidence*) (Andoni et al. 2019; Strbac et al. 2020). Significant progress has been made in the development of technologies essential for the transition to a digitalized energy control paradigm, although the full implementation is still under development. Electrification and the increased integration of the electricity system with other systems will fundamentally transform the operational and planning paradigm of future energy infrastructure. A fully intelligent and sophisticated coordination of the multiple systems through smart control will support this paradigm shift. This shift will provide significant savings through better utilization of existing infrastructure locally, regionally, nationally, and internationally. Supply system reliability will be enhanced through advanced control of local infrastructure (Strbac et al. 2015a). Furthermore, this paradigm shift offers the potential to increase energy efficiency through a combination of technologies that gather and analyse data and consequently optimize energy use in real-time.

The transition to advanced data-driven control of energy system operations (Sun et al. 2019a; Cremer et al. 2019) will require advanced information and communication technologies and infrastructure, including the internet, wireless networks, computers, software, middleware, smart sensors, internet of things components, and dedicated technological developments (Hossein Motlagh et al. 2020). The transition will raise standardization and cybersecurity issues, given that digitalization can become a single point of failure for the complete system (Unsal et al. 2021; Ustun and Hussain 2019). Implementing peer-to-peer energy trading based on blockchain is expected to be one of the key elements of next-generation electricity systems (Qiu et al. 2021). This trading will enable consumers to drive system operation and future design, increasing overall system efficiency and security of supply while reducing emissions without sacrificing users' privacy (Andoni et al. 2019; Ahl et al. 2020). When deployed with smart contracts, this concept will be suitable for energy systems involving many participants, where a prerequisite is digitalization (e.g., smart meters, end-use demand control systems) (Teufel et al. 2019; Juhar and Khaled 2018).

6.4.3.3 System benefits of flexibility technologies and advanced control systems

New sources of flexibility and advanced control systems provide a significant opportunity to reduce low-carbon energy system costs by enhancing operating efficiency and reducing energy infrastructure and low-carbon generation investments, while continuing to meet security requirements (*high confidence*). In the U.S, for example, one study found that flexibility in buildings alone could reduce U.S. CO_2 emissions by 80 MT yr^{-1} and save USD 18 bn yr^{-1} in electricity system costs by 2030 (Satchwell et al. 2021). Key means for creating savings are associated with the following:

- *Efficient energy system operation*: Flexibility technologies such as storage, demand-side response, interconnection, and cross-system control will enable more efficient, real-time demand and supply balancing. This balancing has historically been provided by conventional fossil-fuel generation (Nuytten et al. 2013).
- *Savings in investment in low carbon/renewable generation capacity:* System flexibility sources can absorb or export surplus electricity, thus reducing or avoiding energy curtailment and reducing the need for firm low-carbon capacity such as nuclear and fossil-fuel plants with CCS (Newbery et al. 2013; Solomon et al. 2019). For example, one study found that flexibility technologies and advanced control systems could reduce the need for nuclear power by 14 GW and offshore wind by 20 GW in the UK's low-carbon transition (Strbac et al. 2015b).
- *Reduced need for backup capacity:* System flexibility can reduce energy demand peaks, reducing the required generation capacity to maintain the security of supply, producing significant savings in generation investments (Strbac et al. 2020).
- *Deferral or avoidance of electricity network reinforcement/addition:* Flexibility technologies supported by advanced control systems can provide significant savings in investment in electricity

network reinforcement that might emerge from increased demand, for example, driven by electrification of transport and heat sectors. Historical network planning and operation standards are being revised considering alternative flexibility technologies, which would further support cost-effective integration of decarbonized transport and heat sectors (Strbac et al. 2020).

6.4.4 Energy Storage for Low-Carbon Grids

Energy storage technologies make low carbon electricity systems more cost-effective, allowing VRE technologies to replace more expensive firm low carbon generation technologies (Carbon Trust 2016) and reducing investment costs in backup generation, interconnection, transmission, and distribution network upgrades (*high confidence*). Energy system decarbonization relies on increased electrification (Section 6.6.2.3.). Meeting increasing demands with variable renewable sources presents challenges and could lead to costly infrastructure reinforcements. Energy storage enables electricity from variable renewables to be matched against evolving demands across both time and space, using short-, medium- and long-term storage of excess energy for delivery later or different location. In 2017, an estimated 4.67 TWh (0.017 EJ) of electricity storage was in operation globally (IRENA 2017). If the integration of renewables is doubled from 2014 levels by 2030, the total capacity of global electricity storage could triple, reaching 11.89–15.27 TWh (0.043–0.055 EJ)(IRENA 2017b).

Table 6.5 Suitability of low carbon energy storage technologies, in terms of the grid services they can provide, and overall features such as technology maturity, where Low represents an emerging technology; Med represents a maturing technology and High a fully mature technology. The opportunity for the cost of a technology to reduce over the next decade is represented by Low, Med and High and the lifetime of installations by: Long, for projects lasting more than 25 years; Med for those lasting 15–25 years; Short, for those lasting less than 15 years. (PHS - Pumped Hydroelectric Storage, CAES - Compressed Air Energy Storage, LAES - Liquid Air Energy Storage, TES - Thermal Energy Storage, FES - Flywheel Energy Storage, LiB – Li-ion Batteries, Scap – Supercapacitors, RFB - Redox Flow Batteries, RHFC - Reversible Hydrogen Fuel Cells, PtX – Power to fuels). [Footnote: References: PHS – IRENA 2017, Barbour et al. 2016, Yang 2016; CAES – Brandon et al. 2015, IRENA 2017, Luo et al. 2014; LAES – Luo et al. 2014, Highview 2019; TES – Brandon et al. 2015, Smallbone et al. 2017, Gallo et al. 2016; FES – Yulong et al. 2017, IRENA 2017; LiB – IRENA 2017, Hammond and Hazeldine 2015, Staffell, I. and Rustomji, M. et al. 2016, Schmidt et al. 2017c,Nykvist and Nilsson 2015, May et al. 2018, IRENA 2015b; Scap – Brandon et al. 2015, Gur 2018; RFB – IRENA 2017; RHFC – Gur 2018, IEA 2015]

Suitability factor	PHS	CAES	LAES	TES	FES	LiB	Scap	RFB	PtX	RHFC
Upgrade deferral	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Energy Arbitrage	✓	✓	✓	✓		✓		✓	✓	✓
Capacity firming	✓	✓	✓	✓	✓	✓		✓	✓	✓
Seasonal storage				✓					✓	✓
Stability	✓				✓	✓	✓	✓	✓	✓
Frequency regulation	✓	✓	✓		✓	✓	✓	✓	✓	✓
Voltage support	✓	✓	✓		✓	✓	✓	✓	✓	✓
Black start	✓	✓	✓			✓		✓	✓	✓
Short term reserve	✓	✓	✓			✓		✓	✓	✓
Fast reserve	✓	✓	✓		✓	✓		✓	✓	✓
Islanding		✓	✓	✓		✓		✓	✓	✓
Uninterruptible power supply					✓	✓	✓	✓		✓
Maturity	High	High	Med	Low	High	Med	Low	Low	Low	Low

Opportunity to reduce costs	Low	Low	Low	Med	Med	High	High	High	Med	High
Lifetime	Long	Long	Long	Long	Med	Short	Med	Med	Med	Short
Roundtrip Efficiency	60–80%	30–60%	55–90%	70–80%	90%	>95%	>95 %	80–90%	35–60%	<30%

Energy storage technologies can provide a range of different grid services (Table 6.5). Energy storage enhances security of supply by providing real time system regulation services (voltage support, frequency regulation, fast reserve, and short-term reserve). A greater proportion of variable renewable sources reduces system inertia, requiring more urgent responses to changes in system frequency, which rapid response storage technologies can provide (stability requires responses within sub second timescale for provision of frequency and voltage control services). Energy storage also provides intermittent renewable sources with flexibility, allowing them to contribute a greater proportion of electrical energy and avoiding curtailment (capacity firming). Investment costs in backup generation, interconnection, transmission, and distribution network upgrades can thus be reduced (upgrade deferral), meaning that less low carbon generation will need to be built while still reducing emissions. In the event of an outage, energy storage reserves can keep critical services running (islanding) and restart the grid (black start). The ability to store and release energy as required provides a range of market opportunities for buying and selling of energy (arbitrage).

No single, sufficiently mature energy storage technology can provide all the required grid services - a portfolio of complementary technologies working together can provide the optimum solution (*high confidence*). Different energy storage technologies can provide these services and support cost-effective energy system decarbonization (Carbon Trust 2016). To achieve very low carbon systems, significant volumes of storage will be required (Strbac et al. 2015a; Section 0). There are few mature global supply chains for many of the less-developed energy storage technologies. This means that although costs today may be relatively high, there are significant opportunities for future cost reductions, both through technology innovation and through manufacturing scale. Adding significant amounts of storage will reduce the price variation and, therefore, the profitability of additional and existing storage, increasing investment risk.

Energy storage extends beyond electricity storage and includes technologies that can store energy as heat, cold, and both liquid and gaseous fuels. Energy storage is a conversion technology, enabling energy to be converted from one form to another. This diversification improves the overall resilience of energy systems, with each system being able to cover supply shortfalls in the others. For example, storage can support the electrification of heating or cooling, as well as transport through electric vehicles, powered by batteries or by fuel cells. Storage significantly reduces the need for costly reinforcement of local distribution networks through smart charging schemes and the ability to flow electricity back to the grid (e.g., through vehicle-to-grid). By capturing otherwise wasted energy streams, such as heat or cold, energy storage improves the efficiency of many systems, such as buildings, data centres and industrial processes.

6.4.4.1 Energy Storage Technologies

<u>Pumped Hydroelectric Storage (PHS).</u> PHS makes use of gravitational potential energy, using water as the medium. Water is pumped into an elevated reservoir using off-peak electricity and stored for later release when electricity is needed. These closed-loop hydropower plants have been in use for decades and account for 97% of worldwide electricity storage capacity (IEA, 2018b; IRENA, 2017). PHS is best suited to balancing daily energy needs at a large scale, and advances in the technology now allow both rapid response and power regulation in both generating and pumping mode (Valavi and Nysveen 2018; Kougias et al. 2019; Dong et al. 2019). The construction itself can cause disruption to the local community and environment (Hayes et al. 2019), the initial investment is costly, and extended

construction periods delay return on investment (Section 6.4.2.3). In addition, locations for large-scale PHS plants are limited.

Advanced pump-turbines are being developed, allowing both reversible and variable-speed operation, supporting frequency control and grid stability with improved round-trip efficiencies (Ardizzon et al. 2014). New possibilities are being explored for small-scale PHS installations and expanding the potential for siting (Kougias et al. 2019). For example, in underwater PHS, the upper reservoir is the sea, and the lower is a hollow deposit at the seabed. Seawater is pumped out of the deposit to store off-peak energy and re-enters through turbines to recharge it (Kougias et al. 2019). Using a similar concept, underground siting in abandoned mines and caverns could be developed reasonably quickly (IEA 2020h). Storage of energy as gravitational potential can also be implemented using materials other than water, such as rocks and sand. Pumped technology is a mature technology (Barbour et al. 2016; Rehman et al. 2015) and can be important in supporting the transition to future low carbon electricity grids (IHA 2021).

Batteries. There are many types of batteries, all having unique features and suitability (c), but their key feature is their rapid response times. A rechargeable battery cell is charged by using electricity to drive ions from one electrode to another, with the reverse occurring on discharge, producing a usable electric current (Crabtree et al. 2015). While lead-acid batteries (LABs) have been widely used for automotive and grid applications for decades (May et al. 2018), li-ion batteries (LIBs) are increasingly being used in grid-scale projects (Crabtree et al. 2015), displacing LABs. The rapid response time of batteries makes them suitable for enhanced frequency regulation and voltage support, enabling the integration of variable renewables into electricity grids (Strbac and Aunedi 2016). Batteries can provide almost all electricity services, except for seasonal storage. Lithium-ion batteries, in particular, can store energy and power in small volumes and with low weight, making them the default choice for EVs (Placke et al. 2017). EV batteries are expected to form a distributed storage resource as this market grows, both impacting and supporting the grid (Staffell and Rustomji 2016).

Table 6.6 Technical characteristics of a selected range of battery chemistries, categorized as those which precede LIBs (white background), LIBs (yellow background) and post LIBs (blue background). With the exception of the All Solid-State batteries, all use liquid electrolytes. (1 =Mahmoudzadeh et al. 2017; 2 = Manzetti and Mariasiu 2015; 3 =Placke et al. 2017; 4 = Nykvist and Nilsson 2015; 5 =Cano et al. 2018; 6 = BloombergENF 2019; 7 = You and Manthiram 2017; 8 = Fotouhi et al. 2017; 9 = IRENA 2017; 10 = Yang et al., 2020)

Battery Type	Technology Maturity	Life Span (Cycles)	Energy Density (Wh L^{-1})	Specific Energy (Wh kg^{-1})	Price (USD kWh^{-1}) in 2017
Lead Acid	High	300–800 [5]	102–106 [5]	38–60 [5]	70–160 [5]
Ni MH	High	600–1200 [5]	220–250 [5]	42–110 [5]	210–365 [5]
Ni Cd	High	1350 [2]	100 [2]	60 [2]	700
High-temperature Na batteries	High	1000 [5]	150–280 [8]	80–120 [1]	315–490 [8]
LIB state of the art	High	1000–6000 [5]	200–680 [3]	110–250 [3]	176 [6]
LIB energy-optimized	Under Development		600–850 [3]	300-440 [3]	
Classic Li Metal (CLIM)	Under Development		800–1050 [3]	420–530 [3]	
Metal Sulfur (Li S)	Near Commercialization	100–500 [5]	350–680 [3, 8]	360–560 [3, 8]	36–130 [5]
Metal Sulfur (Na S)	Under Development	5000–10,000 [8]			
Metal Air (Li/air)	Under Development	20–100 [5]		470–900 [4]	70–200 [5]

Metal Air (Zn/air)	Under Development	150–450 [5]		200–410 [4]	70–160 [5]
Na ion	Under Development	500 [7]		600 [7]	
All-Solid-State	Under Development			278–479 [3]	
Redox	Under Development	>12,000–14,000 [10]	15–25[10]	10–20[10]	66[10]

Drawbacks of batteries include relatively short lifespans and the use of hazardous or costly materials in some variants. While LIB costs are decreasing (Schmidt et al. 2017; Vartiainen et al. 2020), the risk of thermal runaway, which could ignite a fire (Gur 2018; Wang et al. 2019a), concerns about long-term resource availability (Sun et al. 2017; Olivetti et al. 2017), and concerns about global cradle-to-grave impacts (Peters et al. 2017; Kallitsis et al. 2020) need to be addressed.

The superior characteristics of LIBs will keep them the dominant choice for EV and grid applications in the medium-term (*high confidence*). There are, however, several next-generation battery chemistries (Placke et al. 2017), which show promise (*high confidence*). Cost reductions through economies of scale are a key area for development. Extending the life of the battery can bring down overall costs and mitigate the environmental impacts (Peters et al. 2017). Understanding and controlling battery degradation is therefore important. The liquid, air-reactive electrolytes of conventional LIBs are the main source of their safety issues (Gur 2018; Janek and Zeier 2016), so All-Solid-State Batteries, in which the electrolyte is a solid, stable material, are being developed. They are expected to be safe, be durable, and have higher energy densities (Janek and Zeier 2016). New chemistries and concepts are being explored, such as lithium-sulfur batteries to achieve even higher energy densities (Van Noorden 2014; Blomgren 2017) and sodium chemistries because sodium is more abundant than lithium (Hwang et al. 2017). Cost-effective recycling of batteries will address many sustainability issues and prevent hazardous and wasteful disposal of used batteries (Harper et al. 2019). Post-LIB chemistries include metal sulfur, metal-air, metal ion (besides Li) and All-Solid-State Batteries.

<u>Compressed Air Energy Storage (CAES).</u> With CAES, off-peak electricity is used to compress air in a reservoir – either in salt caverns for large scale or in high-pressure tanks for smaller-scale installations. The air is later released to generate electricity. While conventional CAES has used natural gas to power compression, new low carbon CAES technologies, such as isothermal or adiabatic CAES, control thermal losses during compression and expansion (Wang et al. 2017c). Fast responses and higher efficiencies occur in small-scale CAES installations, scalable to suit the application as a distributed energy store, offering a flexible, low maintenance alternative (Luo et al. 2014; Venkataramani et al. 2016).

CAES is a mature technology in use since the 1970s. Although CAES technologies have been developed, there are not many installations at present (Blanc et al. 2020; Wang et al. 2017b). While the opportunities for CAES are significant, with a global geological storage potential of about 6.5 PW (Aghahosseini and Breyer 2018), a significant amount of initial investment is required. Higher efficiencies and energy densities can be achieved by exploiting the hydrostatic pressure of deep water to compress air within submersible reservoirs (Pimm et al. 2014). CAES is best suited to bulk diurnal electricity storage for buffering VRE sources and services, which do not need a very rapid response. In contrast to PHS, CAES has far more siting options and poses few environmental impacts.

<u>Liquid Air Energy Storage (LAES).</u> Liquid air energy storage uses electricity to liquefy air by cooling it to –196°C and storing it in this condensed form (largely liquid nitrogen) in large, insulated tanks. To release electricity, the 'liquid air' is evaporated through heating, expanding to drive gas turbines. Low-grade waste heat can be utilized, providing opportunities for integrating with industrial processes to increase system efficiency. There are clear, exploitable synergies with the existing liquid gas infrastructure (Peters and Sievert 2016).

LAES provides bulk daily storage of electricity, with the additional advantage of being able to capture waste heat from industrial processes. This technology is in the early commercial stage (Regen 2017; Brandon et al. 2015). Advances in whole systems integration can be developed to integrate LAES with industrial processes, making use of their waste heat streams. LAES uniquely removes contaminants in the air and could potentially incorporate CO_2 capture (Taylor et al. 2012).

Thermal Energy Storage (TES). Thermal energy storage refers to a range of technologies exploiting the ability of materials to absorb and store heat or cold, either within the same phase (sensible TES), through phase changes (latent TES), or through reversible chemical reactions (thermochemical TES). Pumped Thermal Energy Storage (PTES), a hybrid form of TES, is an air-driven electricity storage technology storing both heat and cold in gravel beds, using a reversible heat-pump system to maintain the temperature difference between the two beds and gas compression to generate and transfer heat (Regen 2017). TES technologies can store both heat and cold energy for long periods, for example in underground water reservoirs for balancing between seasons (Tian et al. 2019; Dahash et al. 2019), storing heat and cold to balance daily and seasonal temperatures in buildings and reducing heat build-up in applications generating excessive waste heat, such as data centres and underground operations.

TES can be much cheaper than batteries and has the unique ability to capture and reuse waste heat and cold, enabling the efficiency of many industrial, buildings, and domestic processes to be greatly improved (*high confidence*). Integration of TES into energy systems is particularly important, as the global demand for cooling is expected to grow (Peters and Sievert 2016; Elzinga et al. 2014). Sensible TES is well developed and widely used; latent TES is less developed with few applications. Thermochemical TES is the least developed, with no application yet (Prieto et al. 2016; Clark et al. 2020). The potential for high-density storage of industrial heat for long periods in thermochemical TES (Brandon et al. 2015) is high, with energy densities comparable to that of batteries (Taylor et al. 2012), but material costs are currently prohibitive, ranging from hundreds to thousands of dollars per tonne.

Flywheel Energy Storage (FES). Flywheels are charged by accelerating a rotor/flywheel. Energy is stored in the spinning rotor's inertia which is only decelerated by friction (minimized by magnetic bearings in a vacuum), or by contact with a mechanical, electric motor. They can reach full charge very rapidly, their state of charge can be easily determined (Amiryar and Pullen 2017), and they operate over a wide range of temperatures. While they are more expensive to install than batteries and supercapacitors, they last a long time and are best suited to stationary grid storage, providing high power for short periods (minutes). Flywheels can be used in vehicles, but not as the primary energy source.

Flywheels are a relatively mature storage technology but not widely used, despite their many advantages over electrochemical storage (Dragoni 2017). Conventional flywheels require costly, high tensile strength materials, but high-energy flywheels, using lightweight rotor materials, are being developed (Amiryar and Pullen 2017; Hedlund et al. 2015).

Supercapacitors, aka Ultracapacitors or Double Layer Capacitors (Scap). Supercapacitors consist of a porous separator sandwiched between two electrodes, immersed in a liquid electrolyte (Gur 2018). When a voltage is applied across the electrodes, ions in the electrolyte form electric double layers at the electrode surfaces, held by electrostatic forces. This structure forms a capacitor, storing electrical charge (Lin et al. 2017; Brandon et al. 2015) and can operate from –40°C to 65°C.

Supercapacitors can supply high peaks of power very rapidly for short periods (seconds up to minutes) and are able to fulfil the grid requirements for frequency regulation, but they would need to be hybridized with batteries for automotive applications. Their commercial status is limited by costly materials and additional power electronics required to stabilize their output (Brandon et al. 2015). Progress in this area includes the development of high energy supercapacitors, LIB-supercapacitor devices (Gonzalez et al. 2016), and cheaper materials (Wang et al. 2017a), all providing the potential to improve the economic case for supercapacitors, either by reducing manufacturing costs or extending their service portfolio.

Redox Flow Batteries (RFB). Redox flow batteries use two separate electrolyte solutions, usually liquids, but solid or gaseous forms may also be involved, stored in separate tanks, and pumped over or through electrode stacks during charge and discharge, with an ion-conducting membrane separating the liquids. The larger the tank, the greater the energy storage capacity, whereas more and larger cells in the stack increase the power of the flow battery. This decoupling of energy from power enables RFB installations to be uniquely tailored to suit the requirements of any given application. There are two commercially available types today: vanadium and zinc bromide, and both operate at near ambient temperatures, incurring minimal operational costs.

RFBs respond rapidly and can perform all the same services as LIBs, except for onboard electricity for EVs. Lower cost chemistries are emerging, to enable cost-effective bulk energy storage (Brandon et al. 2015). A new membrane-free design eliminates the need for a separator and also halves the system requirements, as the chemical reactions can coexist in a single electrolyte solution (Navalpotro et al. 2017; Arenas et al. 2018).

Power to fuels (PtX). **(**see also Section 6.4.3.1) The process of using electricity to generate a gaseous fuel, such as hydrogen or ammonia, is termed power-to-gas (PtG/P2G) (IEA 2020h). When injected into the existing gas infrastructure (section 6.4.5), it has the added benefit of decarbonizing gas (Brandon et al. 2015). Electricity can be used to generate hydrogen, which is then converted back into electricity using combined-cycle gas turbines that have been converted to run on hydrogen. For greater compatibility with existing gas systems and appliances, the hydrogen can combined with captured carbon dioxide to form methane and other synthetic fuels (Thema et al. 2019), however methane has high global warming potential and its supply chain emissions have been found to be significant (Balcombe et al. 2013).

PtX can provide all required grid services, depending on how it is integrated. However, a significant amount of PtX is required for storage to produce electricity again (Bogdanov et al. 2019) due to the low roundtrip efficiency of converting electricity to fuel and back again. However, portable fuels (hydrogen, methane, ammonia, synthetic hydrocarbons) are useful in certain applications, for example in energy systems lacking the potential for renewables, and the high energy density of chemical storage is essential for more demanding applications, such as transporting heavy goods and heating or cooling buildings (IEA 2020h). Research into more efficient and flexible electrolyzers which last longer and cost less is needed (Brandon et al. 2015).

Hydrogen and Reversible Hydrogen Fuel Cells (H/RHFC). Hydrogen is a flexible fuel with diverse uses, capable of providing electricity, heat, and long-term energy storage for grids, industry, and transport, and has been widely used industrially for decades (Section 0). Hydrogen can be produced in various ways and stored in significant quantities in geological formations at moderate pressures, often for long periods, providing seasonal storage (Gabrielli et al. 2020). A core and emerging implementation of PtX is hydrogen production through electrolyzers. Hydrogen is a carbon-free fuel holding three times the energy held by an equivalent mass of gasoline but occupying a larger volume. An electrolyzer uses excess electricity to split water into hydrogen and oxygen through the process of electrolysis. A fuel cell performs the reverse process of recombining hydrogen and oxygen back into water, converting chemical energy into electricity (Elzinga et al. 2014). Reversible hydrogen fuel cells (RHFCs) can perform both functions in a single device, however they are still in the pre-commercial stage, due to prohibitive production costs.

Hydrogen can play an important role in reducing emissions and has been shown to be the most cost-effective option in some cases, as it builds on existing systems (Staffell et al. 2018). Fuel cell costs need to be reduced and the harmonies between hydrogen and complementary technologies, such as batteries, for specific applications need to be explored further. Hydrogen can provide long duration storage to deal with prolonged extreme events, such as very low output of wind generation, to support resilience of future low carbon energy systems. Research in this technology focuses on improving roundtrip efficiencies, which can be as high as 80% with recycled waste heat and in high-pressure electrolyzers, incorporating more efficient compression (Matos et al. 2019). Photo-electrolysis uses solar energy to directly generate hydrogen from water (Amirante et al. 2017).

6.4.4.2 Societal Dimensions of Energy Storage

Public awareness knowledge about electricity storage technologies, their current state, and their potential role in future energy systems is limited (Jones et al. 2018). For instance, people do not perceive energy system flexibility and storage as a significant issue, or assume storage is already taking place. Public perceptions differ across storage technologies. Hydrogen is considered a modern and clean technology, but people also have safety concerns. Moreover, the public is uncertain about hydrogen storage size and the possibility of storing hydrogen in or near residential areas (Eitan and Fischhendler 2021). Battery storage both on the household and community level was perceived as slightly positive in one study in the UK (Ambrosio-Albala et al. 2020). However, financial costs are seen as a main barrier. The potential of electric vehicle batteries to function as flexible storage is limited by the current numbers of EV owners and concerns that one's car battery might not be fully loaded when needed.

6.4.5 Energy Transport and Transmission

The linkage between energy supply and distribution, on the one hand, and energy use on the other is facilitated by various mechanisms for transporting energy. As the energy system evolves, the way that energy is transported will also evolve.

6.4.5.1 Hydrogen: Low-Carbon Energy Fuel

Hydrogen is a promising energy carrier for a decarbonized world (Box 6.9). It can be utilized for electricity, heat, transport, industrial demand, and energy storage (Abdin et al. 2020). In low-carbon energy systems, hydrogen is expected to be utilized in applications that are not as amenable to electrification, such as a fuel for heavy-duty road transport and shipping, or as a chemical feedstock (Griffiths et al. 2021; Schemme et al. 2017). Hydrogen could also provide low-carbon heat for industrial processes or be utilized for direct reduction of iron ore (Vogl et al. 2018). Hydrogen could replace natural gas-based electricity generation (do Sacramento et al. 2013) in certain regions and support the integration of variable renewables into electricity systems by providing a means of long-term electricity storage. Hydrogen-based carriers, such as ammonia and synthetic hydrocarbons, can likewise be used in energy-intensive industries and the transport sector (Schemme et al. 2017; IRENA 2019b) (e.g., synthetic fuels for aviation). These hydrogen-based energy carriers are easier to store than hydrogen. At present hydrogen has limited applications – mainly being produced onsite for the creation of methanol and ammonia (IEA 2019c), as well as in refineries.

Low- or zero-carbon produced hydrogen is not currently competitive for large-scale applications, but it is likely to have a significant role in future energy systems, due to its wide-range of applications (*high confidence*). Key challenges for hydrogen are: (a) cost-effective low/zero carbon production, (b) delivery infrastructure cost, (c) land area (i.e., 'footprint') requirements of hydrogen pipelines, compressor stations, and other infrastructure, (d) challenges in using existing pipeline infrastructure, (e) maintaining hydrogen purity, (e) minimizing hydrogen leakage, and (f) the cost and performance of end-uses. Furthermore, it is necessary to consider the public perception and social acceptance of hydrogen technologies and their related infrastructure requirements (Scott and Powells 2020; Iribarren et al. 2016)

Hydrogen Production. Low- or zero-carbon hydrogen can be produced from multiple sources. While there is no consensus on the hydrogen production spectrum, "blue" hydrogen (Goldmann and

Dinkelacker 2018) generally refers to hydrogen produced from natural gas combined with CCS through processes such as steam methane reforming (SMR)(Sanusi and Mokheimer 2019) and advanced gas reforming (Zhou et al. 2020). Low-carbon hydrogen could also be produced from coal coupled with CCS (Hu et al. 2020) (Table 6.7). Current estimates are that adding CCS to produce hydrogen from SMR will add on average 50% on the capital cost, 10% to fuel, and 100% to operating costs. For coal gasification, CCS will add 5% to the capital and fuel costs and 130% to operating costs (IEA 2019d; Staffell et al. 2018). Further, biomass gasification could produce renewable hydrogen, and when joined with CCS could provide negative carbon emissions. "Green" hydrogen (Jaszczur et al. 2016) most often is referred to as hydrogen produced from zero-carbon electricity sources such as solar power and wind power (Schmidt et al. 2017) (Table 6.8). Nuclear power could also provide clean hydrogen, via electrolysis or thermochemical water splitting (EERE 2020). Hydrogen can even be produced pyrolysis of methane (Sánchez-Bastardo et al. 2020), sometimes called as "turquoise" hydrogen, solar thermochemical water splitting, biological hydrogen production (cyanobacteria) (Velazquez Abad and Dodds 2017), and microbes that use light to make hydrogen (under research)(EIA 2020).

Table 6.7 Key performance and cost characteristics of different non-electric hydrogen production technologies (including CCS)

(1) CSIRO 2021; (2) IEA 2020; (3) IRENA 2019; (4) Hydrogen Council 2020; (5) CCC 2018; (6) BEIS 2021; (7) Ishaq et al. 2021; (8) Al-Mahtani et al. 2021; (9) IEA 2019

Technology	LHV Efficiency (%)		Carbon Intensity (kg_{CO2} $(kg_{H2})^{-1}$)	Cost Estimates* (USD $(kg_{H2})^{-1}$)	
	Current	Long-term		Current	Long-term
SMR	65[5]	74[5,6]	1.0–3.6[5,9]	1.0–2.7[1,2,3,4,5]	1.5–2.6[5]
Advanced gas reforming	-	81–84[5,6]	0.9–2.9[5]	1.3–2.1[5]	1.2–3.4[5,6]
Hydrogen from coal gasification	54[5]	54[5]	2.1–5.5[5,9]	1.8–3.1[1,2,3,4,5]	2.4–3.3[5]
Hydrogen from biomass gasification	53.6[7]	40–60[5]	Potential to achieve-Negative emission[5,8]	4.9[5]	2.9–5.9[5,6]

*USD per GBP exchange rate: 0.72 (August 2021); LHV: Lower Heating Values; Long-term refers to 2040 and 2050 according to different references

Table 6.8 Efficiency and cost characteristics of electrolysis technologies for hydrogen production

(1) CSIRO 2021; (2) IEA 2020; (3) IRENA 2019; (4) Hydrogen Council 2020; (5) CCC 2018; (6) BEIS 2021; (7) IEA 2019; (8) Christensen 2020

Technology	LHV Efficiency (%)		CAPEX (USD kW_e^{-1})		Cost Estimates*,+ (USD $(kg_{H2})^{-1}$)	
	Current	Long-term (2,5,6,8)	Current (7)	Long-term (7)	Current	Long-term
Alkaline Electrolysers	58–77[1,2,5,6,8]	70–82	500–1400	200–700	2.3–6.9[1,2,3,5]	0.9–3.9[3,5]
PEM	54–72[1,2,5,6,8]	67–82	1100–1800	200–900	3.5–9.3[1,4,5,6]	2.2–7.2[5,6]
SOEC	74–81[2,6,8]	77–92	2800–5600	500–1000	4.2[5]	2.6–3.6[5]

*USD per GBP exchange rate: 0.72 (August 2021); + The cost of hydrogen production from electrolysers is highly dependent on the technology, source of electricity, and operating hours, and here some values based on the assumptions made in the references are provided.

Hydrogen energy carriers. Hydrogen can be both an energy carrier itself, be converted further for into other energy carriers (such as synthetic fuels) and be a means of transporting other sources of energy. For example, hydrogen could be transported in its native gaseous form or liquified. Hydrogen can also be combined with carbon and transported as a synthetic hydrocarbons (Gumber and Gurumoorthy 2018) (IRENA 2019d) as well as be transported via liquid organic hydrogen carriers (LOHCs) or ammonia (IRENA 2019d). For synthetic hydrocarbons such as methane or methanol to be considered zero carbon, the CO_2 used to produce them would need to come from the atmosphere either directly through DACCS or indirectly through BECCS (IRENA 2019b). LOHCs are organic substances in liquid or semi-solid states, which store hydrogen based on reversible catalytic hydrogenation and de-hydrogenation of carbon double bounds (Rao and Yoon 2020; Niermann et al. 2019). Hydrogen produced from electrolysis could also be seen as an electricity energy carrier. This is an example of the PtX processes (section 6.4.4), entailing the conversion of electricity to other energy carriers for subsequent use.

Ammonia is a promising cost-effective hydrogen carrier (Creutzig et al. 2019). Onsite generation of hydrogen for the production of ammonia already occurs today, and the NH_3 could be subsequently "cracked" (with a 15–25% energy loss) to reproduce hydrogen (Bell and Torrente-Murciano 2016; Hansgen et al. 2010; Montoya et al. 2015). Because the energy density of ammonia is 38% higher than liquid hydrogen (Osman and Sgouridis 2018), it is potentially a suitable energy carrier for long-distance transport and storage (Salmon et al. 2021) Moreover, ammonia is more easily condensable (liquefied at 0.8 MPa, 20°C), which provides economically viable hydrogen storage and supply systems. Ammonia production and transport are also established industrial processes (~180 MMT yr^{-1} (Valera-Medina et al. 2017), and hence ammonia is considered to be a scalable and cost-effective hydrogen-based energy carrier. At present, most ammonia is used in fertilizers (~80%), followed by many industrial processes, such as the manufacturing of mining explosives and petrochemicals (Jiao and Xu 2018). In contrast to hydrogen, ammonia can be used directly as a fuel without any phase change for internal combustion engines, gas turbines, and industrial furnaces (Kobayashi et al. 2019). Ammonia can also be used in low and high temperature fuel cells (Lan and Tao 2014), whereby both electricity and hydrogen can be produced without any NOx emissions. Furthermore, ammonia provides the flexibility to be dehydrogenated for hydrogen-use purposes. Ammonia is considered a carbon-free sustainable fuel for electricity generation, since in a complete combustion, only water and nitrogen are produced (Valera-Medina et al. 2017). Like hydrogen, ammonia could facilitate management of variable RES, due to its cost-effective grid-scale energy storage capabilities. In this regard, production of ammonia via hydrogen from low- or zero-carbon generation technologies along with ammonia energy recovery technologies (Afif et al. 2016) could play a major role in forming a hydrogen and/or ammonia economy to support decarbonization. However, there are serious concerns regarding the ability to safely use ammonia for all these purposes, given its toxicity - whereas hydrogen is not considered toxic.

In general, challenges around hydrogen-based energy carriers - including safety issues around flammability, toxicity, storage, and consumption - require new devices and techniques to facilitate their large-scale use. Relatively high capital costs and large electricity requirements are also challenges for technologies that produce hydrogen energy carriers. Yet, these energy carriers could become economically viable through the availability of low-cost electricity generation and excess of renewable energy production (Daiyan et al. 2020) A key challenge in use of ammonia is related to significant amount of NO_x emissions, which is released from nitrogen and oxygen combustion, and unburned ammonia. Both have substantial air pollution risks, which can result in lung and other injuries, and can reduce visibility (EPA 2001). Due to the low flammability of hydrogen energy carriers such as liquified hydrogen (Nilsson et al. 2016) and ammonia (Li et al. 2018), a stable combustion (Zengel et al. 2020; Lamas and Rodriguez 2019) in the existing gas turbines is not currently feasible. In recent developments, however, the proportion of hydrogen in gas turbines has been successfully increased, and further development of gas turbines may enable them to operate on 100% hydrogen by 2030 (Pflug et al. 2019)

Long-Distance Hydrogen Transport. Hydrogen can allow regional integration and better utilization of low- or zero-carbon energy sources (Box 6.9 and Box 6.10). Hydrogen produced from renewables or other low-carbon sources in one location could be transported for use elsewhere (Philibert 2017; Ameli et al. 2020). Depending on the distance to the user and specific energy carrier utilized (e.g., gaseous hydrogen or LOHC), various hydrogen transport infrastructures, distribution systems, and storage facilities would be required (Hansen 2020; Schönauer and Glanz 2021) (Figure 6.17).

Hydrogen can be liquefied and transported at volume over the ocean without pressurization. This requires a temperature of –253ºC and is therefore energy-intensive and costly (Niermann et al. 2021). Once it reaches its destination, the hydrogen needs to be re-gasified, adding further cost. A demonstration project is under development exporting liquid hydrogen from Australia to Japan (Yamashita et al. 2019). Hydrogen could also be transported as ammonia by ocean in liquid form. Ammonia is advantageous because it is easier to store than hydrogen (Zamfirescu and Dincer 2008; Nam et al. 2018; Soloveichik 2016). Liquid ammonia requires temperatures below –33ºC and is therefore more straightforward and less costly to transport than liquified hydrogen and even liquified natural gas (Singh and Sahu 2018). A project exporting ammonia from Saudi Arabia to Japan is under consideration (Nagashima 2018). LOHCs could also be used to transport hydrogen at ambient temperature and pressure. This advantageous property of LOHCs makes them similar to oil products, meaning they can be transported in existing oil infrastructure including oil tankers and tanks (Niermann et al. 2019; IEA 2019). A project is under development to export hydrogen from Brunei to Japan using LOHCs (Kurosaki 2018).

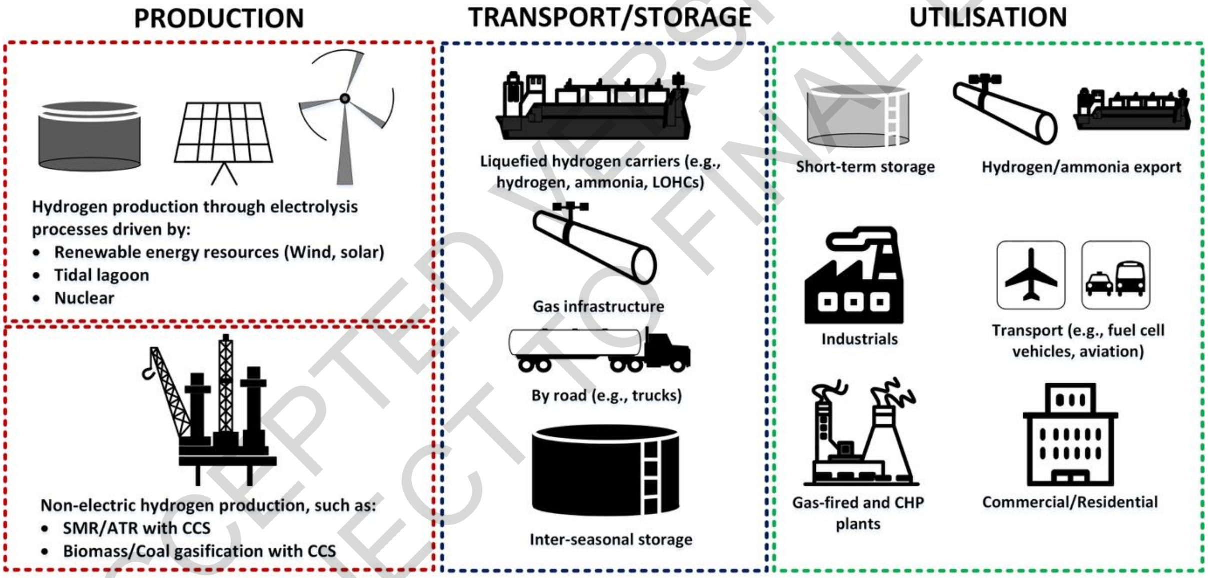


Figure 6.17 Hydrogen value chain. Hydrogen can be produced by various means and input and fuel sources. These processes have different emissions implications. Hydrogen can be transported by various means and in various forms, and it can be stored in bulk for longer-term use. It also has multiple potential end uses. CHP: Combined heat and power

Intra-Regional Hydrogen Transportation. Within a country or region, hydrogen would likely be pressurized and delivered as compressed gas. About three times as much compressed hydrogen by volume is required to supply the same amount of energy as natural gas. Security of supply is therefore more challenging in hydrogen networks than in natural gas networks. Storing hydrogen in pipelines (linepack) would be important to maintaining security of supply (Ameli et al. 2019, 2017). Due to the physics of hydrogen, in most cases exiting gas infrastructure would need to be upgraded to transport hydrogen. Transporting hydrogen in medium- or high-pressure networks most often would require reinforcements in compressor stations and pipeline construction routes (Dohi et al. 2016). There are several recent examples of efforts to transport hydrogen by pipeline. For example, in the Iron Mains Replacement Programme in the UK, the existing low pressure gas distribution pipes are being converted from iron to plastic (Committee on Climate Change 2018). In the Netherlands, an existing low-pressure 12 km natural gas pipeline has been used for transporting hydrogen (Dohi et al. 2016).

To bypass gas infrastructure in transporting hydrogen, methane can be transported using the existing gas infrastructure, while hydrogen can be produced close to the demand centres. This approach will only make sense if the methane is produced in a manner that captures carbon from the atmosphere and/or if CCS is used when the methane is used to produce hydrogen.

Bulk Hydrogen Storage. Currently, hydrogen is stored in bulk in chemical processes such as metal and chemical hydrides as well as in geologic caverns (Andersson and Grönkvist 2019; Caglayan et al. 2019) (e.g., salt caverns operate in Sweden) (Elberry et al. 2021). There are still many challenges, however, due to salt or hard rock geologies, large size, and minimum pressure requirements of the sites (IEA 2019c). Consequently, alternative carbon-free energy carriers, which store hydrogen, may become more attractive (Kobayashi et al. 2019; Lan et al. 2012).

6.4.5.2 Electricity Transmission

Given the significant geographical variations in the efficiency of renewable resources across different regions and continents, electricity transmission could facilitate cost effective deployment of renewable generation, enhance resilience and security of supply, and increase operational efficiency (*high confidence*). The diurnal and seasonal characteristics of different renewable energy sources such as wind, solar, and hydropower can vary significantly by location. Through enhanced electricity transmission infrastructure, more wind turbines can be deployed in areas with high wind potential and more solar panels in areas with larger solar irradiation. Increases in electricity transmission and trade can also enhance operational efficiency and reduce or defer the need for investment in peaking plants, storage, or other load management techniques needed to meet security of supply requirements associated with localized use of VRE sources. Increased interconnectivity of large-scale grids also allows the aggregation of 'smart grid' solutions such as flexible heating and cooling devices for flexible demand in industrial, commercial, and domestic sectors (Hakimi et al. 2020) and EVs (Li et al. 2021; Muratori and Mai 2020). In general, interconnection is more cost-optimal for countries that are geographically close to each other and can benefit from the diversity of their energy mixes and usage (Schlachtberger et al. 2017). Such developments are not without price, however, and amongst other concerns, raise issues surrounding land use, public acceptance, and resource acquisition for materials necessary for renewable developments (Vakulchuk et al. 2020; Capellán-Pérez et al. 2017).

A number of studies have demonstrated the cost benefits of interconnected grids in a range of geographical settings, including across the United States (Bloom et al. 2020), across Europe (2020; Newbery et al. 2013; Cluet et al. 2020), between Australia and parts of Asia (Halawa et al. 2018), and broader global regions, for example between the Middle East and Europe or North Africa and Europe (Tsoutsos et al. 2015). While there is growing interest in interconnection among different regions or continents, a broad range of geopolitical and socio-techno-economic challenges would need to be overcome to support this level of international co-operation and large-scale network expansion (Bertsch et al. 2017; Palle 2021).

Status of electricity transmission technology. Long-distance electricity transmission technologies are already available. High voltage alternating current (HVAC), high-voltage direct current (HVDC), and ultra HVDC (UHVDC) technologies are well-established and widely used for bulk electricity transmission (Alassi et al. 2019). HVDC is used with underground cables or long-distance overhead lines (typically voltages between 100–800 kV (Alassi et al. 2019) where HVAC is infeasible or not economic. A ~USD 17 bn project development agreement was signed in January 2021 that would connect 10 GW of PVs in the north of Australia via a 4500 km 3 GW HVDC cable to Singapore, suggesting that this would be cost effective (Sun Cable 2021). In September 2019, the Changji-Guquan ±1,100 kV ultra-high voltage direct current (UHVDC) transmission project built by State Grid

Corporation of China was officially completed and put into operation. The transmission line is able to transmit up to 12 GW over 3341 km (Pei et al. 2020). This is the UHVDC transmission project with the highest voltage level, the largest transmission capacity, and the longest transmission distance in the world (Liu 2015).

Other technologies that could expand the size of transmission corridors and/or improve the operational characteristics include low-frequency AC transmission (LFAC) (Xiang et al. 2021; Tang et al. 2021b) and half-wave AC transmission (HWACT) (Song et al. 2018; Xu et al. 2019). LFAC is technically feasible, but the circumstances in which it is the best economic choice compared to HVDC or HVAC still needs to be established (Xiang et al. 2016). HWACT is restricted to very long distances, and it has not been demonstrated in practice, so its feasibility is unproven. There are still a number of technological challenges for long-distance transmission networks such as protection systems for DC or hybrid AC-DC networks (Franck C. et al. 2017; Chaffey 2016), improvement in cabling technology, and including the use of superconductors and nanocomposites (Ballarino et al. 2016; Doukas 2019), which require advanced solutions.

Challenges, barriers, and recommendations. The main challenge to inter-regional transmission is the absence of appropriate market designs and regulatory and policy frameworks. In addition, there are commercial barriers for further enhancement of cross-border transmission. The differing impacts of cross-border interconnections on costs and revenues for generation companies in different regions could delay the development of these interconnectors. It is not yet clear how the investment cost of interconnections should be allocated and recovered, although there is growing support for allocating costs in accordance with the benefits delivered to the market participants. Increased cross-border interconnection may also require new business models which provide incentives for investment and efficient operation, manage risks and uncertainties, and facilitate coordinated planning and governance (Poudineh and Rubino 2017).

Optimizing the design and operation of the interconnected transmission system, both onshore and offshore grids, also requires more integrated economic and reliability approaches (Moreno et al. 2012) to ensure the optimal balance between the economics and the provision of system security while maximizing the benefits of smart network technologies.

A wide range of factors, including generation profiles, demand profiles circuit losses, reliability characteristics, and maintenance, as well as the uncertainties around them will need to be considered in designing and operating long-distance transmission systems if they are to be widely deployed (De Sa and Al Zubaidy 2011; Du 2009; Djapic et al. 2008; E3G 2021). Public support for extending transmission systems will also be crucial, and studies indicate that such support is frequently low (Perlaviciute et al. 2018; Vince 2010).

6.4.6 Demand Side Mitigation Options from an Energy Systems Perspective

Demand-side measures are fundamental to an integrated approach to low carbon energy systems *(high confidence)*. Mitigation options, such as wind parks, CCS, and nuclear power plants, may not be implemented when actors oppose these options. Further, end users, including consumers, governments, businesses and industry, would need to adopt the relevant options, and then use these as intended; user adoption can be a key driver to scale up markets for low carbon technologies. This section discusses which factors shape the likelihood that end users engage in relevant mitigation actions, focusing on consumers; strategies to promote mitigation actions are discussed in Section 6.7.6.1.

A wide range of actions of end users would reduce carbon emissions in energy systems (Abrahamse et al. 2007; Dietz 2013; Creutzig et al. 2018; Hackmann et al. 2014; Grubler et al. 2018), including:

- use of low carbon energy sources and carriers. Actors can produce and use their own renewable energy (e.g., install solar PV, solar water heaters, heat pumps), buy shares in a renewable energy project (e.g., wind shares), or select a renewable energy provider.

- adoption of technologies that support flexibility in energy use and sector coupling, thereby providing flexibility services by balancing demand and renewable energy supply. This would reduce the need to use fossil fuels to meet demand when renewable energy production is low and put less pressure on deployment of low-emission energy supply systems. Examples are technologies to store energy (e.g., batteries and electric vehicles) or that automatically shift appliances on or off (e.g., fridges, washing machines).
- adoption of energy-efficient appliances and systems and increase of resource efficiency of end uses so that less energy is required to provide the same service. Examples are insulating buildings, and passive or energy positive buildings.
- change behaviour to reduce overall energy demand or to match energy demand to available energy supplies. Examples include adjusting indoor temperature settings, reducing showering time, reducing car use or flying, and operating appliances when renewable energy production is high.
- purchase and use products and services that are associated with low GHG emissions during their production (e.g., reduce dairy and meat consumption) or for transporting products (e.g., local products). Also, end users can engage in behaviour supporting a circular economy, by reducing waste (e.g., of food), sharing products (e.g., cars, equipment), and refurbishing products (e.g., repair rather than buying new products) so that less new products are used.

Various factors shape whether such mitigation actions are feasible and considered by end users, including contextual factors, individual abilities, and motivational factors. Mitigation actions can be facilitated and encouraged by targeting relevant barriers and enablers (section 6.7.6.2).

Contextual factors, such as physical and climate conditions, infrastructure, available technology, regulations, institutions, culture, and financial conditions define the costs and benefits of mitigation options that enable or inhibit their adoption (*high confidence*). Geographic location and climate factors may make some technologies, such as solar PV or solar water heaters, impractical (Chang et al. 2009). Culture can inhibit efficient use of home heating or PV (Sovacool and Griffiths 2020), low carbon diets (Dubois et al. 2019), and advanced fuel choices (Van Der Kroon et al. 2013). Also, favourable financial conditions promote the uptake of PV (Wolske and Stern 2018), good facilities increase recycling (Geiger et al. 2019), and vegetarian meal sales increase when more vegetarian options are offered..

Mitigation actions are more likely when individuals feel capable to adopt them (Pisano and Lubell 2017; Geiger et al. 2019), which may depend on income and knowledge. Low-income groups may lack resources to invest in refurbishments and energy-efficient technology with high upfront costs (Andrews-Speed and Ma 2016; Chang et al. 2009; Wolske and Stern 2018). Yet, higher income groups can afford more carbon-intensive lifestyles (Golley and Meng 2012; Namazkhan et al. 2019; Frederiks et al. 2015; Santillán Vera and de la Vega Navarro 2019; Mi et al. 2020; Wiedenhofer et al. 2017). Knowledge of the causes and consequences of climate change and of ways to reduce GHG emissions is not always accurate, but lack of knowledge is not a main barrier of mitigation actions (Boudet 2019).

Motivation to engage in mitigation action, reflecting individuals' reasons for actions, depends on general goals that people strive for in their life (i.e., values). People who strongly value protecting the environment and other people are more likely to consider climate impacts and to engage in a wide range of mitigation actions than those who strongly value individual consequences of actions, such as pleasure and money (Taylor et al. 2014; Steg 2016). Values affect which types of costs and benefits people consider and prioritize when making choices, including individual, affective, social, and environmental costs and benefits (Gowdy 2008; Steg 2016).

First, people are more likely to engage in mitigation behaviour (i.e., energy savings, energy efficiency, resource efficiency in buildings, low-carbon energy generation) when they believe such behaviour has more individual benefits than costs (Harland et al. 1999; Steg and Vlek 2009; Kastner and Matthies 2016; Kastner and Stern 2015; Kardooni et al. 2016; Wolske et al. 2017; Korcaj et al. 2015), including financial benefits, convenience, comfort, autonomy, and independence in energy supply (Wolske and

Stern 2018). Yet, financial consequences seem less important for decisions to invest in energy-efficiency and renewable energy production than people indicate (Zhao et al. 2012).

Second, people are less likely to engage in mitigation behaviours that are unpleasurable or inconvenient (Steg 2016), and more likely to do so when they expect to derive positive feelings from such actions (Smith et al. 1994; Pelletier et al. 1998; Steg 2005; Carrus et al. 2008; Brosch et al. 2014; Taufik et al. 2016). Positive feelings may be elicited when behaviour is pleasurable, but also when it is perceived as meaningful (Bolderdijk et al. 2013; Taufik et al. 2015).

Third, social costs and benefits can affect climate action (Farrow et al. 2017), although people do not always recognize this (Nolan et al. 2008; Noppers et al. 2014). People engage more in mitigation actions when they think others expect them to do so and when others act as well (Rai et al. 2016; Harland et al. 1999; Nolan et al. 2008). Being part of a group that advocates mitigation actions encourages such actions (Biddau et al. 2016; Fielding and Hornsey 2016; Jans et al. 2018). Talking with peers can reduce uncertainties and confirm benefits about adoption of renewable energy technology (Palm 2017), and peers can provide social support (Wolske et al. 2017). People may engage in mitigation actions when they think this would signal something positive about them (Griskevicius et al. 2010; Milinski et al. 2006; Kastner and Stern 2015; Noppers et al. 2014). Social influence can also originate from political and business leaders (Bouman and Steg 2019); GHG emissions are lower when legislators have strong environmental records (Jensen and Spoon 2011; Dietz et al. 2015).

Fourth, mitigation actions, including saving energy and hot water, limiting meat consumption, and investing in energy efficiency, resource efficiency in buildings, and renewable energy generation are more likely when people more strongly care about others and the environment (Van Der Werff and Steg 2015; Steg et al. 2015; Wolske et al. 2017). People across the world generally strongly value the environment (Bouman and Steg 2019; Steg 2016), suggesting that they are motivated to mitigate climate change. The more individuals are aware of the climate impact of their behaviour, the more they think their actions can help reduce such impacts, which strengthens their moral norms to act accordingly, and promotes mitigation actions (Steg and de Groot 2010; Jakovcevic and Steg 2013; Chen 2015; Wolske et al. 2017).

Initial mitigation actions can encourage engagement in other mitigation actions when people experience that such actions are easy and effective (Lauren et al. 2016), and when initial actions make them realize they are a pro-environmental person, motivating them to engage in more mitigation actions so as to be consistent (van der Werff et al. 2014; Lacasse 2015, 2016; Peters et al. 2018). This implies it would be important to create conditions that make it likely that initial mitigation actions motivate further actions.

6.4.7 Summary of Mitigation Options

Designing feasible, desirable, and cost-effective energy sector mitigation strategies requires comparison between the different mitigation options. One such metric is the cost of delivering one unit of energy, for example, the levelized cost, or USD MWh^{-1}, of electricity produced from different sources. LCOEs are useful because they normalize the costs per unit of service provided. While useful in characterizing options in broad strokes, it is important to acknowledge and understand several caveats associated with these metrics, particularly when applied globally. They may be constructed with different discount rates; they require information on energy input costs for options that require energy inputs (e.g., fossil electricity generation, biofuels); they depend on local resource availability, for example solar insolation for solar power, wind classes for wind power, and rainfall and streamflow for hydropower; and actual implementation costs may include additional elements, for example, the costs of managing electricity grids heavily dependent on VRE electricity sources. These complicating factors vary across regions, some depend strongly on the policy environment in which mitigation options are deployed, and some depend on how technologies are constructed and operated.

The literature provides multiple LCOE estimates for mitigation options today and in the future (see Table 6.9 for electricity generation options). LCOE ranges for low- and zero-carbon electricity technologies overlap with LCOE's of fossil generation without CCS. For example, LCOEs for utility solar and wind today and in the future overlap with those of new coal and gas without CCS (Figure 6.18, NREL 2021; Lazard, 2020; IEA WEO 2020, IEA WEO 2020). Some of the overlap stems from differences in assumptions or regional conditions that apply to all technologies (e.g., variations in assumed discount rates), but the overlap also reflects the fact that low- and zero-carbon electricity generation options are, and will be, less expensive than emitting options in many regions. Future cost projections also illustrate that several technologies are anticipated to experience further cost declines over the coming decades, reinforcing the increasingly competitiveness of low- and zero-carbon electricity. For example, IEA's LCOEs estimates for offshore wind halve between 2020 and 2040 in several regions (IEA WEO 2020).

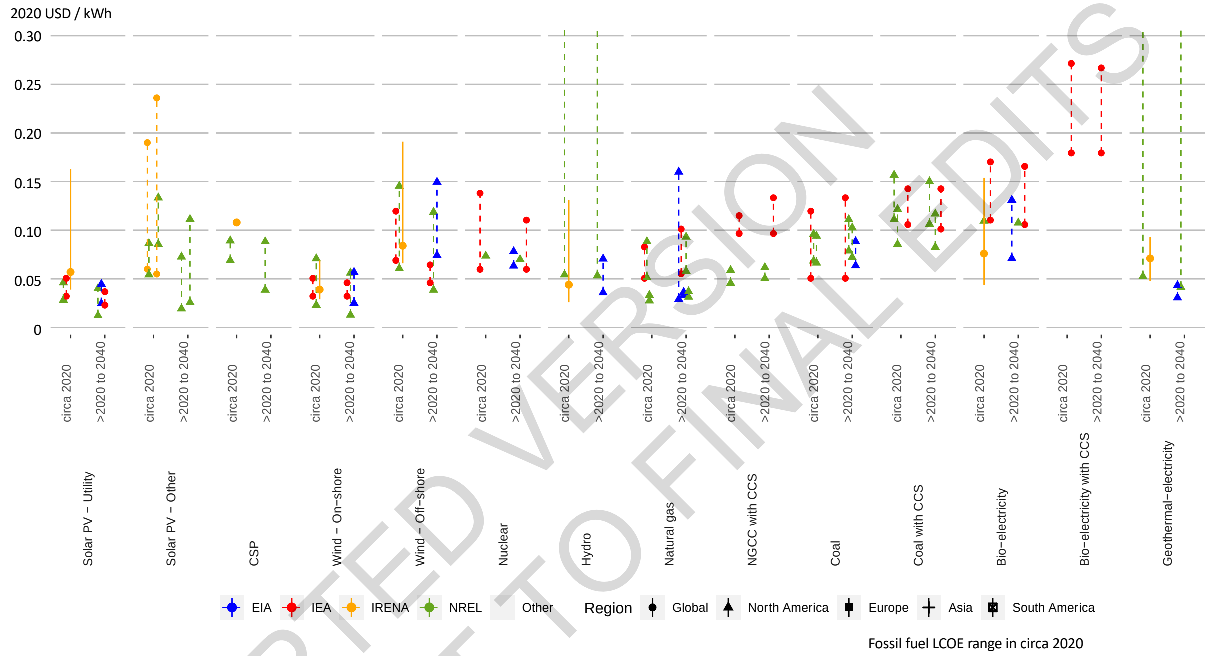


Figure 6.18 Range of LCOEs (in USD cents kWh[-1]) from recent studies for different electricity generating technologies circa 2020 and in the future between 2020-2040. LCOEs are primarily taken from recent studies, because the costs of some technologies are changing rapidly. To make the figure more tractable across the studies, we highlight the data from IEA WEO 2020 STEPS scenario in red (EIA, 2020), the EIA AEO 2021 in blue (EIA, 2021), NREL ATB 2021 in green, (NREL, 2021), and IRENA Renewable Power Generation Costs in 2020 in yellow (IRENA, 2021). All other studies are shown in light grey markers. Marker shapes identify the regions included in the studies. Studies that included several regions are labelled as global. Only sources that provided LCOEs are included. Ranges for studies frequently reflect variations among regional estimates. Studies that are shown as a mid-point and a solid line represent studies that reported either a median or an average, and that had either a confidence interval or a minimum and a maximum reported. Dashed lines with markers at the end represent the range of values reported in studies that had several point estimates for either different regions or used different assumptions. All estimates were converted to 2020 USD. The publication year was used if no USD year was provided. Some studies included transmissions costs, and some the CCS studies included storage and sequestration costs, while others did not. Vertical axis is capped at USD_{2020} 0.30 kWh^{-1}, but some estimates for hydro, geothermal, natural gas and bioelectricity were higher than 0.30. The grey horizontal band denotes the range of fossil fuel electricity LCOEs in circa 2020.

A more direct metric of mitigation options is the cost to reduce one tonne of CO_2 or equivalent GHGs, or USD tCO_2-eq^{-1} avoided. In addition to the comparison challenges noted above, this metric must account for the costs and emissions of the emitting options that is being displaced by the low-carbon option. Assumptions about the displaced option can lead to very different mitigation cost estimates

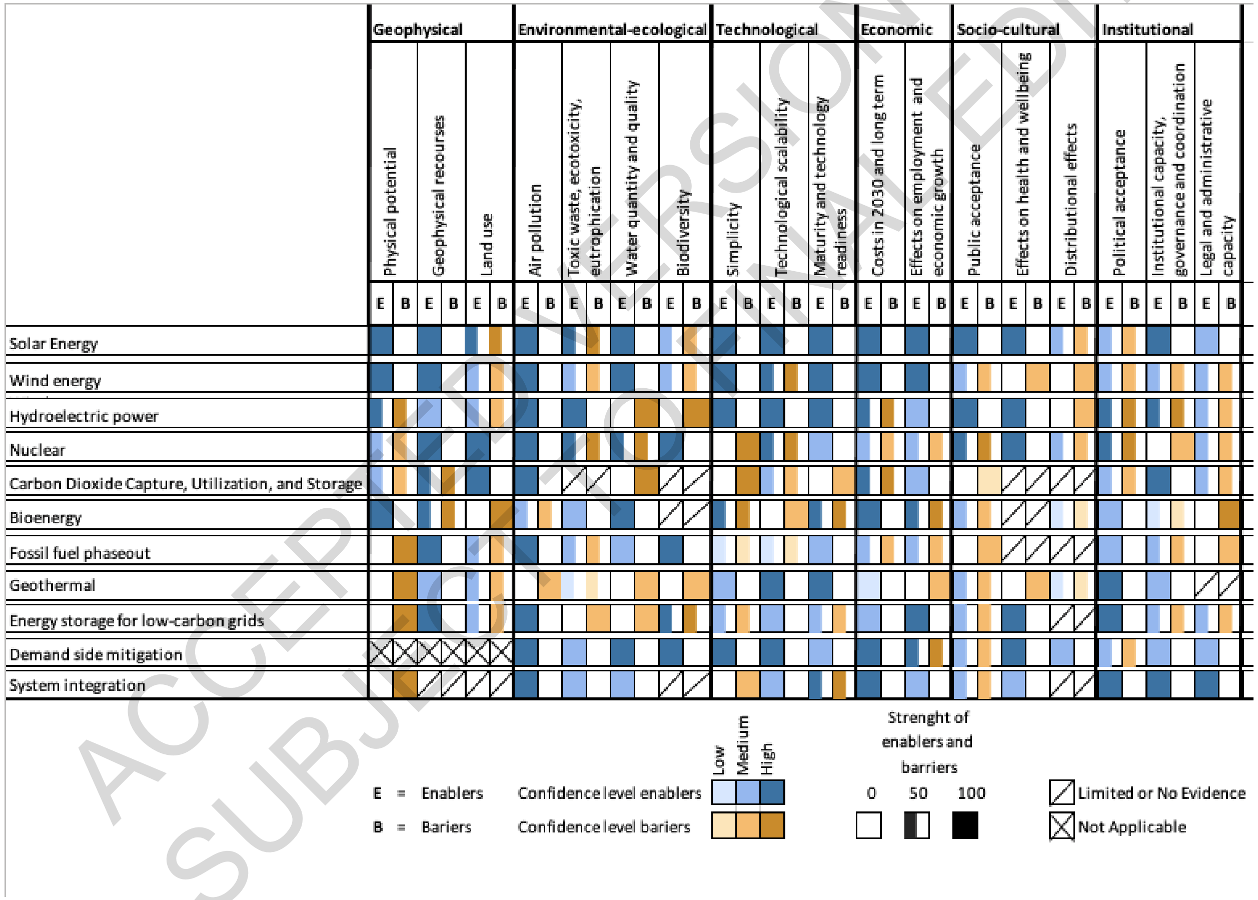
(Table 6.9). Despite these challenges, these metrics are useful for identifying broad trends and making broad comparisons, even from the global perspective in this assessment. But local information will always be critical to determine which options are most cost-effective in any specific applications.

Table 6.9 Examples of cost of mitigation for selected electricity options. Results represent variations in mitigation options and displaced fossil generation. LCOEs are illustrative, but consistent with recent estimates. Negative values mean that the mitigation option is cheaper than the displaced option, irrespective of emissions benefits.

		Baseline			
		New coal	Existing coal	New NGCC	Existing NGCC
	Baseline emissions rate (tonCO_2 MWh^{-1})	0.8	0.9	0.34	0.42
	LCOE (USD$_{2020}$ kWh^{-1})	0.065	0.041	0.044	0.028
Utility scale solar PV (poor resource site)	0.100	44 USD tCO2-eq^{-1}	66 USD tCO2-eq^{-1}	165 USD tCO2-eq^{-1}	171 USD tCO2-eq^{-1}
Utility scale solar PV (good resource site)	0.035	–38 USD tCO2-eq^{-1}	–7 USD tCO2-eq^{-1}	–26 USD tCO2-eq^{-1}	17 USD tCO2-eq^{-1}

The feasibility and desirability of mitigation options extends well beyond the market economic costs of installation and operation (Section 6.4.1). Figure 6.19 summarizes the barriers and enablers for implementing different mitigation options in energy systems. The feasibility of different options can be enhanced by removing barriers and/or strengthening enablers of the implementation of the options. The feasibility of options may differ across context (e.g., region), time (e.g., 2030 versus 2050), scale (e.g., small versus large) and the long-term warming goal (e.g., 1.5°C versus 2°C).

Figure 6.19 Summary of the extent to which different factors would enable or inhibit the deployment of mitigation options in energy systems. Blue bars indicate the extent to which the indicator enables the implementation of the option (E) and orange bars indicate the extent to which an indicator is a barrier (B) to the deployment of the option, relative to the maximum possible barriers and enablers assessed. An X signifies the indicator is not applicable or does not affect the feasibility of the option, while a forward slash indicates that there is no or limited evidence whether the indicator affects the feasibility of the option. The shading indicates the level of confidence, with darker shading signifying higher levels of confidence. Appendix II provides an overview of the factors affecting the feasibility of options and how they differ across context (e.g., region), time (e.g., 2030 versus 2050), and scale (e.g., small versus large), and includes a line of sight on which the assessment is based. The assessment method is explained in Annex II.11.



6.5 Climate Change Impacts on the Energy System

6.5.1 Climate Impacts on the Energy System

Many components of the energy system are affected by individual weather events and climate conditions (Table 6.10). In addition, a range of compounding effects can be anticipated, as the complex, interconnected climate and energy system are influenced by multiple weather and climate conditions. This raises the question of whether the energy system transformation needed to limit warming will be impacted by climate change.

1 **Table 6.10 Relevance of the key climatic impact-drivers (and their respective changes in intensity, frequency, duration, timing, and spatial extent) for major**
2 **categories of activities in the energy sector. The climate impact-drivers (CIDs) are identified in AR6/GWI/Chapter 12 (ref). The relevance is assessed as:**
3 **positive/negative (+ or –), or both (±). D&O: Design and Operation, CF: Capacity Factor.**

4

Energy sector	Energy activity	Climate Impact Driver: Heat and cold				Wet and dry								Wind				Snow and ice						Coastal			Oceanic					Other		
		Mean air temperature	Extreme heat	Cold spell	Frost	Mean precipitation	River flood	Heavy precipitation and pluvial flood	Landslide	Aridity	Hydrological drought	Agricultural and ecological drought	Fire weather	Mean wind speed	Severe wind storm	Tropical cyclone	Sand and dust storm	Snow, glacier and ice sheet	Permafrost	Lake, river and sea ice	Heavy snowfall and ice storm	Hail	Snow avalanche	Relative sea level	Coastal flood	Coastal erosion	Mean ocean temperature	Marine heatwave	Ocean acidity	Ocean salinity	Dissolved oxygen	Air pollution weather	Atmospheric CO2 at surface	Radiation at surface
Hydropower	Resources (dammed)					+	+			–	–	–						±		–														
	D&O (dammed)							±	–												–													
	Resources (undammed)					+	+	+			–	–																						
	D&O (undammed)							±	–									±		–	–													
Wind power	Capacity factors	–			–									+	–	–																		
	D&O (onshore)				–										–	–	–				–	–			–	–								
	D&O (offshore)														–	–						–		–										
Solar power	CF (PV)	–	–																													–		+
	CF (CSP)			–																												–		+
	D&O												–				–	–				–												
Ocean energy	Resources													+	±	+						–		±	±		–			±				
Bio-energy	Resources	±	–			±					–	–	–																				+	
Thermal power plants (incl nuclear)	Efficiency	±	–								–																							
	Vulnerability		–	–	–		–	–	–		–		–								–			–	–									
CCS	Efficiency	±								–	–	–																						
Energy consumption	Heating	+		–										–																				+
	Cooling	–	–											±																				–
Electric power transmission system	D&O	–	–										–																					
	Vulnerability		–										–		–	–					–		–											

The impacts of *climate change* on the energy system can be divided into three areas: impacts on the energy supply, impacts on energy consumption, and impacts on energy infrastructure. The rest of this section focuses on how the *future changes* in climate drivers might affect the ability of the energy system transformation needed to mitigate climate change. The discussion of energy infrastructure in this section is limited to electric electricity system vulnerability.

6.5.2 Impacts on Energy Supply

The increased weather-dependency of future low-carbon electricity systems amplifies the possible impacts of climate change (Staffell and Pfenninger 2018). However, *globally* climate change impacts on electricity generation – including hydro, wind and solar power potentials – should not compromise climate mitigation strategies (*high confidence*). Many of the changes in the climate system will be geographically complex at the regional and local levels. Thus, *regionally* climate change impacts on electricity generation could be significant. Climate change impacts on bioenergy potentials are more uncertain because of uncertainties associated with the crop response to climate change, future water availability and crop deployment. Climate change can reduce the efficiency of thermal power generation and increase the risk of power plant shutdowns during droughts. The potential additional cooling water needs of CCS can increase these risks.

6.5.2.1 Hydropower

The impacts of climate change on hydropower will vary by region. High latitudes in the northern hemisphere are anticipated to experience increased runoff and hydropower potential. For other regions, studies find both increasing and decreasing runoff and hydropower potential. Areas with decreased runoff are anticipated to experience reduced hydropower production and increased water conflict among different economic activities. (*high confidence*)

Hydropower production is directly related to the availability of water. Changes in runoff and its seasonality and changes in temperature and precipitation intensity will influence hydro electricity production (IHA 2019). In general, increased precipitation will increase water availability and hydropower production. Increased precipitation intensity, however, may impact the integrity of dam structures and affect power production by increasing debris accumulation and vegetation growth. Additionally, increased precipitation intensity results in the silting of the reservoirs or increases the amount of water spilt, resulting in erosion (Schaeffer et al. 2012; IHA 2019). Climate change will likely lead to higher air temperatures, resulting in more surface evaporation, less water storage, and loss of equipment efficiency (Ebinger and Vergara 2011; Fluixá-Sanmartín et al. 2018; Hock et al. 2019; Mukheibir 2013). Climate change may alter the demands for water use by other sectors that often rely on stored water in multi-purpose reservoirs and may therefore generate conflicts over water use. The increased need for water for irrigation and/or industry can affect the availability of water for hydropower generation (Solaun and Cerdá 2017; Spalding-Fecher et al. 2016). Higher temperatures increase glacier melt, increasing water availability for hydropower while the glaciers exist. Changes in the timing of snow and ice melt may require upgrading in storage capacity and adaptation of the hydropower plant management for fully exploiting the increase in water availability.

Global Solar Atlas (ESMAP 2019)

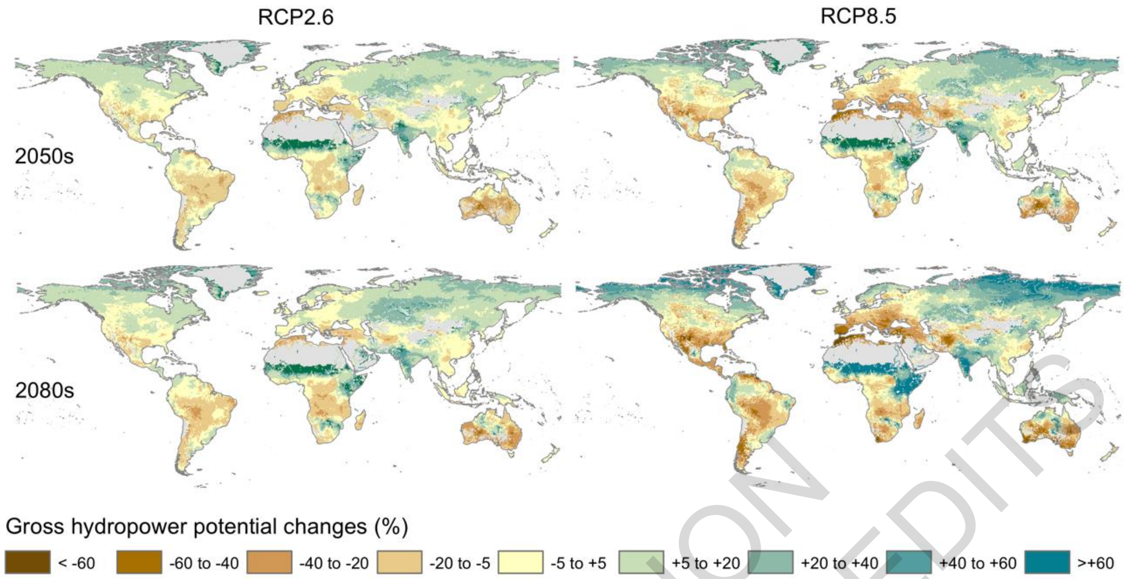


Figure 6.20 Global spatial patterns of changes in gross hydropower potential based on climate forcing from five climate models. Changes are shown for the 2050s (upper) and the 2080s (lower) for the low emission scenario (RCP2.6; left) and highest emission scenario (RCP8.5; right) scenarios relative to the control period (1971–2000). [Data source: (van Vliet et al. 2016a)].

The conclusions regarding climate change impacts on hydropower vary due to differences in modelling assumptions and methodology, such as choice of the climate and hydrological models, choice of metrics (e.g., projected production vs hydropower potential), level of modelling details between local and global studies, reservoir operation assumptions. Also important is how hydropower production matches up with other reservoir purposes, accounting for other water and energy users, and how the competing uses are impacted by climate change (Turner et al. 2017; van Vliet et al. 2016b). Nonetheless, analyses consistently demonstrate that the global impact of climate change on hydropower will be small, but the regional impacts will be larger, and will be both positive and negative (Figure 6.20) Gross global hydropower potential in the 2050s has been estimated to slightly decrease (Hamududu and Killingtveit 2012) between 0.4% (for the low emission scenario) and 6.1% (for the highest emission scenario) for the 2080s compared to 1971–2000 (van Vliet et al. 2016a).

Regional changes in hydropower are estimated from 5–20% increases for most areas in high latitudes (van Vliet et al. 2016b; Turner et al. 2017) to decreases of 5–20% in areas with increased drought conditions (Cronin et al. 2018). Models show a consistent increase in streamflow and hydropower production by 2080 in high latitudes of the northern hemisphere and parts of the tropics (Figure 6.20) (e.g., central Africa and southern Asia) while decreasing in the U.S., southern and central Europe, Southeast Asia and southern South America, Africa and Australia (van Vliet et al. 2016c,a). Decreases in hydropower production are indicated for parts of North America, central and southern Europe, the Middle East, central Asia and Southern South America. Studies disagree on the changes in hydropower production in China, central South America, and partially in southern Africa (Solaun and Cerdá 2019; Hamududu and Killingtveit 2012; van Vliet et al. 2016b; Fan et al. 2020).

6.5.2.2 Wind Energy

Climate change will not substantially impact future wind resources and will not compromise the ability of wind energy to support low-carbon transitions (*high confidence*). Changing wind variability may have a small to modest impact on backup energy and storage needs (*low confidence*); however, current evidence is largely from studies focused on Europe.

Long-term global wind energy resources are not expected to substantially change in future climate scenarios (Karnauskas et al. 2018; Yalew et al. 2020; Pryor et al. 2020). However, recent research has indicated consistent shifts in the geographic position of atmospheric jets in the high emission scenarios (Harvey et al. 2014), which would decrease wind power potentials across the Northern Hemisphere mid-latitudes and increase wind potentials across the tropics and the Southern Hemisphere. However, the climate models used to make these assessments differ in how well they can reproduce the historical wind resources and wind extremes, which raises questions about the robustness of their predictions of future wind resources (Pryor et al. 2020).

There are many regional studies on changes in wind resources from climate change. For Europe, there is medium evidence and moderate agreement that wind resources are already increasing and will continue to increase in Northern Europe and decrease in Southern Europe (Moemken et al. 2018; Carvalho et al. 2017; Devis et al. 2018). For North America, the various studies have low agreement for the changes in future wind resources in part because the year-to-year variations in wind resources are often larger than the future change due to climate change (Johnson and Erhardt 2016; Wang et al. 2020b; Costoya et al. 2020; Chen 2020). Studies show increases in future wind resources in windy areas in South America (Ruffato-Ferreira et al. 2017; de Jong et al. 2019). No robust future changes in wind resources have been identified in China (Xiong et al. 2019). However, none of the global or regional studies of the effects of climate change on wind resources considers the fine-scale dependence of wind resources on the topography and wind direction (Sanz Rodrigo et al. 2016; Dörenkämper et al. 2020) or the effect of expanding wind energy exploitation (Lundquist et al. 2019; Volker et al. 2017). There is limited evidence that extreme wind speeds, which can damage wind turbines, will increase due to climate change (Pes et al. 2017; Pryor et al. 2020). Nevertheless, projected changes in Europe and North America – regions where the most extensive analysis has been undertaken – are expected to be within the estimates embedded in the design standards of wind turbines (Pryor and Barthelmie 2013).

Future wind generation in Europe could decrease in summer and autumn, increasing in winter in northern-central Europe but decreasing in southernmost Europe (Carvalho et al. 2017). Towards 2100, intra-annual variations increase in most of Europe, except around the Mediterranean area (Reyers et al. 2016), but this may reflect natural multidecadal variability (Wohland et al. 2019b). Wind speeds may become more homogeneous over large geographical regions in Europe due to climate change, increasing the likelihood of large areas experiencing high or low wind speeds simultaneously (Wohland et al. 2017). These changes could result in fewer benefits in the transmission of wind generation between countries and increased system integration costs. Europe could require a modest increase (up to 7%) in backup energy towards the end of the 21st century due to more homogeneous wind conditions over Europe (Wohland et al. 2017; Weber et al. 2018). However, other studies report that impact of climate change is substantially smaller than interannual variability, with no significant impact on the occurrence of extreme low wind production events in Europe (Van Der Wiel et al. 2019). If European electricity systems are designed to manage the effects of existing weather variability on wind power, they can likely also cope with climate change impacts on wind power (Ravestein et al. 2018). Changes in wind generation variability caused by climate change are also reported for North America (Haupt et al. 2016; Losada Carreño et al. 2018), with modest impacts on electricity system operation (Craig et al. 2019).

6.5.2.3 Solar Energy

Climate change is not expected to substantially impact global solar insolation and will not compromise the ability of solar energy to support low-carbon transitions (*high confidence*). Models show dimming and brightening in certain regions, driven by cloud, aerosol and water vapour trends [WGI,ch12,p31]. The increase in surface temperature, which affects all regions, decreases solar power output by reducing the PV panel efficiency. In some models and climate scenarios, the increases in solar insolation are counterbalanced by reducing efficiency due to rising surface air temperatures, which increase significantly in all models and scenarios (Jerez et al. 2015; Bartók et al. 2017; Emodi et al. 2019). Increases in aerosols would reduce the solar resource available and add to maintenance costs [AR6,WGI,ch12].

In many emission scenarios, the effect on solar PV from temperature-induced efficiency losses is smaller than the effect expected from changes on solar insolation due to variations in water vapour and clouds in most regions. Also, future PV technologies will likely have higher efficiency, which would offset temperature-related declines (Müller et al. 2019). Cloud cover is projected to decrease in the subtropics (around –0.05% per year), including parts of North America, vast parts of Europe and China, South America, South Africa and Australia (medium agreement, medium evidence). Thus, models project modest (< 3%) increases in solar PV by the end of the century for southern Europe, northern and southern Africa, Central America, and the Caribbean (Emodi et al. 2019). There are several studies projecting decreasing solar production, but these are generally influenced by other factors, for example, increasing air pollution (Ruosteenoja et al. 2019). The multi-model means for solar insolation in regional models decrease 0.60 W m^{-2} per decade from 2006 to 2100 over most of Europe (Bartók et al. 2017), with the most significant decreases in the Northern countries (Jerez et al. 2015).

6.5.2.4 Bioenergy

Climate change can affect biomass resource potential directly, via changes in the suitable range (i.e., the area where bioenergy crops can grow) and/or changes in yield, and indirectly, through changes in land availability. Increases in CO_2 concentration increase biomass yield; climate changes (e.g., temperature, precipitation, etc.) can either increase or decrease the yield and suitable range.

Climate change will shift the suitable range for bioenergy towards higher latitudes, but the net change in the total suitable area is uncertain (*high confidence*). Several studies show northward shifts in the suitable range for bioenergy in the northern hemisphere (Tuck et al. 2006; Bellarby et al. 2010; Preston et al. 2016; Barney and DiTomaso 2010; Hager et al. 2014; Conant et al. 2018; Cronin et al. 2018; Wang et al. 2014a), but the net effect of climate change on total suitable area varies by region, species, and climate model (Barney and DiTomaso 2010; Hager et al. 2014; Wang et al. 2014a).

The effect of climate change on bioenergy crop yields will vary across region and feedstock (*high confidence*); however, in general, yields will decline in low latitudes (*medium confidence*) and increase in high latitudes (*low confidence*) (Haberl et al. 2010; Cosentino et al. 2012; Mbow et al. 2019; Cronin et al. 2018; Preston et al. 2016). However, the average change in yield varies significantly across studies, depending on the feedstock, region, and other factors (Dolan et al. 2020; Kyle et al. 2014) Mbow et al. (2019); Beringer et al. (2011). Only a few studies extend the modelling of climate change impacts on bioenergy to quantify the effect on bioenergy deployment or its implications on the energy system (Calvin et al. 2013, 2019; Thornton et al. 2017; Kyle et al. 2014). These studies find that changes in deployment are of the same sign as changes in yield; that is, if yields increase, then deployment increases.

Some of the uncertainty in the sign and magnitude of the impacts of climate change on bioenergy potential is due to uncertainties in CO_2 fertilization (the increase in photosynthesis due to increases in atmospheric CO_2 concentration) (Bonjean Stanton et al. 2016; Haberl et al. 2011; Cronin et al. 2018; Solaun and Cerdá 2019; Yalew et al. 2020). For example, earlier studies found that without CO_2

fertilization, climate change will reduce global bioenergy potential by about 16%; with CO_2 fertilization, however, climate change increases this potential by 45% (Haberl et al. 2011). However, newer studies in the U.S. find little effect of CO_2 fertilization on switchgrass yield (Dolan et al. 2020). There is also a considerable uncertainty across climate and crop models in estimating bioenergy potential (Hager et al. 2014).

6.5.2.5 Thermal power plants

The operation of thermal power plants will be affected by climate change, deriving from changes in the ambient conditions like temperature, humidity and water availability (Schaeffer et al. 2012) (*high confidence*). Changes in ambient temperature have relatively small impacts on coal-fired and nuclear power plants (Rankine cycle); however, gas-fired power plants (Brayton or combined-cycle) may have their thermal efficiency and power output significantly decreased (De Sa and Al Zubaidy 2011; Schaeffer et al. 2012). Droughts decrease potential cooling water for thermal power plants and increase the probability of water outlet temperatures exceeding regulatory limits, leading to lower production or even shutdowns. Thermal power utilization has been reported to be on average 3.8% lower during drought years globally (van Vliet et al. 2016c). and further significant decreases in available thermal power plant capacity due to climate change are projected (Koch et al. 2014; van Vliet et al. 2016b; Yalew et al. 2020) . An increase in climate-related nuclear power disruptions has been reported in the past decades globally (Ahmad 2021).

Carbon capture may increase cooling water usage significantly, especially in retrofits, with up to 50% increase in water usage for coal-fired power plants globally, depending on the CCS technology (Rosa et al. 2020, Section 6.4). In Asia, planned coal capacity is expected to be vulnerable to droughts, sea level rise, and rising air temperatures, and this may be exacerbated by incorporating carbon capture (Wang et al. 2019c). Recently, however, studies have proposed designs of CCS with a minimal increase in water requirements (Mikunda et al. 2021; Magneschi et al. 2017).

Older thermal power plants can be retrofitted to mitigate climate impacts by altering and redesigning the cooling systems (Westlén 2018), although the costs for these solutions may be high. For example, dry cooling may be used instead of once-through cooling; however, it lowers thermal efficiency and would leave plants vulnerable to ambient temperature increase (Ahmad 2021). Closed-circuit cooling is much less sensitive to water temperature than once-through cooling (Bonjean Stanton et al. 2016). Modifying policies and regulation of water and heat emissions from power plants may also be used to mitigate plant reliability problems induced by climate change (Eisenack 2016; Mu et al. 2020), albeit with potential impacts for other water users and ecology. Improvements in water use and thermal efficiencies and the use of transmission capabilities over large geographical regions to mitigate risks on individual plants are also possible mitigation options (Miara et al. 2017).

6.5.3 Impacts on Energy Consumption

Heating demand will decrease, and cooling demand will increase in response to climate change. Peak load may increase more than energy consumption, and the changing spatial and temporal load patterns can impact transmission and needs for storage, demands-side management, and peak-generating capacity. (*high confidence*)

Climate change will decrease heating demands, especially in cold regions, and it will increase cooling demands, especially in warm regions (Yalew et al. 2020). Recent studies report significant net impacts, with the commercial and industrial sectors and substantial air condition penetration driving an increase in energy demand (De Cian and Sue Wing 2019; Levesque et al. 2018; van Ruijven et al. 2019; Davis and Gertler 2015; Yalew et al. 2020). For example, globally, De Cian and Sue Wing (2019) found a 7–17% increase in energy consumption due to climate change in 2050, with the range depending on the climate change scenario. The overall effects of climate change on building energy consumption are regionally dependent. For example, Zhang et al. (2019) find that reduced heating will outweigh increased cooling in the residential buildings in Europe, but the reverse will be true in China.

While many studies have focused on energy consumption, climate extremes are expected to alter peak energy demands, with the potential for blackouts, brownouts, and other short-term energy system impacts (Yalew et al. 2020). For example, peak energy demand during heatwaves can coincide with reduced transmission and distribution capacity at higher temperatures. In large cities, extreme heat events increase cooling degree days significantly, with the urban heat island effect compounding the impact (Morakinyo et al. 2019). One study found that total electricity consumption at the end of the century in the U.S. could increase on average by 20% during summer months and decrease on average by 6% in the winder (Ralston Fonseca et al. 2019). While the average increase in consumption is modest, climate change is projected to have severe impacts on the frequency and intensity of peak electricity loads. (Auffhammer et al. 2017). Bartos et al. (2016) find that peak per-capita summertime load in the U.S. may rise by 4.2%–15% by mid-century. Efficient cooling technologies and other demand side measures can limit cooling energy loads during periods of particularly high demand(Dreyfus et al. 2020; International Energy Agency (IEA) 2018).

[START BOX 6.6 HERE]

Box 6.6 Energy Resilience

In February 2021, the state of Texas was hit by three major storms and suffered significant scale power outages. More than 4.5 million homes and businesses on the Texas electric grid were left without electricity for days, limiting the ability to heat homes during dangerously low temperatures and leading to food and clean water shortages (Busby et al. 2021). The Texas and other events – e.g., during Typhoon Haiyan that affected Southeast Asia in 2013; the Australian bush fires in 2019–2020 and forest fires in 2018 in California; water shortages in Cape Town, South Africa in 2018 and the western United States during 2021 – raise the question of whether future low-carbon energy systems will be more or less resilient than those of today.

Some characteristics of low-carbon energy systems will make them less resilient. Droughts reduce hydroelectric electricity generation (Gleick 2016; van Vliet et al. 2016c); wind farms do not produce electricity in calm conditions or shut down in very strong winds (Petersen and Troen 2012); solar PV generation is reduced by clouds and is less efficient under extreme heat, dust storms, and wildfires (Perry and Troccoli 2015; Jackson and Gunda 2021). In addition, the electrification of heating will increase the weather dependence of electricity consumption (Staffell and Pfenninger 2018; Gea-Bermúdez et al. 2021). Non-renewable generation, for example from nuclear and fossil power plants, are also vulnerable to high temperatures and droughts as they depend on water for cooling (Cronin et al. 2018; Ahmad 2021).

But some aspects of low-carbon energy systems will make them more resilient. Wind and solar farms are often spread geographically, which reduces the chances of being affected by the same extreme weather event (Perera et al. 2020). The diversification of energy sources, in which each component has different vulnerabilities, increases resilience. Less reliance on thermal electricity generation technologies will reduce the risks of curtailment or efficiency losses from droughts and heat waves. (Lohrmann et al. 2019). More generally, increased electricity system integration and flexibility (Section 6.4.3) and weatherization of generators increases electricity system resilience (Heffron et al. 2021; Busby et al. 2021). Likewise, local district micro-grids with appropriate enabling technologies (e.g., distributed generation, energy storage, greater demand-side participation, electric vehicles) may ensure access to electricity during major long-duration power outage events and radically enhance the resilience of supply of essential demand (Stout et al. 2019).

[END BOX 6.6 HERE]

6.5.4 Impacts on Electricity System Vulnerability

While long-term trends are important for electricity system planning, short-term effects associated with loss of power can be disruptive and lead to significant economic losses along with cascading impacts on health and safety. Extreme weather and storms threaten the electricity system in different ways, affecting system resilience, reliability, and adequacy (Moreno-Mateos et al. 2020). The implications of climate change for electricity system vulnerability will depend on the degree to which climate change alters the frequency and intensity of extreme weather events. The complex compounding effects of simultaneous events (e.g., high winds and lightning occurring at the same time) are not well understood.

High wind speeds can shear lines through mechanical failure or cause lines to collide, causing transient events (Panteli and Mancarella 2015; Yalew et al. 2020). Hurricane conditions can damage electricity system infrastructures, including utility-scale wind and solar PV plants. Electricity systems may experience high demand when lines are particularly at risk from mechanical failure from wind and storm-related effects. However, except for medium evidence of increases in heavy precipitation associated with tropical cyclones, there is limited evidence that extreme wind events will increase in frequency or intensity in the future (Kumar et al. 2015; Pryor et al. 2020).

Wildfires pose a significant threat to electricity systems in dry conditions and arid regions (Dian et al. 2019). With climate change, wildfires will probably become more frequent (Flannigan et al. 2013) and more difficult to address given that they frequently coincide with dry air and can be exacerbated by high winds (Mitchell 2013).

Lightning can cause wildfires or common-mode faults on electricity systems associated with vegetation falling on power substations or overhead lines but is more generally associated with flashovers and overloads (Balijepalli et al. 2005). Climate change may change the probability of lightning-related events (Romps et al. 2014).

Snow and icing can impact overhead power lines by weighing them down beyond their mechanical limits, leading to collapse and cascading outages (Feng et al. 2015). Snow can also lead to flashovers on lines due to wet snow accumulation on insulators (Croce et al. 2018; Yaji et al. 2014) and snow and ice can impact wind turbines (Davis et al. 2016). Climate change will lower risk of snow and ice conditions (McColl et al. 2012), but there is still an underlying risk of sporadic acute cold conditions such as those associated with winter storms in Texas in 2021 (Box 6.).

Flooding poses a threat to the transmission and distribution systems by inundating low-lying substations and underground cables. Coastal flooding also poses a threat to electricity system infrastructure. Rising sea levels from climate change and associated storm surge may also pose a significant risk for coastal electricity systems (Entriken and Lordan 2012).

Temperature increases influence electricity load profiles and electricity generation, as well as potentially impact supporting information and communication infrastructure. Heat can pose direct impacts to electricity system equipment such as transformers. Referred to as solar heat faults, they occur under high temperatures and low wind speeds and can be exacerbated by the urban heat island effect (McColl et al. 2012). Increasing temperatures affect system adequacy by reducing electric transmission capacity, simultaneously increasing peak load due to increased air conditioning needs (Bartos et al. 2016).

[START BOX 6.7 HERE]

Box 6.7 Impacts of Renewable Energy Production on Climate

While climate change will affect energy systems (Section 6.5), the reverse is potentially also true: increasing the use of renewable energy sources could affect local climate. Large solar PV arrays and hydroelectric dams darken the land surface, and wind turbines extract the wind's kinetic energy near the Earth's surface. Their environmental impacts of renewable energy production are mostly confined to areas close to the production sources and have shown to be trivial compared to the mitigation benefits of renewable energy (*high confidence*).

Solar Energy. Observations and model simulations have addressed whether large-scale solar PV power plants can alter the local and regional climate. In rural areas at the local scale, large-scale solar PV farms change the surface characteristics and affect air temperatures (Taha 2013). Measurements in rural Arizona, U.S. show local nighttime temperatures 3–4°C warmer at the PV farm than surroundings (Barron-Gafford et al. 2016). In contrast, measurements in urban settings show that solar PV panels on roofs provide a cooling effect (Ma et al. 2017; Taha 2013). On the regional scale, modelling studies suggest cooling in urban areas (0.11–0.53°C) and warming in rural areas (up to 0.27°C) (Millstein and Menon 2011). Global climate model simulations show that solar panels induce regional cooling by converting part of the incoming solar energy to electricity (Hu et al. 2016). However, converting the generated electricity to heat in urban areas increases regional and local temperatures, compensating for the cooling effect.

Wind Energy. Surface temperature changes in the vicinity of wind farms have been detected (Xia et al. 2019; Smith et al. 2013; Lee and Lundquist 2017; Takle et al. 2019) in the form of nighttime warming. Data from field campaigns suggest that a "suppression of cooling" can explain the observed warming (Takle et al. 2019). Regional and climate models have been used to describe the interactions between turbines and the atmosphere and find minor impacts (Vautard et al. 2014). More sophisticated models confirm the local warming effect of wind farms but report that the impact on the regional area is slight and occasional (Wang et al. 2019d). Wind turbines alter the transport and dissipation of momentum near the surface but do not directly impact the Earth's energy balance (Fischereit et al. 2021). However, the secondary modifications to the energy and water exchanges have added implications for the climate system (Jacobson and Archer 2012).

Hydropower. The potential climate impacts of hydropower concentrate on the GHG emissions from organic matter decomposition when the carbon cycle is altered by the flooding of the hydroelectric power plant reservoir (Ocko and Hamburg 2019), but emissions from organic matter decomposition decrease over time. The darker surface of the reservoir, compared to the lighter surrounding land may counterbalance part of the reduced GHG emissions by hydropower production (Wohlfahrt et al. 2021). However, these impacts vary significantly among facilities due to the surrounding land properties and the area inundated by the reservoir.

[END BOX 6.7 HERE

6.6 Key Characteristics of Net Zero Energy Systems

6.6.1 What is a Net Zero Energy System?

Limiting warming to well below 2°C requires that CO_2 emissions from the energy sector be reduced to near zero or even below zero (Chapter 3, 6.7). Policies, technologies, behaviours, investments, and other factors will determine the speed at which countries transition to net zero energy systems – those that emit very little or no emissions. An understanding of these future energy systems can help to chart a course toward them over the coming decades.

This section synthesizes current understanding of net zero energy systems. Discussions surrounding efforts to limit warming are frequently communicated in terms of the point in time at which net anthropogenic CO_2 emissions reach zero, accompanied by substantial reductions in non-CO_2 emissions

(IPCC 2018, Chapter 3). Net-zero GHG goals are also common, and they require net-negative CO_2 emissions to compensate for residual non-CO_2 emissions. Economy-wide CO_2 and GHG goals appear in many government and corporate decarbonization strategies, and they are used in a variety of ways. Most existing carbon-neutrality commitments from countries and subnational jurisdictions aim for economies with very low emissions rather than zero emissions. Offsets, carbon dioxide removal (CDR) methods, and/or land sink assumptions are used to achieve net zero goals (Kelly Levin et al. 2020).

Precisely describing a net zero energy system is complicated by the fact that different scenarios attribute different future CO_2 emissions to the energy system, even under scenarios where economy-wide CO_2 emissions reach net zero. It is also complicated by the dependence of energy system configurations on unknown future conditions like population and economic growth, and technological change. The energy system is not the only source or sink of CO_2 emissions. Terrestrial systems may store or emit carbon, and CDR options like BECCS or DACCS can be used to store CO_2, relieving pressure on the energy system (Chapter 3). The location of such CDR options is ambiguous, as it might be deployed within or outside of the energy sector (Figure 6.21), and many CDR options, such as DACCS, would be important energy consumers (Bistline and Blanford 2021a, 6.6.2). If CDR methods are deployed outside of the energy system (e.g., net negative agriculture, forestry, and land use CO_2 emissions), it is possible for the energy system to still emit CO_2 but have economy-wide emissions of zero or below. When global energy and industrial CO_2 emissions reach net zero, the space remaining for fossil energy emissions is determined by deployment of CDR options (Figure 6.21).

This section focuses on energy systems that produce very little or no CO_2 emissions, referred to in this chapter as net zero energy systems. While energy systems may not reach net zero concurrently with economy-wide CO_2 or GHG emissions, they are a useful benchmark for planning a path to net zero. Note that the focus here is on energy systems with net zero CO_2 emissions from fossil fuel combustion and industrial processes, but the lessons will be broadly applicable to net zero GHG energy systems as well. Net-zero GHG energy systems would incorporate the major efforts made to reduce non-CO_2 emissions (e.g., CH_4 from oil, gas and coal as discussed in Section 6.4) and would also need to incorporate more CDR to compensate for remaining non-CO_2 GHG emissions. Energy sector emissions in many countries may not reach net zero at the same time as global energy system emissions (Figure 6.25, Cross-Chapter Box 3 in Chapter 3).

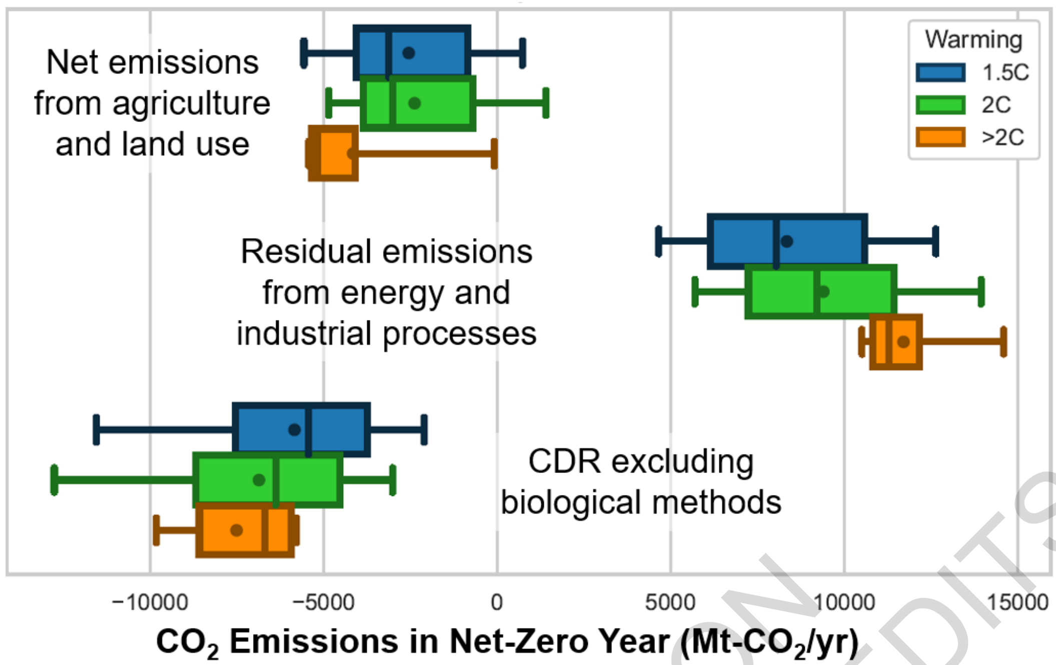


Figure 6.21 Residual emissions and CDR when global energy and industrial CO_2 emissions reach net zero. Residual emissions and CDR in net zero scenarios show global differences across warming levels (blue = <1.5˚C, green = <2.0˚C, orange = >2.0˚C). Points represent different models and scenarios from the AR6 database. In each case, the boxes show the 25th to 75th percentile ranges, and whiskers show the 5th and 95th percentiles. Lines and circles within the boxes denote the median and mean values, respectively.

6.6.2 Configurations of Net-zero Energy Systems

Net-zero energy systems entail trade-offs across economic, environmental, and social dimensions (Davis et al. 2018). Many socioeconomic, policy, and market uncertainties will also influence the configuration of net zero energy systems (van Vuuren et al. 2018; Krey et al. 2019; Bistline et al. 2019; Smith et al. 2015, Azevedo et al. 2021, Pye et al, 2021). There are reasons that countries might focus on one system configuration versus another, including cost, resource endowments, related industrial bases, existing infrastructure, geography, governance, public acceptance, and other policy priorities (Section 6.6.4 and Chapter 18 of WGII).

Explorations of net zero energy systems have been emerging in the detailed systems modelling literature (Azevedo et al. 2021; Bistline 2021b). Reports associated with net zero economy-wide targets for countries and subnational entities typically do not provide detailed roadmaps or modelling but discuss high-level guiding principles, though more detailed studies are emerging at national levels (Williams et al. 2021a; Duan et al. 2021; Capros et al. 2019; Wei et al. 2020). Most analysis has focused on identifying potential decarbonization technologies and pathways for different sectors, enumerating opportunities and barriers for each, their costs, highlighting robust insights, and characterizing key uncertainties (Hepburn et al. 2019; Davis et al. 2018).

The literature on the configuration of net zero energy systems is limited in a few respects. On the one hand, there is a robust integrated assessment literature that provides characterizations of these systems in broad strokes (AR6 database), offering internally consistent global scenarios to link global warming targets to regional/national goals. All integrated assessment scenarios that discuss net zero energy system CO_2 emissions provide high-level characterizations of net zero systems. Because these characterizations have less temporal, spatial, technological, regulatory, and societal detail, however, they may not consider the complexities that could ultimately influence regional, national, or local pathways. High-fidelity models and analyses are needed to assess the economic and environmental characteristics and the feasibility of many aspects of net zero or net negative emissions energy systems (*high confidence*) (Bistline and Blanford 2020; Blanford et al. 2018). For example, evaluating the competitiveness of electricity sector technologies requires temporal, spatial, and technological detail to accurately represent system investments and operations (Bistline 2021c; Victoria et al. 2021; Helistoe et al. 2019; Collins et al. 2017; Santen et al. 2017).

Configurations of net zero energy systems will vary by region but are likely to share several common characteristics (*high confidence*) (Figure 6.22). We focus on seven of those common characteristics in the remainder of this subsection.

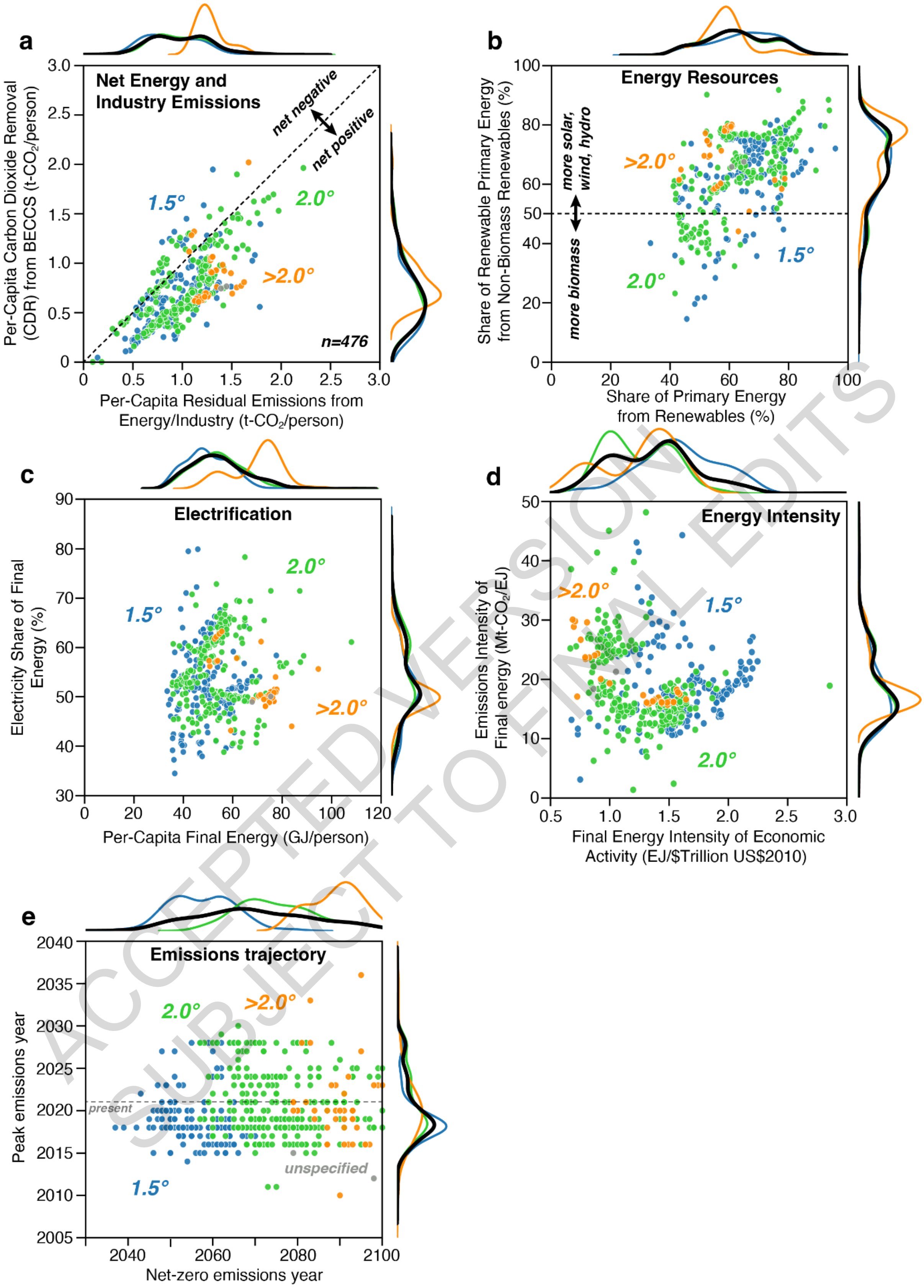


Figure 6.22 Characteristics of global net zero energy systems when global energy and industrial CO_2 emissions reach net zero. Scenarios reaching net zero emissions show differences in residual emissions

and carbon removal (a), energy resources (b), electrification (c), energy intensity (as measured here by energy GDP^{-1}) (d), and emissions trajectory (e), particularly with respect to warming levels (blue = <1.5˚C, green = <2.0˚C, orange = >2.0˚C, gray = unspecified). Points represent individual scenarios, with probability density distributions shown along each axis for each warming level (colours corresponding to warming levels) and for all scenarios (black). Points represent different models and scenarios from the AR6 database.

6.6.2.1 Limited and/or Targeted Use of Fossil Fuels

Net-zero energy systems will use far less fossil fuel than today (*high confidence*). The precise quantity of fossil fuels will largely depend upon the relative costs of such fuels, electrification, alternative fuels, and CDR (see Section 6.6.2.4) in the energy system (*high confidence*). All of these are affected by regional differences in resources (McGlade and Ekins 2015), existing energy infrastructure (Tong et al. 2019), demand for energy services, and climate and energy policies. Fossil fuel use may persist, for example, if and where the costs of such fuels and the compensating carbon management (e.g., CDR, CCS) are less than non-fossil energy. For most applications, however, it is likely that electrification (McCollum et al. 2014; Madeddu et al. 2020; Zhang and Fujimori 2020) or use of non-fossil alternative fuels (Zeman and Keith 2008; Graves et al. 2011; Hänggi et al. 2019; Ueckerdt et al. 2021) will prove to be the cheapest options. Most residual demand for fossil fuels is likely to predominantly be petroleum and natural gas given their high energy density (Davis et al. 2018), while demand for coal in net zero energy systems is likely to be very low (Luderer et al. 2018; Jakob et al. 2020, Section 6.7.4) (*high confidence*).

There is considerable flexibility regarding the overall quantity of liquid and gaseous fuels that will be required in net zero energy systems (*high confidence*) (Figure 6.22, Section 6.7.4). This will be determined by the relative value of such fuels as compared to systems which rely more or less heavily on zero-emissions electricity. In turn, the share of any fuels that are fossil or fossil-derived is uncertain and will depend on the feasibility of CCS and CDR technologies and long-term sequestration as compared to alternative, carbon-neutral fuels. Moreover, to the extent that physical, biological, and/or socio-political factors limit the availability of CDR (Smith et al. 2015; Field and Mach 2017), carbon management efforts may prioritize residual emissions related to land use and other non-energy sources.

6.6.2.2 Zero or Negative CO_2 Emissions from Electricity

Net-zero energy systems will rely on decarbonized or net-negative CO_2 emissions electricity systems, due to the many lower-cost options for producing zero-carbon electricity and the important role of end-use electrification in decarbonizing other sectors (*high confidence*).

There are many possible configurations and technologies for zero- or net-negative-emissions electricity systems (*high confidence*). These systems could entail a mix of variable renewables, dispatchable renewables (e.g., biomass, hydropower), other firm, dispatchable ("on-demand") low-carbon generation (e.g., nuclear, CCS-equipped capacity), energy storage, transmission, carbon removal options (e.g., BECCS, DACCS), and demand management (Bistline and Blanford 2021b; Bistline et al. 2018; Jenkins et al. 2018b; Luderer et al. 2017). The marginal cost of deploying electricity sector mitigation options increases as electricity emissions approach zero; in addition, the most cost-effective mix of system resources changes as emissions approach zero and, therefore, so do the implications of electricity sector mitigation for sustainability and other societal goals (Cole et al. 2021; Jayadev et al. 2020; Bistline et al. 2018; Mileva et al. 2016; Sepulveda et al. 2018). Key factors influencing the electricity mix include relative costs and system benefits, local resource bases, infrastructure availability, regional integration and trade, co-benefits, societal preferences and other policy priorities, all of which vary by country and region (Section 6.6.4). Many of these factors depend on when the net zero point is reached (Figure 6.22).

Based on their increasing economic competitiveness, VRE technologies, especially wind and solar power, will likely comprise large shares of many regional generation mixes (*high confidence*) (Figure 6.22). While wind and solar will likely be prominent electricity resources, this does not imply that 100% renewable energy systems will be pursued under all circumstances, since economic and operational challenges increase nonlinearly as shares approach 100% (Box 6.8) (Bistline and Blanford 2021a; Cole et al. 2021; Shaner et al. 2018; Frew et al. 2016; Imelda et al. 2018b). Real-world experience planning and operating regional electricity systems with high instantaneous and annual shares of renewable generation is accumulating, but debates continue about how much wind and solar should be included in different systems, and the cost-effectiveness of mechanisms for managing variability (Box 6.8). Either firm, dispatchable generation (including nuclear, CCS-equipped capacity, dispatchable renewables such as geothermal, and fossil units run with low capacity factors and CDR to balance emissions) or seasonal energy storage (alongside other balancing resources discussed in Box 6.8) will be needed to ensure reliability and resource adequacy with high percentages of wind and solar (Jenkins et al. 2018b; Dowling et al. 2020; Denholm et al. 2021) though each option involves uncertainty about costs, timing, and public acceptance (Albertus et al. 2020).

Electricity systems require a range of different functional roles – for example, providing energy, capacity, or ancillary services. As a result, a range of different types of generation, energy storage, and transmission resources may be deployed in these systems (Baik et al. 2021). There are many options for each of these roles, each with their strengths and weaknesses (Sections 6.4.3 and 6.4.4), and deployment of these options will be influenced by the evolution of technological costs, system benefits, and local resources (Veers et al. 2019; Mai et al. 2018; Bistline et al. 2018; Hirth 2015; Fell and Linn 2013).

System management is critical for zero- or negative-emissions electricity systems. Maintaining reliability will increasingly entail system planning and operations that account for characteristics of supply- and demand-side resources (Hu et al. 2018). Coordinated planning and operations will likely become more prevalent across portions of the electricity system (e.g., integrated generation, transmission, and distribution planning), across sectors, and across geographies (Bistline and Young 2019; Chan et al. 2018; Konstantelos et al. 2017; EPRI 2017, Section 6.4.3).

Energy storage will be increasingly important in net zero energy systems, especially in systems with shares of VRE (*high confidence*). Deployment of energy storage will vary based on the system benefits and values of different options (Arbabzadeh et al. 2019; Denholm and Mai 2019). Diurnal storage options like lithium-ion batteries have different value than storing and discharging electricity over longer periods through long-duration energy storage with less frequent cycling, which require different technologies, supporting policies, and business models (Sepulveda et al. 2021; Dowling et al. 2020; Gallo et al. 2016; Albertus et al. 2020; Blanco and Faaij 2017) (Section 6.4.4). The value of energy storage varies with the level of deployment and on the competitiveness of economic complements such as VRE options (Bistline and Young 2020; Mileva et al. 2016) and substitutes such as flexible demand (Brown et al. 2018; Merrick et al. 2018), transmission (Merrick et al. 2018; Brown et al. 2018; Schlachtberger et al. 2017; Bistline and Young 2019), trade (Bistline et al. 2020b), dispatchable generators (Hittinger and Lueken 2015; Gils et al. 2017; Arbabzadeh et al. 2019), DAC (Daggash et al. 2019), and efficiencies in system operations (Tuohy et al. 2015).

The approach to other sectors could impact electricity sector planning, and the role of some technologies (e.g., hydrogen, batteries, CCS) could depend on deployment in other sectors. CCS offers opportunities for CO_2 removal when fuelled with syngas or biomass containing carbon captured from the atmosphere (Hepburn et al. 2019); however, concerns about lifecycle environmental impacts, uncertain costs, and public acceptance are potential barriers to widespread deployment (Section 6.4.2). It is unclear whether CDR options like BECCS will be included in the electricity mix to offset continued emissions in other parts of the energy system or beyond (Mac Dowell et al. 2017; Luderer et al. 2018; Bauer et al. 2018a).

Some applications may also rely on PtX electricity conversion to create low-emissions synthetic fuels (Sections 6.6.2.6, 6.4.4, and 6.4.5), which could impact electricity system planning and operations. Additionally, if DAC technologies are used, electricity and heat requirements to operate DAC could impact electricity system investments and operations (Bistline and Blanford 2021a; Realmonte et al. 2019).

[START BOX 6.8 HERE]

Box 6.8 100% Renewables in Net Zero Energy Systems

The decreasing cost and increasing performance of renewable energy has generated interest in the feasibility of providing nearly all energy services with renewables. Renewable energy includes wind power, solar power, hydroelectric power, bioenergy, geothermal energy, tidal power, and ocean power. There are two primary frames around which 100% renewable energy systems are discussed: 100% renewable electricity systems and 100% renewable energy systems, considering not only electricity but all aspects of the energy system.

It is technically feasible to use very high renewable shares (e.g., above 75% of annual regional generation) to meet hourly electricity demand under a range of conditions, especially when VRE options, notably wind and solar, are complemented by other resources (*high confidence*). There are currently many grids with high renewable shares and large anticipated roles for VRE sources, in particular wind and solar (see Section 6.4), in future low-carbon electricity systems. An increasingly large set of studies examines the feasibility of high renewable penetration and economic drivers under different policy, technology, and market scenarios (Denholm et al. 2021; Blanford et al. 2021; Bistline et al. 2019; Hansen et al. 2019; Jenkins et al. 2018b; Cochran et al. 2014; Dowling et al. 2020; Deason 2018). High wind and solar penetration involves technical and economic challenges due to their unique characteristics such as spatial and temporal variability, short- and long-term uncertainty, and non-synchronous generation (Cole et al. 2017). These challenges become increasingly important as renewable shares approach 100% (Sections 6.6.2.2 and 6.4.3).

There are many balancing options in systems with very high renewables (Denholm et al. 2021; Bistline 2021a; Mai et al. 2018; Milligan et al. 2015; Jenkins et al. 2018b).

- **Energy storage:** Energy storage technologies like batteries, pumped hydro, and hydrogen can provide a range of system services (Balducci et al. 2018; Bistline et al. 2020a; Section 6.4.4). Lithium-ion batteries have received attention as costs fall and installations increase, but very high renewable shares typically entail either dispatchable generation or long-duration storage in addition to short-duration options (Schill 2020; Arbabzadeh et al. 2019; Jenkins et al. 2018b). Energy storage technologies are part of a broad set of options (including synchronous condensers, demand-side measures, and even inverter-based technologies themselves) for providing grid services (Castillo and Gayme 2014; EPRI 2019a).
- **Transmission and trade:** To balance differences in resource availability, high renewable systems will very likely entail investments in transmission capacity (Zappa et al. 2019; Pleßmann and Blechinger 2017; Macdonald et al. 2016; Mai and Et al 2014; Section 6.4.5) and changes in trade (Abrell and Rausch 2016; Bistline et al. 2019). These increases will likely be accompanied by expanded balancing regions to take advantage of geographical smoothing.
- **Dispatchable ("on-demand") generation:** Dispatchable generation could include flexible fossil units or low-carbon fuels such as hydrogen with lower minimum load levels (Bistline 2019; Denholm et al. 2018), renewables like hydropower, geothermal, or biomass (Hansen et al. 2019; Hirth 2016), or flexible nuclear (Jenkins et al. 2018a). The composition depends on costs and other policy goals, though in all cases, capacity factors are low for these resources (Mills et al. 2020).
- **Demand management:** Many low-emitting and high-renewables systems also utilize increased load flexibility in the forms of energy efficiency, demand response, and demand flexibility, utilizing

newly electrified end uses such as electric vehicles to shape demand profiles to better match supply (Bistline 2021a; Imelda et al. 2018a; Hale 2017; Brown et al. 2018; Ameli et al. 2017).
- **Sector coupling:** Sector coupling includes increased end-use electrification and PtX electricity conversion pathways, which may entail using electricity to create synthetic fuels such as hydrogen (Ueckerdt et al. 2021; Davis et al. 2018) (see Sections 6.4.3, 6.4., 6.4.5, 6.6.4.3, and 6.6.4.6).

Deployment of integration options depends on their relative costs and value, regulations, and electricity market design. There is considerable uncertainty about future technology costs, performance, availability, scalability, and public acceptance (Kondziella and Bruckner 2016; Bistline et al. 2019). Deploying balanced resources likely requires operational, market design, and other institutional changes, as well as technological changes in some cases (Denholm et al. 2021; Cochran et al. 2014). Mixes will differ based on resources, system size, flexibility, and whether grids are isolated or interconnected.

Although there are no technical upper bounds on renewable electricity penetration, the economic value of additional wind and solar capacity typically decreases as their penetration rises, creating economic challenges at higher deployment levels (Denholm et al. 2021; Millstein et al. 2021; Cole et al. 2021; Gowrisankaran et al. 2016; Hirth 2013). The integration options above, as well as changes to market design, can mitigate these challenges but likely will not solve them, especially since these options can exhibit declining value themselves (Denholm and Mai 2019; Bistline 2017; De Sisternes et al. 2016) and may be complements or substitutes to each other.

Energy systems that are 100% renewable (including all parts of the energy sector, and not only electricity generation) raise a range of technological, regulatory, market, and operational challenges that make their competitiveness uncertain (*high confidence*). These systems require decarbonizing all electricity, using this zero-carbon electricity broadly, and then utilizing zero-carbon energy carriers for all end uses not served by electricity, for example, air travel, long-distance transport, and high-temperature process heat. Broader questions emerge regarding the attractiveness of supplying all energy, and not just electricity, with renewables (Figure 6.22). Integrated assessment and energy systems research suggest large roles for renewables, but energy and electricity shares are far from 100%, even with stringent emissions reductions targets and optimistic assumptions about future cost reductions (Huntington et al. 2020; Jenkins et al. 2018b; Bauer et al. 2018; Bistline et al. 2018, Section 6.7.1). Scenarios with 100% renewable energy systems are an emerging subset in the decarbonization literature, especially at regional levels (Denholm et al. 2021; Hansen et al. 2019). Many 100% renewables studies focus more heavily on electrification for decarbonizing end uses, and include less biofuels and hydrogen than the broader literature on deep decarbonization (Bauer et al. 2018a). These studies typically assume a constrained set of available technologies to demonstrate the technical feasibility of very high renewable systems and do not optimize to find least-cost, technology-neutral decarbonization pathways, and many 100% renewables studies focus on the electricity sector or a limited number of sectors (Hansen et al. 2019; Jenkins et al. 2018a). In addition to renewables, studies broadly agree that including additional low-carbon options – including not only low-carbon electricity but also targeted use of fossil fuels with and without CCS (Section 6.6.2.1) and alternative fuels for sectors that are difficult to electrify (Section 6.6.2.4) – can lower the cost of decarbonization even with very high shares of renewables (Figure 6.22). However, there is disagreement about the magnitude of cost savings from larger portfolios, which depend on context- and scenario-specific assumptions about technologies, markets, and policies.

[END BOX 6.8 HERE]

6.6.2.3 Widespread Electrification of End Uses

Net-zero energy systems will rely more heavily on increased use of electricity (electrification) in end uses (*high confidence*). The literature on net zero energy systems almost universally calls for increased electrification (Williams et al. 2012; Sugiyama 2012; Williams et al. 2014; Rogelj et al. 2015a; Sachs et al. 2016; Kriegler et al. 2014a; Sven et al. 2018; Luderer et al. 2018; Schreyer et al. 2020). At least 30% of the global final energy needs are expected to be served by electricity, with some estimates suggesting upwards of 80% of total energy use being electrified (Figure 6.22, panel c). Increased electrification is especially valuable in net zero energy systems in tandem with decarbonized electricity generation or net-negative emissions electricity generation (Section 6.5.4.2). Flexible electric loads (electric vehicles, smart appliances) can in turn facilitate incorporation of VRE electricity options, increase system flexibility, and reduce needs for grid storage (Section 6.4.3) (Mathiesen et al. 2015); Lund et al., 2018).

Several end-uses such as passenger transportation (light-duty electric vehicles, two and three wheelers, buses, rail) as well as building energy uses (lighting, cooling) are likely to be electrified in net zero energy systems (*high confidence*). Variations in projections of electrification largely result from differences in expectations about the ability and cost-competitiveness of electricity to serve other end uses such as non-rail freight transport, aviation, and heavy industry (McCollum et al. 2014; Breyer et al. 2019; Bataille et al. 2016; EPRI 2018) (Section 6.5.4.4), especially relative to biofuels and hydrogen ('low carbon fuels') (Sachs et al. 2016; Rockström et al. 2017; McCollum et al. 2014), the prospects for which are still quite uncertain (Section 6.4). The emergence of CDR technologies and the extent to which they allow for residual emissions as an alternative to electrification will also affect the overall share of energy served by electricity (Section 6.6.2.7).

Regions endowed with cheap and plentiful low-carbon electricity resources (wind, solar, hydropower) are likely to emphasize electrification, while those with substantial bioenergy resources or availability of other liquid fuels might put less emphasis on electrification, particularly in hard-to-electrify end-uses (*medium confidence*). For example, among a group of Latin American countries, relative assumptions about liquid fuels and electricity result in an electrification range of 28–82% for achieving a net zero energy system (Bataille et al. 2020). Similarly, the level of penetration of biofuels that can substitute for electrification will depend on regional circumstances such as land-use constraints, competition with food, and sustainability of biomass production (Section 6.6.2.4).

Electrification of most buildings services, with the possible exception of space heating in extreme climates, is expected in net zero energy systems (*high confidence*) (Chapter 9). Space cooling and water heating are expected to be largely electrified. Building electrification is expected to rely substantially on heat pumps, which will help lower emissions both through reduced thermal requirements and higher efficiencies (Mathiesen et al. 2015; Rissman et al.; Sven et al. 2018). The level of electrification for heating will depend on the tradeoffs between building or household level heat pumps versus more centralized district heating network options (Mathiesen et al. 2015; Brown et al. 2018), as well as the cost and performance of heat pumps in more extreme climates and grid infrastructure (EPRI 2018; Waite and Modi 2020).

A significant share of transportation, especially road transportation, is expected to be electrified in net zero energy systems (*high confidence*). In road transportation, two-three wheelers, light-duty vehicles (LDVs), and buses, are especially amenable to electrification, with more than half of passenger LDVs expected to be electrified globally in net zero energy systems (*medium confidence*) ((Bataille et al. 2020; Sven et al. 2018; Khalili et al. 2019; Fulton et al. 2015). Long-haul trucks, large ships, and aircraft are expected to be harder to electrify absent technological breakthroughs (Mathiesen et al. 2015; Fulton et al. 2015), although continued improvements in battery technology may enable electrification of long-haul trucks (Nykvist and Olsson 2021; Chapter 10). Due to the relative ease of rail electrification, near complete electrification of rail and a shift of air and truck freight to rail is expected in net zero energy systems (Sven et al. 2018; Khalili et al. 2019; Rockström et al. 2017; Fulton et al. 2015). The degree of modal shifts and electrification will depend on local factors such as infrastructure availability and location accessibility. Due to the challenges associated with electrification of some transport modes, net zero energy systems may include some residual emissions associated with the freight sector that are offset through CDR technologies (Muratori et al. 2017b), or reliance on low and zero-carbon fuels instead of electrification.

A non-trivial number of industry applications could be electrified as a part of a net zero energy system, but direct electrification of heavy industry applications such as cement, primary steel manufacturing, and chemical feedstocks is expected to be challenging (*medium confidence*) (Davis et al. 2018; Madeddu et al. 2020; Philibert 2019; van Sluisveld et al. 2021). Process and boiler heating in industrial facilities are anticipated to be electrified in net zero energy systems. Emissions intensity reductions for cement and concrete production can be achieved through the use of electrified cement kilns, while emissions associated with steel production can be reduced through the use of an electric arc furnace (EAF) powered by decarbonized electricity (Rissman et al.). Electricity can also be used to replace thermal heat such as resistive heating, electric arc furnaces, and laser sintering (Rissman et al.; Madeddu et al. 2020). One study found that as much as 60% of the energy end-use in European industry could be met with direct electrification using existing and emerging technologies (Madeddu et al. 2020). Industry electrification for different regions will depend on the economics and availability of alternative emissions mitigation strategies such as carbon neutral fuels and CCS (Davis et al. 2018; Madeddu et al. 2020).

6.6.2.4 Alternative Fuels in Sectors not Amenable to Electrification

Net-zero energy systems will need to rely on alternative fuels – notably hydrogen or biofuels – in several sectors that are not amenable to electricity and otherwise hard to decarbonize (*medium confidence*). Useful carbon-based fuels (e.g., methane, petroleum, methanol), hydrogen, ammonia, or alcohols can be produced with net zero CO_2 emissions and without fossil fuel inputs (Sections 6.4.4 and 6.4.5). For example, liquid hydrocarbons can be synthesized via hydrogenation of non-fossil carbon by processes such as Fischer-Tropsch (Mac Dowell et al. 2017) or by conversion of biomass (Tilman et al. 2009). The resulting energy-dense fuels can serve applications that are difficult to electrify, but it is not clear if and when the combined costs of obtaining necessary feedstocks and producing these fuels without fossil inputs will be less than continuing to use fossil fuels and managing the related carbon through, for example, CCS or CDR (Ueckerdt et al. 2021)

CO_2 emissions from some energy services are expected to be particularly difficult to cost-effectively avoid, among them aviation; long-distance freight by ships; process emissions from cement and steel production; high-temperature heat (e.g., >1000°C); and electricity reliability in systems with high penetration of variable renewable energy sources (NAS; Davis et al. 2018; Luderer et al. 2018; Chiaramonti 2019; Sepulveda et al. 2018; Bataille 2020; Rissman et al.; Thiel and Stark 2021; Madeddu et al. 2020). The literature focused on these services and sectors is growing, but remains limited, and provides minimal guidance on the most promising or attractive technological options and systems for avoiding these sectors' emissions. Technological solutions do exist, but those mentioned in the literature are prohibitively expensive, exist only at an early stage, and/or are subject to much broader concerns about sustainability (e.g., biofuels) (Davis et al. 2018).

Liquid biofuels today supply about 4% of transportation energy worldwide, mostly as ethanol from grain and sugar cane and biodiesel from oil seeds and waste oils (Davis et al. 2018). These biofuels could conceivably be targeted to difficult-to-electrify sectors, but face substantial challenges related to their life-cycle carbon emissions, cost, and further scalability (Tilman et al. 2009; Staples et al. 2018), (Section 6.4.2). The extent to which biomass will supply liquid fuels or high temperature heat for industry in a future net zero energy system will thus depend on advances in conversion technology that enable use of feedstocks such as woody crops, agricultural residues, algae, and wastes, as well as competing demands for bioenergy and land, the feasibility of other sources of carbon-neutral fuels, and integration of bioenergy production with other objectives, including CDR, economic development, food security, ecological conservation, and air quality (Lynd 2017; Laurens 2017; Williams and Laurens

2010; Strefler et al. 2018; Bauer et al. 2018a; Fargione 2010; Creutzig et al. 2015; Bauer et al. 2018b; Muratori et al. 2020b; Chatziaras et al. 2016; Fennell et al. 2021) (Section 6.4.2.6).

Costs are the main barrier to synthesis of net zero emissions fuels (*high confidence*), particularly costs of hydrogen (a constituent of hydrocarbons, ammonia, and alcohols) (Section 6.4.5). Today, most hydrogen is supplied by steam reformation of fossil methane (CH_4 into CO_2 and H_2) at a cost of 1.30-1.50 USD kg^{-1} (Sherwin 2021). Non-fossil hydrogen can be obtained by electrolysis of water, at current costs of 5-7 USD kg^{-1} H_2^{-1} (assuming relatively low electricity costs and high utilization rates) (Graves et al. 2011; Newborough and Cooley 2020; Peterson et al. 2020; DOE 2020a). At these costs for electrolytic hydrogen, synthesized net zero emissions fuels would cost at least 1.6 USD per liter of diesel equivalent (or 6 USD $gallon^{-1}$ and 46 USD GJ^{-1}, assuming non-fossil carbon feedstock costs of 100 USD per ton of CO_2 and low process costs of 0.05 USD $liter^{-1}$ or 1.5 USD GJ^{-1}). Similar calculations suggest that synthetic hydrocarbon fuels could currently avoid CO_2 emissions at a cost of 936-1404 USD ton^{-1} (Ueckerdt et al. 2021). However, economies of scale are expected to bring these costs down substantially in the future (Ueckerdt et al. 2021; IRENA 2020c), and R&D efforts are targeting 60-80% reductions in costs (to less than 2 USD kg^{-1} $(H2)^{-1}$) possibly by use of less mature but promising technologies such as high-temperature electrolysis and thermochemical water splitting (Schmidt et al. 2017; Pes et al. 2017; DOE 2018; Saba et al. 2018; Kuckshinrichs et al. 2017; DOE 2020b). Technologies capable of producing hydrogen directly from water and sunlight (photoelectrochemical cells or photocatalysts) are also under development, but still at an early stage (DOE 2020a; Nielander et al. 2015). High hydrogen production efficiencies have been demonstrated, but costs, capacity factors, and lifetimes need to be improved in order to make such technologies feasible for net zero emissions fuel production at scale (DOE 2020a; Newborough and Cooley 2020; McKone et al. 2014).

The carbon contained in net zero emissions hydrocarbons must have been removed from the atmosphere either through DAC, or, in the case of biofuels, by photosynthesis (which could include CO_2 captured from the exhaust of biomass or biogas combustion) (Zeman and Keith 2008; Graves et al. 2011). A number of different groups are now developing DAC technologies, targeting costs of 100 USD per ton of CO_2 or less (Darton and Yang 2018; Keith et al. 2018; Fasihi et al. 2019).

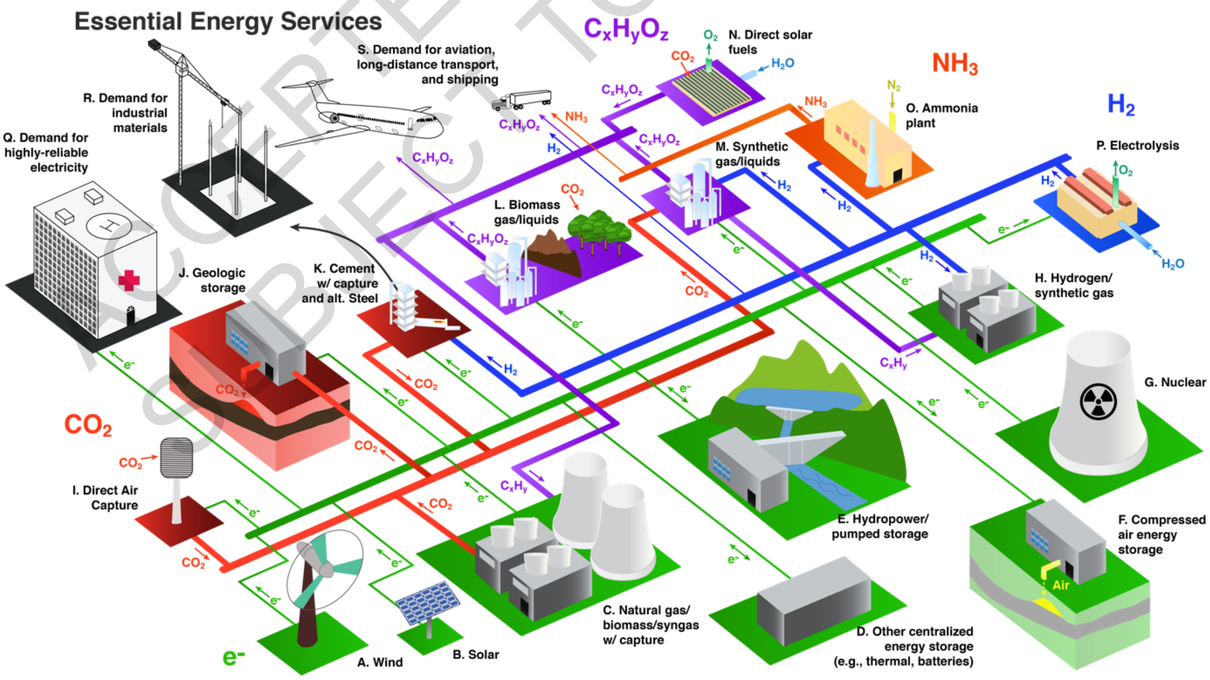


Figure 6.23 Schematic of net zero emissions energy system, including methods to address difficult-to-electrify sectors. (Source: Davis et al. 2018)

[START BOX 6.9 HERE]

Box 6.9 The Hydrogen Economy

The phrase "hydrogen economy" is often used to describe future energy systems in which hydrogen plays a prominent role. These future energy systems would not use hydrogen for all end uses; they would use hydrogen to complement other energy carriers, mainly electricity, where hydrogen might have advantages. Hydrogen could provide long-term electricity storage to support high-penetration of intermittent renewables and could enable trading and storage of electricity between different regions to overcome seasonal or production capability differences (Dowling et al. 2020; Sepulveda et al. 2021). It could also be used in lieu of natural gas for peaking generation, provide process heat for industrial needs, or be used in the metal sector via direct reduction of iron ore (Chapter 11). Clean hydrogen could be used as a feedstock in the production of various chemicals and synthetic hydrocarbons. Finally, hydrogen-based fuel cells could power vehicles. Recent advances in battery storage make electric vehicles the most attractive alternative for light-duty transport. However, fuel cell technology could complement electric vehicles in supporting the decarbonisation of heavy-duty transport segments (e.g., trucks, buses, ships, and trains) (Chapter 10).

Hydrogen production costs have historically been prohibitive, but recent technological developments are bringing costs down. These developments include improvements in hydrogen production technologies in terms of efficiency and capital costs (e.g., SMR) (Alrashed and Zahid 2021; Boretti and Banik 2021) and the emergence of alternative production technologies such as electrolysers (Dawood et al. 2020). These technological changes, along with decreasing costs of renewable power, are increasing the viability of hydrogen. Other improvements in hydrogen-based technologies are also emerging quickly. Gas turbines now run on blended fuels containing 5-95% hydrogen by volume (GE 2020) and could operate entirely on hydrogen by 2030 (Pflug et al. 2019). Fuel cell costs have decreased by 80-95% since the early 2000s, while power density and durability have improved (Kurtz et al. 2019; IEA 2019e; Jouin et al. 2016).

For hydrogen to support decarbonisation, it will need to be produced from zero-carbon or extremely low-carbon energy sources. One such production category is "green hydrogen." While there is no unified definition for green hydrogen, it can be produced by the electrolysis of water using electricity generated without carbon emissions (such as renewables). Hydrogen can also be produced through biomass gasification with CCS (BECCS), leading to negative carbon emissions (del Pozo et al. 2021). Additionally, "blue hydrogen" can be produced from natural gas through the process of auto-thermal reforming (ATR) or steam methane reforming (SMR), combined with CCS technology that would absorb most of the resulting CO_2 (80-90%).

However, the potential role of hydrogen in future energy systems depends on more than just production methods and costs. For some applications, the competitiveness of hydrogen also depends on the availability of the infrastructure needed to transport and deliver it at relevant scales (Lee et al. 2021). Transporting hydrogen through existing gas pipelines is generally not feasible without changes to the infrastructure itself (Muratori et al. 2018; Gumber and Gurumoorthy 2018). Existing physical barriers, such as steel embrittlement and degradation of seals, reinforcements in compressor stations, and valves, require retrofitting during the conversion to H_2 distribution or new H_2 dedicated pipelines to be constructed (Dohi et al. 2016). The capacity to leverage and convert existing gas infrastructure to transport hydrogen will vary regionally, but in many cases could be the most economically viable pathway (Brändle et al. 2021; Cerniauskas et al. 2020; Brooks 2021; Wettengel 2021). Hydrogen could also be transported as liquid gas or as liquid organic hydrogen carriers such as ammonia, for which industry knowledge exists (Hong et al. 2021; Wulf et al. 2018; Demir et al. 2018). Additionally, improvements in fuel cell technologies are needed to make hydrogen-based transport economically viable. There are also safety concerns associated with the flammability (Nilsson et al. 2017) and storage (Andersson and Grönkvist 2019; Caglayan et al. 2019) of hydrogen which will need to be considered.

[END BOX 6.9 HERE]

6.6.2.5 Using Less Energy and Using It More Efficiently

Demand-side or demand reduction strategies include technology efficiency improvements, strategies that reduce energy consumption or demand for energy services (such as reducing the use of personal transportation, often called "conservation") (Creutzig et al. 2018), and strategies such as load curtailment.

Net-zero energy systems will use energy more efficiently than those of today (*high confidence*). Energy efficiency and energy use reduction strategies are generally identified as being flexible and cost-effective, with the potential for large scale deployment (Chapters 5, 9, 10, and 11). For this reason, existing studies find that energy efficiency and demand reduction strategies will be important contributors to net zero energy systems (Creutzig et al. 2018; Davis et al. 2018; DeAngelo et al. 2021). Lower demand reduces the need for low-carbon energy or alternative fuel sources.

Characterizing efficiency of net zero energy systems is problematic due to measurement challenges (*high confidence*). Efficiency itself is difficult to define and measure across full economies (Saunders et al. 2021). There is no single definition of energy efficiency and the definition understandably depends on the context used (Patterson 1996), which ranges from device level efficiency all the way to the efficient use of energy throughout an economy. Broadly, energy efficient strategies allow for the same level of services or output while using less energy. At the level of the entire economy, measures such as primary or final energy per capita or per GDP are often used as a proxy for energy efficiency, but these measures reflect not only efficiency, but also many other factors such as industrial structure, endowed natural resources, consumer preferences, policies, and regulations. Energy efficiency and other demand-side strategies represent such a large set of technologies, strategies, policies, market and consumers' responses and policies that aggregate measures can be difficult to define (Saunders et al. 2021).

Measurement issues notwithstanding, virtually all studies that address net zero energy systems assume improved energy intensity in the future (*high confidence*). The overall efficiency outcomes and the access to such improvements across different nations, however, is not clear. Energy consumption will increase over time despite energy efficiency improvements due to population growth and development (DeAngelo et al. 2021).

A study (DeAngelo et al. 2021) reviewed 153 IAM scenarios that attain net zero energy sector CO2 emissions and found that, under a scenario with net zero emissions: global final energy per capita lies between 21–109 GJ per person (median: 57), in comparison to 2018 global final energy use of 55 GJ per person; many countries use far more energy per capita than today as their incomes increase; global final energy use per unit of economic output ranges from 0.7–2.2 EJ per trillion USD (median: 1.5), in comparison to 5 EJ per trillion USD in 2018; and the median final energy consumption is 529 EJ. By comparison, final energy consumption would be 550 EJ if current energy consumption per capita continued under a future population of 10 billion people. Across all scenarios, total final energy consumption is higher today than in the year in which net zero emissions are attained, and regionally, only the OECD+EU and Eurasia have lower median total final energy than in 2010.

Net-zero energy systems will be characterized by greater efficiency and more efficient use of energy across all sectors (*high confidence*). Road transportation efficiency improvements will require a shift from liquid fuels (Chapters 5 and 10). Emissions reductions will come from a transition to electricity, hydrogen, or synthetic fuels produced with low carbon energy sources or processes. Vehicle automation, ride-hailing services, online shopping with door delivery services, and new solutions like last mile delivery with drones may result in increased service share. Lighter vehicles, a shift to public transit, and incorporation of 2- and 3-wheelers will be features of a net zero energy system (Chapter 10). Teleworking and automation of work may provide reductions in driving needs. Other sectors, such as air travel and marine transportation may rely on alternative fuels such as biofuels, synthetic fuels, ammonia, produced with zero carbon energy source (Section 6.6.2.4).

Under net zero energy systems, buildings would by characterized by improved construction materials, an increase in multi-family dwellings, early retirement of inefficient buildings, smaller floor areas, and smart controls to optimize energy use in the building, namely for heating, cooling, LED lighting, and water heating (Chapter 9). End-uses would utilize electricity, or potentially hydrogen, produced from zero carbon sources. The use of electricity for heating and cooking may often be a less efficient process at converting primary energy to energy services than using natural gas, but using natural gas would require CDR in order to be considered net zero emissions. Changes in behaviour may modestly lower demand. Most economies would have buildings with more efficient technologies powered by zero carbon electricity, and developing economics would shift from biomass to electricity, raising their energy consumption as population and wealth increase under net zero energy systems.

Industry has seen major efficiency improvements in the past, but many processes are now close to their thermodynamic limits. Electrification and breakthrough processes (such as producing steel with electricity and H_2), using recycled materials, using heat more efficiently by improving thermal insulation, and using waste heat for heat pumps, as well using advanced sensors, monitoring, and visualization and communication technologies may provide further efficiency improvements. (Chapter 11)

6.6.2.6 Greater Reliance on Integrated Energy System Approaches

Energy systems integration refers to connected planning and operations across energy carriers, including electricity, fuels, and thermal resources. Coordinated planning could be important in lowering system costs, increasing reliability, minimizing environmental impacts, and ensuring that costs of R&D and infrastructure account for not just current needs but also for those of future energy systems (Section 6.4.3). Integration includes not only the physical energy systems themselves but also simultaneous societal objectives (e.g., sustainable development goals), innovation processes (e.g., coordinating R&D to increase the likelihood of beneficial technological spillovers), and other institutional and infrastructural transformations (Sachs et al. 2019). Given system variability and differences in regional resources, there are economic and technical advantages to greater coordination of investments and policies across jurisdictions, sectors, and levels of government (Schmalensee and Stavins 2017). Coordinated planning and operations can improve system economics by sharing resources, increasing the utilization of capital-intensive assets, enhancing the geographical diversity of resource bases, and smoothing demand. But integration could require regulatory and market frameworks to facilitate and appropriate price signals to align incentives and to coordinate investments and operations.

Carbon-neutral energy systems are likely to be more interconnected than those of today (*high confidence*). The many possible feedstocks, energy carriers, and interconversion processes imply a greater need for the integration of production, transport, storage, and consumption of different fuels (Davis et al. 2018). For instance, electrification is expected to play an important role in decarbonizing light-duty vehicles (Chapter 10, Section 6.4.3), yet the electricity and transport sectors have few direct interactions today. Systems integration and sectoral coupling are increasingly relevant to ensure that net zero energy systems are reliable, resilient, and affordable (EPRI 2017; O'Malley et al. 2020; Buttler and Spliethoff 2018; Martin et al. 2017). Deep decarbonization offers new opportunities and challenges for integrating different sectors as well as supply- and demand-side options. For instance, increasing electrification will change daily and seasonal load shapes, and end-use flexibilities and constraints could impact the desirability of different supply-side technologies (EPRI 2019b; Brown et al. 2018). The feasibility of net zero energy system configurations could depend on demonstrating cross-sector benefits like balancing VRE sources in the electricity sector, and on offering the flexibility to produce multiple products. For instance, low-emissions synthetic fuels could help to bridge stationary and mobile applications, since fuel markets have more flexibility than instantaneously balanced electricity markets due to the comparative ease and cost of large-scale, long-term storage of chemical fuels (Davis et al. 2018).

There are few detailed archetypes of integrated energy systems that provide services with zero- or net-negative CO_2 emissions (such as (Jacobson et al. 2019)), so there is considerable uncertainty about integration and interactions across parts of the system. Although alternate configurations, tradeoffs, and pathways are still being identified, common elements include fuels and processes like zero- or negative-CO_2 electricity generation and transmission, hydrogen production and transport, synthetic hydrocarbon production and transport, ammonia production and transport, and carbon management, where linkages across pathways could include the use of electricity to produce hydrogen via electrolysis (Davis et al. 2018; Jenkins et al. 2018b; van Vuuren et al. 2018; Shih et al. 2018; Moore 2017; Smith et al. 2016). Linked analytical frameworks are increasing being used to understand the potential role for system coupling with greater temporal resolution, spatial resolution, and heterogeneity of consumer and firm decisions (Pye et al. 2021; Gerboni et al. 2017; Santen et al. 2017; Collins et al. 2017; Bistline and de la Chesnaye 2017; Bohringer and Rutherford 2008).

Challenges associated with integrating net zero energy systems include rapid technological change, the importance of behavioural dimensions in domains with limited experience and data, policy changes and interactions, and path dependence. Technological cost and public acceptance will influence the degree of integration. Sectoral pathways will likely be adaptive and adjust based on the resolution of uncertainties over time, and the relative competitiveness will evolve as the technological frontier evolves, which is a complex and path-dependent function of deployment, R&D, and inter-industry spillovers. Supply-side options interact with demand-side measures in increasingly integrated energy systems (van Vuuren et al. 2018; Sorrell 2015).

6.6.2.7 Carbon Dioxide Removal

While CDR is likely necessary for net zero energy systems, the scale and mix of strategies is unclear – nonetheless some combination of BECCS and DACCS are likely to be part of net zero energy systems (*high confidence*). Studies indicate that energy-sector CDR may potentially remove 5–12 $GtCO_2$ annually globally in net zero energy systems (Fuss et al. 2018) (Figure 6.22; Section 6.7; Chapter 12). CDR is not intended as a replacement for emissions reduction, but rather as a complementary effort to offset residual emissions from sectors that are not decarbonized and from other low-carbon technologies such as fossil CCS (McLaren et al. 2019; Gaffney et al. 2020; Iyer et al. 2021).

CDR covers a broad set of methods and implementation options (Chapters 7 and 12). The two CDR methods most relevant to the energy sector are BECCS, which is used to produce energy carriers, and DACCS which is an energy user (Smith et al. 2016; Singh and Colosi 2021). BECCS has value as an electricity generation technology, providing firm, dispatchable power to support electricity grids with large amounts of VRE sources, and reducing the reliance on other means to manage these grids, including electricity storage (Bistline and Blanford 2021a; Mac Dowell et al. 2017). BECCS may also be used to produce liquid fuels or gaseous fuels, including hydrogen (Section 6.4.2.6) (Muratori et al. 2020b). For instance, CO_2 from bio-refineries could be captured at <45 USD tCO_2^{-1} (Sanchez et al. 2018). Similarly, while CO_2 capture is expensive, its integration with hydrogen via biomass gasification can be achieved at an incremental capital cost of 3-35% ((Muratori et al. 2020b); Section 6.4). As with all uses of bioenergy, linkages to broad sustainability concerns may limit the viable development, as will the presence of high-quality geologic sinks in close proximity (Melara et al. 2020).

DACCS offers a modular approach to CDR (Creutzig et al. 2019), but it could be a significant consumer of energy. DAC could also interact with other elements of the energy systems as the captured CO_2 could be reused to produce low-carbon methanol and other fuels (Realmonte et al. 2019; Hoppe et al. 2018; Zhang and Fujimori 2020). DACCS might also offer an alternative for use of excess electricity produced by variable renewables (Wohland et al. 2018), though there are uncertainties about the economic performance of this integrated approach.

6.6.3 The Institutional and Societal Characteristics of Net-zero Energy Systems

The transition to net zero energy systems is not just technological; it requires shifts in institutions, organizations, and society more generally. As such, it involves institutional changes alongside changes in supply, technology, or markets (Andrews-Speed 2016, Pai et al. 2021). Institutional relationships between governments and energy sector actors (e.g., consumers, electricity companies) affect the nature of net zero systems, as these entities may collaborate on or dispute net zero goals and measures to achieve them. For example, following the Fukushima disaster, Japan placed emphasis on government-utility-public cooperation on use of nuclear power as a means of reducing carbon emissions (Sklarew 2018). Institutions are instrumental in shaping net zero energy systems in multiple ways, complemented by and interacting with the behaviours of actors and policy regimes in these systems (Figure 6.24).

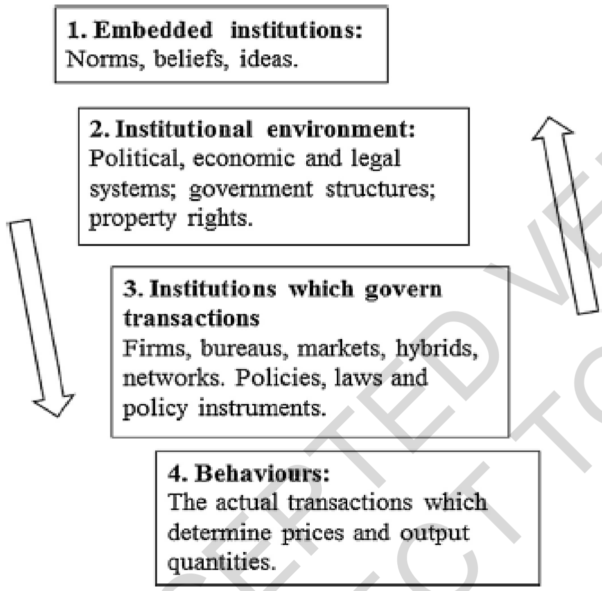


Figure 6.24 A four-level framework for institutional change. The diagram depicts three levels of institutions (1-3) which collectively govern actor behaviours (4). Source: Andrews-Speed 2016

One level of institutional interactions reflects embedded institutions, norms, beliefs, and ideas that would need to change to support net zero energy systems. This applies, for example, to the objectives of modern economies and the potentially contradictory dynamics embedded in the concept of "green growth" (Stegemann and Ossewaarde 2018; Stoknes and Rockström 2018). The institutional environment – the political and legal systems that govern exchanges and protect property rights – would also need to be different in net zero energy systems. In this setting, changing regulations or subsidies that continue to favour carbon-intensive systems over the technologies of a net zero energy system might prove difficult (Sovacool 2017). More generally, net zero energy systems will need new regulatory frameworks to undertake new challenges, from managing a more interconnected grid to adequately governing underground storage of CO_2. Institutions may also govern specific transactions, such as firms or networks that supply energy fuels or services. Current actors are typically resistant to disruptions, even if such disruptions may broadly benefit society (Kungl 2015, Mori 2018, Schmid et al. 2017).

For example, one energy system characterized by differentiated institutional interactions is the United States, where delivery of liquid fuels is lightly regulated, while electricity delivery is closely regulated (Dworkin et al. 2013). Reforming this two-pronged system for decarbonization would require four types of institutional change: (1) changes to the control systems that coordinate generation and transmission through a pyramidal architecture for the operational control, dispatch, and delivery of electricity with a primary emphasis on reliability; (2) changes to the financing of central-station power plants through long-term bonds, as valued by Wall Street ratings analysts; (3) changes to the structure of investor-owned utilities that attract private investors who expected decades of technological stability to yield long-term, low-risk revenues; and (4) changes to regulations to restructure and limit excessive returns and easy entry of new retail competitors, all recognizing local and national concerns through state and federal regulatory agencies. The example shows how decision-making and the infrastructures involved are layered, and can create "nested hierarchies" where institutions fulfill multiple roles for energy governance or regulation simultaneously (Stern et al. 2016b). Internationally and across different parts of the energy system, institutional challenges such as these could become even more stark and complex (Van de Graaf 2013).

6.6.4 Regional Circumstances and Net-zero Energy Systems

Countries have flexibility to pursue options that make the most sense for their national circumstances (Figure 6.25). They may emphasize supply transformation over demand reduction; deploy different resources; engage at different levels in international energy trade; support different energy industries; focus on different energy carriers (e.g., electricity, hydrogen); or focus more on distributed or integrated systems, among others. Many factors may influence the long-term net zero energy systems that are appropriate for any country's national circumstances, including the following.

Future Technology. Technological transitions have often been driven by the relative merits of different technology options. Recent trends in the use of PV cells, wind power, and in batteries, for example, have been spurred by their increasing economic competitiveness (Section 6.3). Yet future technology cannot be fully predicted, so it provides only a partial guide today for charting a path toward future systems.

Indigenous Energy Resources. Countries may emphasize approaches that take advantage of indigenous energy resources such as solar power, wind, hydroelectric resources, land for bioenergy crops, CO_2 storage capability, or fossil resources to be used with CCS. Countries with less abundant resources may put greater emphasis on demand reductions and regional integration. Countries with resource bases that are easily tradeable, like low-carbon electricity or bioenergy, may choose to trade those resources rather than use them domestically (Box 6.10, Section 6.4.3, 6.4.5).

Regional Climate. Climate influences heating and cooling demand, both of which influence countries' energy demands and energy infrastructure to meet those demands (Section 6.5). In addition to daily demand profiles, heating and cooling are seasonal, influencing which energy sources may serve these loads and the seasonal storage they require. Cooling is almost entirely served by electricity today, and heating has commonly been served by non-electric fuels. In low-carbon energy systems, heating may be increasingly served by electricity (Section 6.6.4), meaning that the influence of regional climate may be strongest on countries' electricity systems.

Current Energy System Configuration. Future sectoral energy demands and the potential for demand-side transformation are partially determined by existing infrastructure (e.g., building stocks, transport infrastructure). Countries with less developed or growing energy systems will have more flexibility to create the systems that best match their long-term goals, but there may be substantial challenges in transitioning directly to the most advanced low-carbon technology options, and countries may have different capacities to absorb technology from other countries.

Regional Integration. Regional integration will allow countries to bridge energy gaps using external linkages, including regional electricity integration and trade in hydrogen, biomass, and other fuels. Countries with greater integration can rely more heavily on imports and may therefore rely less on indigenous resources (Box 6.10).

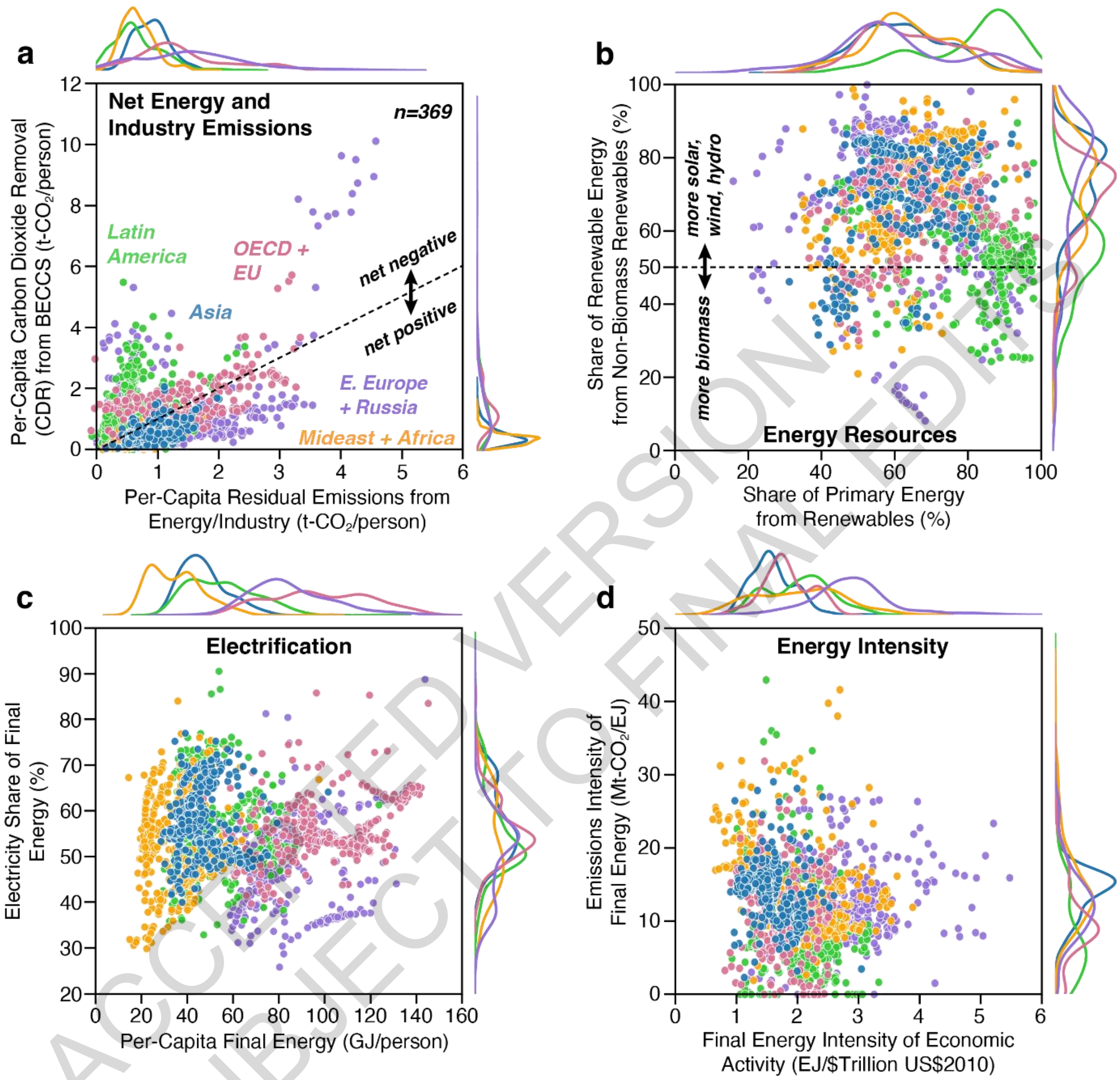


Figure 6.25 Characteristics of regional energy systems and emissions when energy and industrial CO_2 emissions reach net zero. Regional differences are shown for residual emissions and carbon removal (panel a), energy resources (panel b), electrification (panel c), and energy intensity (panel d). Distributions of scenarios are shown along each axis for each region. Colour scheme is shown in panel a. Points represent different models and scenarios from the AR6 database.

Societal Preferences. Citizens in every country have preferences for certain technological options or mitigation approaches over others that will influence energy system choices. The public generally prefers a future energy system based largely on renewables. Preferences for non-renewable energy differ across regions and groups. For example, studies have found that people in the U.K., Germany, the Netherlands, and Switzerland prefer renewable energy and personal energy efficiency and savings to nuclear, fossil fuels and CCS (Demski et al. 2017; Jones et al. 2012; Scheer et al. 2013; Volken et al. 2018; Bessette and Arvai 2018; Steg 2018). Studies have found that people with higher education levels, higher incomes, females, and liberals prefer renewables to fossil fuels and nuclear (Van Rijnsoever et al. 2015; Bertsch et al. 2016; Blumer et al. 2018; Jobin et al. 2019). The willingness to pay for renewable electricity differs by source (Ma et al. 2015; Sundt and Rehdanz 2015).

Technological Leadership, Economic Opportunities, and Growth. Countries may emphasize technologies in which they intend to have technological leadership and a competitive advantage. These could emerge over time or be based on current areas of opportunity or leadership. Industrial policy will influence future energy system as technological choices can benefit or hamper incumbents or new market actors.

Energy Security. Countries emphasizing import security will tend to rely more heavily on indigenous resources (Section 6.3). Some indigenous resources may raise security of supply issues that will influence energy system configurations. Bioenergy and hydropower, for example, can be subject to import climate risks (6.5), and significant integration of VRE technologies will influence electricity system infrastructure and management (6.6.2, Box 6.8).

Other Factors. Countries will consider a wide range of other factors in building toward low-carbon energy systems. Population density, for example, will influence building and transportation energy demands; economic transitions will influence industrial energy demands. Societal priorities beyond climate, notably SDGs may influence technology choices and types of energy systems (Sections 6.3 and 6.7.7).

[START BOX 6.10 HERE]

Box 6.10 Regional Integration of Energy Systems

Energy systems are linked across countries in many ways: countries transport crude oil across the ocean in supertankers, pipelines carry oil and natural gas across country boundaries, electric power lines cross country boundaries, and countries trade industrial commodities that carry embodied energy or that are essential inputs to mitigation technologies. Future systems will generate electricity using different mixes of technologies, produce and transport different carriers (e.g., hydrogen or biofuels), and use far less fossil fuel, among other major changes. Important examples include electricity, hydrogen, and biomass.

Electricity System Integration. Net-zero energy systems will rely more heavily on electricity generated from low-emissions technologies. Given the significant variations in the location of low-carbon electricity resources and the temporal variability of some renewable electricity sources, notably solar and wind power, regional electricity grids could reduce overall costs of net zero energy systems (Section 6.4.5). Furthermore, electricity transmission interconnections could significantly reduce local energy balancing costs and investment in peaking plants needed to meet security of supply requirements, and it could increase system resilience, especially in the case of extreme events such as heat waves or cold spells (Fasihi and Bogdanov 2016). Important challenges to regional electricity integration include geopolitical concerns from cross-border trade and societal and technological challenges associated with building new transmission lines.

Hydrogen Trade. Hydrogen may play an important role in future net zero energy systems, particularly in applications where electricity is not economically advantageous (see Box 6.9). Hydrogen can be used to decarbonize regions in which it is produced, and it can also be transported long distances to facilitate decarbonization of sectors distant from sources of low-cost supply. Methods of long-distance, high-volume hydrogen transport could include liquid storage, chemical carriers, and gaseous delivery via pipelines (Section 6.4.5). In net zero systems with substantial wind and solar power generation, hydrogen can be generated through electrolysis and then shipped to other locations. Important challenges to hydrogen trade include cost-effective low carbon production, cost of delivery infrastructure, storage, and end-use technology costs and safety.

Trade in Biomass. Biomass may also play an important role in net zero energy systems (Section 6.6.4, Chapter 3). Large-scale bioenergy production and consumption is likely to trigger global biomass trade. Global bioenergy trade volumes presently exceed 1 EJ yr^{-1}, of which 60% is directly traded for energy purposes (Proskurina et al. 2019b). Established trade mechanisms include wood pellet transport, ethanol, and biodiesel (Proskurina et al. 2019a). In a net zero global energy system, bioenergy trade could be greater than current trade of coal or natural gas, but less than that of petroleum (Sharmina et al. 2017) (Mandley et al, 2020). Some studies indicate that Latin America and Africa could become key exporting regions, with the EU, the USA, and East Asia emerging as key importers (Rentizelas et al. 2019; Alsaleh and Abdul-Rahim 2018). Studies have found that net bioenergy exports could be as high as 10% of GDP for some Latin American countries, while other regions like the EU may be faced with burgeoning import reliance (Mahlknecht et al. 2020; Daioglou et al. 2020b). In addition to challenges associated with bioenergy production (Section 6.4, Chapter 7), important challenges to biomass trade include differences in sustainability criteria and land/biomass definitions in different jurisdictions, and difficulties in establishing consistent monitoring and auditing systems (Lamers et al, 2016).

[END BOX 6.10 HERE]

6.7 Low-Carbon Energy System Transitions in the Near- and Medium-Term

6.7.1 Low-Carbon Energy System Transition Pathways

6.7.1.1 Energy System Emissions

Without additional efforts to reduce emissions, it is very unlikely that energy system CO_2 emissions will decrease sufficiently to limit warming to well below 2°C (*high confidence*). Scenarios assuming improvements in technology but no additional climate policies beyond those in place today provide a benchmark for comparison against energy-related CO_2 emissions in mitigation scenarios (Figure 6.26). Emissions in these reference scenarios increase through 2050 but span a broad range (Chapter 3 Figure 3.16; Riahi et al. 2017; Wei et al. 2018). The highest emissions levels are about four times current emissions; the lowest are modestly below today's emissions. Emissions in these scenarios increase in most regions, but they diverge significantly across regions (Bauer et al. 2017). Asia and the Middle East and Africa account for the majority of increased emissions across these scenarios (Figure 6.27). While it is unlikely that there will be no new climate policies in the future, these scenarios nonetheless support the conclusion that the energy sector will not be decarbonized without explicit policy actions to reduce emissions.

Warming cannot be limited to well below 2°C without rapid and deep reductions in energy system GHG emissions (*high confidence*). Energy sector CO_2 emissions fall by 87-97% (interquartile range) by 2050 in scenarios limiting warming to 1.5°C with no or limited overshoot and 60-79% in scenarios limiting likely warming to 2°C (Figure 6.26). Energy sector GHG emissions fall by 85-95% (interquartile range) in scenarios limiting warming to 1.5°C with no or limited overshoot and 62-78% in scenarios limiting likely warming to 2°C (Figure 6.26). In 2030, in scenarios limiting warming to 1.5°C with no or limited overshoot, net CO2 and GHG emissions fall by 35-51% and 38-52% respectively. Key characteristics of emissions pathways – the year of peak emissions, the year when net emissions reach zero, and the pace of emissions reductions – vary widely across countries and regions. These differences arise from differences in economic development, demographics, resource endowments, land use, and potential carbon sinks (Schreyer et al. 2020)(Schaeffer, et al.2020; Schreyer, et al., 2020; van Soest, Heleen, et al., 2021;Figure 6.27, Figure 6.28, Box 6.11). If countries do not move quickly to reduce emissions – if reductions are delayed – a more rapid energy transition will subsequently be required to limit warming to 2°C or below (Rogelj et al. 2015a, 2018a; IPCC 2018).

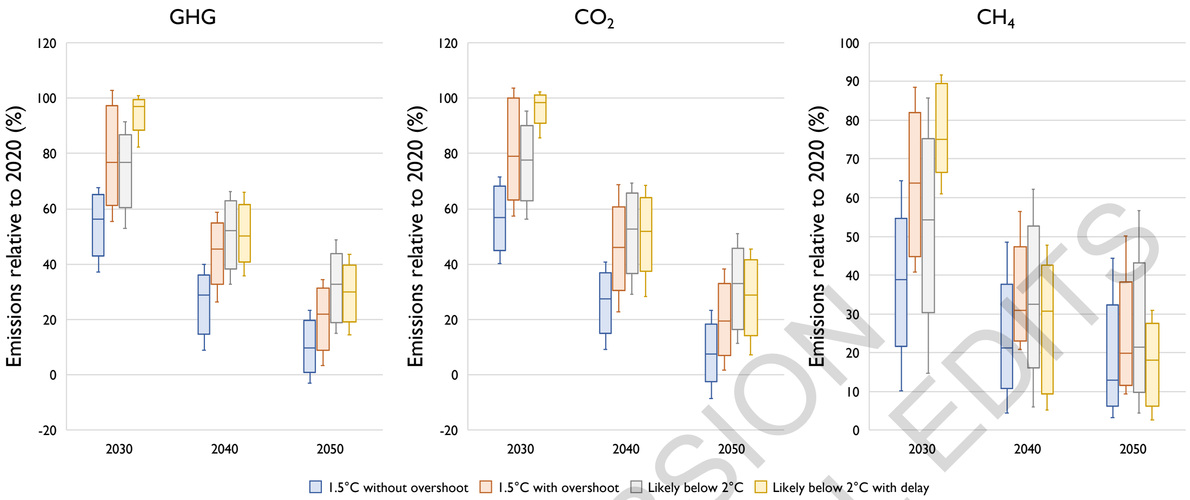


Figure 6.26 Projected energy sector GHG emissions for the 1.5°C scenarios (without and with overshoot), and likely below 2°C scenarios (without and with delayed policy action) during 2020-2050 (Source: AR6 Scenario Database). Boxes indicate 25th and 75th percentiles while whiskers indicate 5th and 95th percentiles. GHG emissions are inclusive of energy sector CO_2, CH_4, N_2O emissions and 80% of global HFC emissions. Number of model-scenario combinations in AR6 database: 1.5°C without overshoot: 170, 1.5°C with overshoot: 177, 2°C without delay: 297, 2°C without delay: 124.

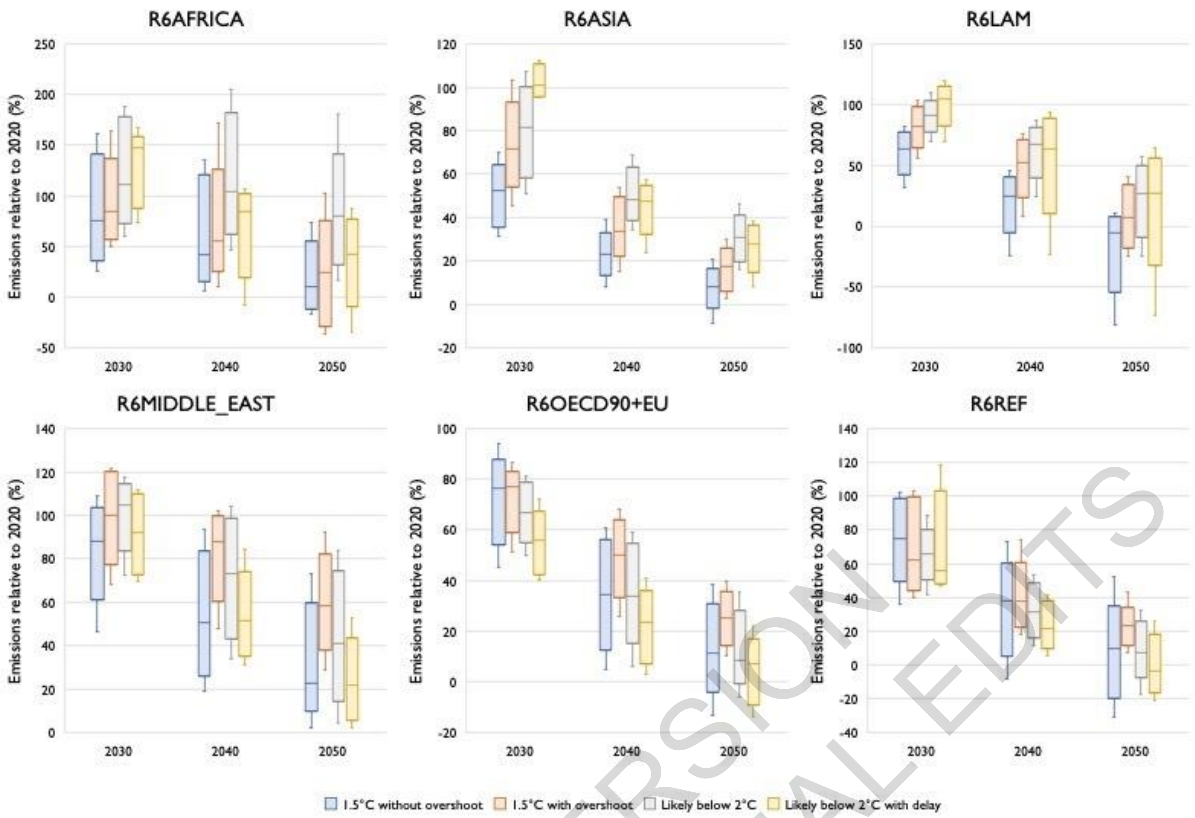


Figure 6.27 Net regional (R5) CO_2 emissions from energy across scenarios. for the 1.5°C scenarios (without and with overshoot), and likely below 2°C scenarios (without and with delayed policy action) during 2020-2050 (Source: AR6 Scenario Database). Boxes indicate 25th and 75th percentiles while whiskers indicate 5th and 95th percentiles. Most mitigation scenarios are based on a cost-minimizing framework that does not consider historical responsibility or other equity approaches.

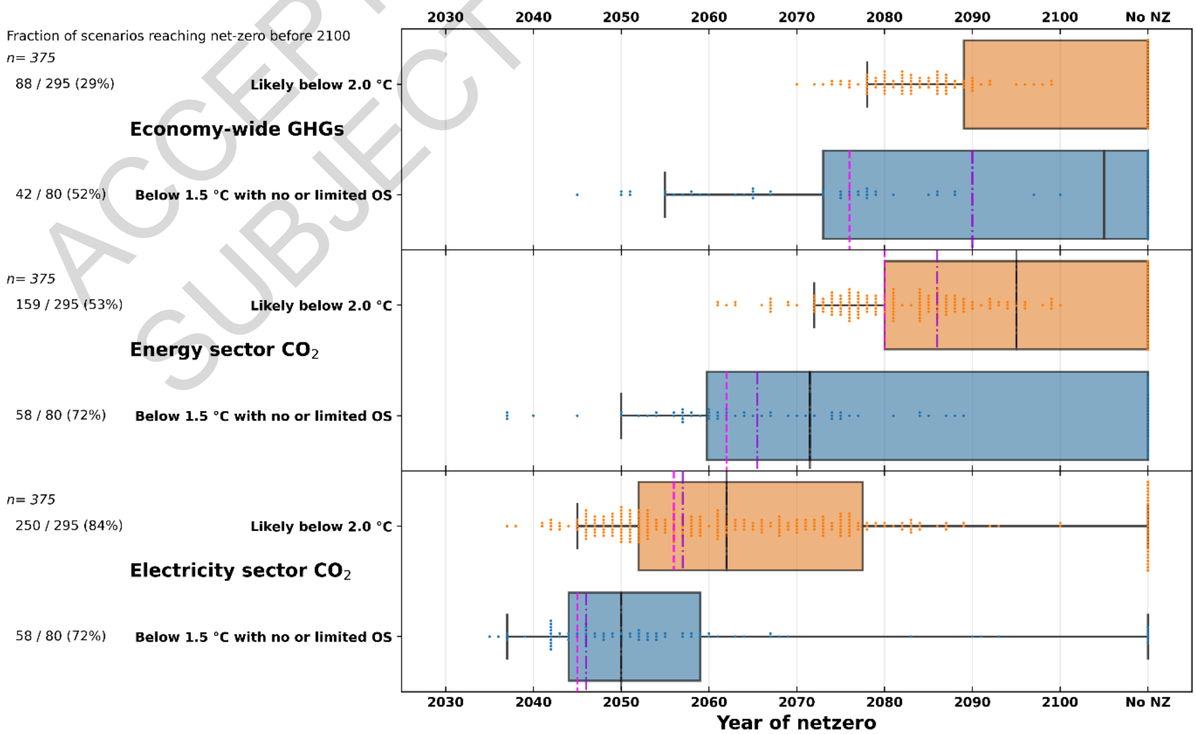


Figure 6.28 The timing of net zero emissions for full economy GHGs, energy sector CO_2, and electricity sector CO_2. Boxes indicate 25th and 75th percentiles, centre black line is the median, while whiskers indicate 1.5x the inter-quartile range. The vertical dashed lines represent the median point at which emissions in the scenarios have dropped by 95% (pink) and 97.5% (purple), respectively. Dots represent individual scenarios. The fraction indicates the number of scenarios reaching net zero by 2100 out of the total sample. (Source: AR6 Scenario Database)

The timing of net zero energy system emissions varies substantially across scenarios. In scenarios limiting warming to 1.5°C with no or limited overshoot (likely below 2°C), the energy system reaches net zero CO_2 emissions (interquartile range) from 2060 onwards (2080-). (Figure 6.28). However, net emissions reach near-zero more quickly. For example, in scenarios limiting warming to 1.5C with no or limited overshoot (likely below 2C) net energy system CO_2 emissions drop by 95% between 2056 and 2075 (2073 and 2093). Net full economy GHG emissions reach zero more slowly than net CO_2 emissions. In some scenarios, net energy system CO_2 and total GHG emissions do not reach zero this century, offset by CDR in other sectors.

The timing of emissions reductions will vary across the different parts of the energy sector (Figure 6.28). To decarbonize most cost-effectively, global net CO_2 emissions from electricity generation will likely reach zero before the rest of the energy sector (*medium confidence*). In scenarios limiting warming to 1.5C with no or limited overshoot (likely below 2C), net electricity sector CO_2 emissions (interquartile range) reach zero globally between 2044 and 2055 (2052 and 2078) (Figure 6.28). It is likely to be less-costly to reduce net CO_2 emissions close to or below zero in the electricity sector than in other sectors, because there are relatively more low-emissions options in electricity. Sectors such as long-distance transport, air transport, and process heat are anticipated to face greater challenges to decarbonization than the electricity sector (Rogelj et al. 2018b, 2015b; Clark and Herzog 2014; IPCC 2018; Luderer et al. 2018).

In addition, there are potential options to remove CO_2 from the atmosphere in the electricity sector, notably BECCS, which would allow electricity sector emissions to drop below zero. Without CDR options, electricity sector emissions may not fall all the way to zero. If CDR is accomplished in other sectors and not in electricity, some fossil fuel plants may still lead to positive net electricity sector CO_2 emissions even in net zero economies (Williams et al. 2021a; Bistline and Blanford 2021b)

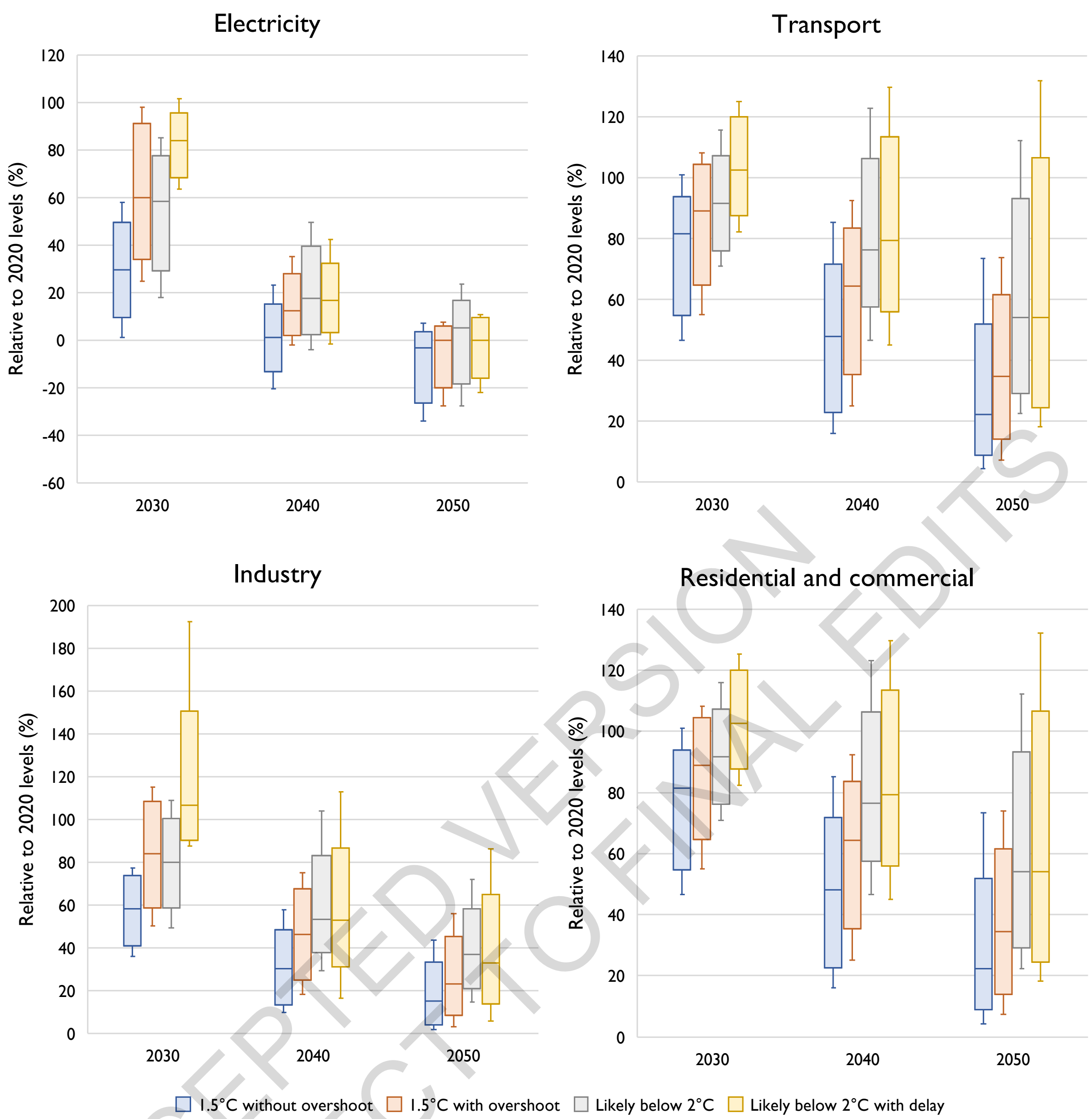


Figure 6.29 Reductions in CO_2 emissions relative to 2020 levels for the 1.5°C scenarios (without and with overshoot), and likely below 2°C scenarios (without and with delayed policy action) during 2030-2050 (Source: AR6 Scenario Database). Boxes indicate 25th and 75th percentiles while whiskers indicate 5th and 95th percentiles.

We lack sufficient understanding to pin down precise dates at which energy system CO_2 emissions in individual countries, regions, or sectors will reach net zero. Net-zero timing is based on many factors that are not known today or are bound up in development of key technologies, such as energy storage, bioenergy, or hydrogen. Some countries have low-carbon resource bases that could support deep emissions reductions, while others do not. Timing is also affected by the availability of CDR options, whether these options are in the energy sector or elsewhere, and the discount rate used to assess strategies (Bednar et al. 2019; Emmerling et al. 2019). Moreover, while many scenarios are designed to minimize global mitigation costs, many other frameworks exist for allocating mitigation effort across countries (Chapter 4; van den Berg, N. J., et al., 2019).

6.7.1.2 Low-carbon energy transition strategies

There are multiple technological routes to reduce energy system emissions (see Section 6.6). Here we discuss three of these: (1) decarbonizing primary energy and electricity generation, (2) switching to electricity, bioenergy, hydrogen, and other fuels produced from low-carbon sources, and (3) limiting energy use through improvement of efficiency and conservation. CDR is discussed in Section 6.7.1.X; Fossil fuel transitions are discussed in Section 6.7.4.

Decarbonizing Primary Energy and Electricity Generation. Limiting warming to well below 2°C requires a rapid and dramatic increase in energy produced from low- or zero-carbon sources *(high confidence)*. Low- and zero-carbon technologies produce 74-82% (interquartile range) of primary energy in 2050 in scenarios limiting warming to 1.5°C with no or limited overshoot and 55-68% in likely below 2°C scenarios (Figure 6.29). The share of low-carbon technologies in global primary energy supply today is below 20% (Section 6.3, Chapter 3,Figure 6.29). The percentage of low- and zero-carbon energy will depend in part on the evolution of energy demand – the more that energy demand grows, the more energy from low- and zero-carbon sources will be needed and the higher the percentage of total primary energy these sources will represent.

Low- and zero-carbon sources produce 97-99% of global electricity in 2050 in scenarios limiting warming to 1.5°C with no or limited overshoot and 93-97% in likely below 2°C scenarios (Figure 6.29) (*medium confidence*). Decarbonizing electricity generation, in tandem with increasing use of electricity (see below), is an essential near-term strategy for limiting warming. The increase in low- and zero-carbon electricity will occur while electricity demand grows substantially. Studies have projected that global electricity demand will roughly double by 2050 and quadruple to quintuple by 2100 irrespective of efforts to reduce emissions (Bauer et al. 2017; Luderer et al. 2017; IEA 2019a).

Renewable energy, especially generation from solar and wind, is likely to have an important role in many low-carbon electricity systems. The contributions of wind and solar electricity will depend on their levelized costs relative to other options, integration costs, system value, and the ability to integrate variable resources into the grid (Section 6.6). Electric sector technology mixes will vary by region but will typically include additional resources such as hydropower, nuclear power, fossil generation with CCS, energy storage resources, and geothermal energy, among others. Contributions of different options vary widely across scenarios based on different assumptions about these factors (Figure 6.30).

Nonetheless, it is likely that wind and solar will dominate low-carbon generation and capacity growth over the next couple decades due to supporting policies in many countries and due to their significant roles in early electric sector decarbonization, alongside reductions in coal generation (Bistline and Blanford 2021b; Pan et al. 2021). Clean firm technologies play important roles in providing flexibility and on-demand generation for longer durations, though deployment of these technologies is typically associated with deeper decarbonization levels (e.g., beyond 70-80% reductions), which are likely to be more important after 2030 in many regions, and with more limited CDR deployment (Baik et al. 2021; Williams et al. 2021a; Bistline and Blanford 2021a).

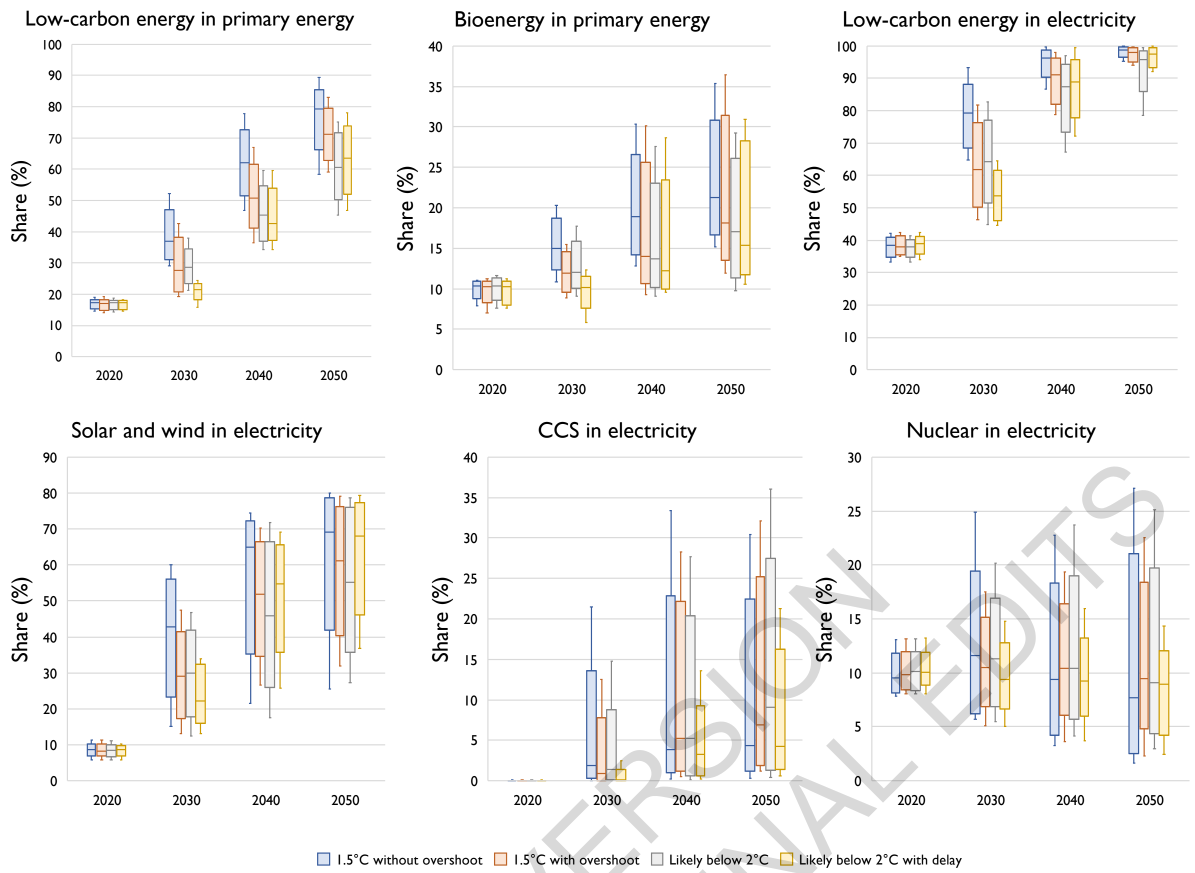
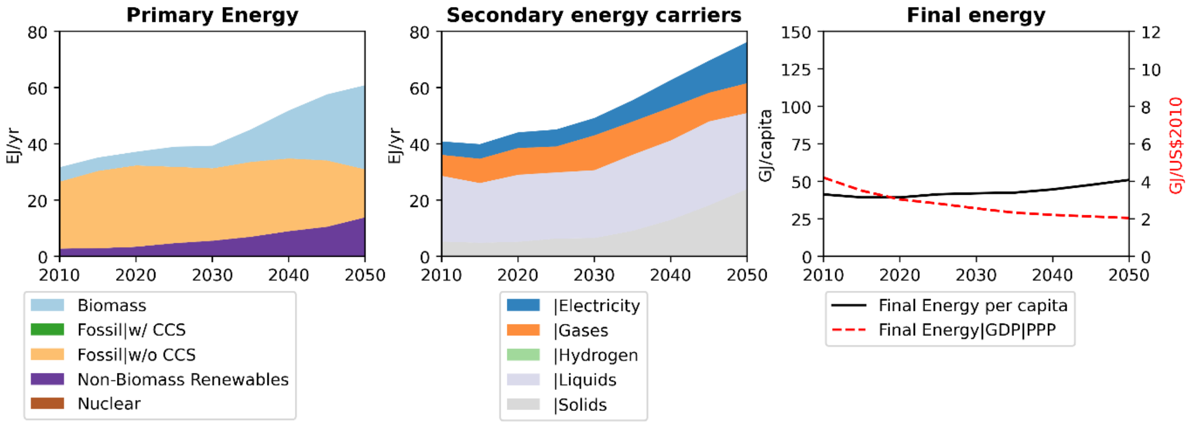


Figure 6.30 Shares of low carbon energy (all sources except unabated fossil fuels) and bioenergy (including both traditional and commercial biomass) in total primary energy, and solar+wind, CCS and nuclear in electricity for the 1.5°C scenarios (without and with overshoot), and likely below 2°C scenarios (without and with delayed policy action) during 2020-2050 (Source: AR6 Scenario Database). Boxes indicate 25th and 75th percentiles while whiskers indicate 5th and 95th percentiles.

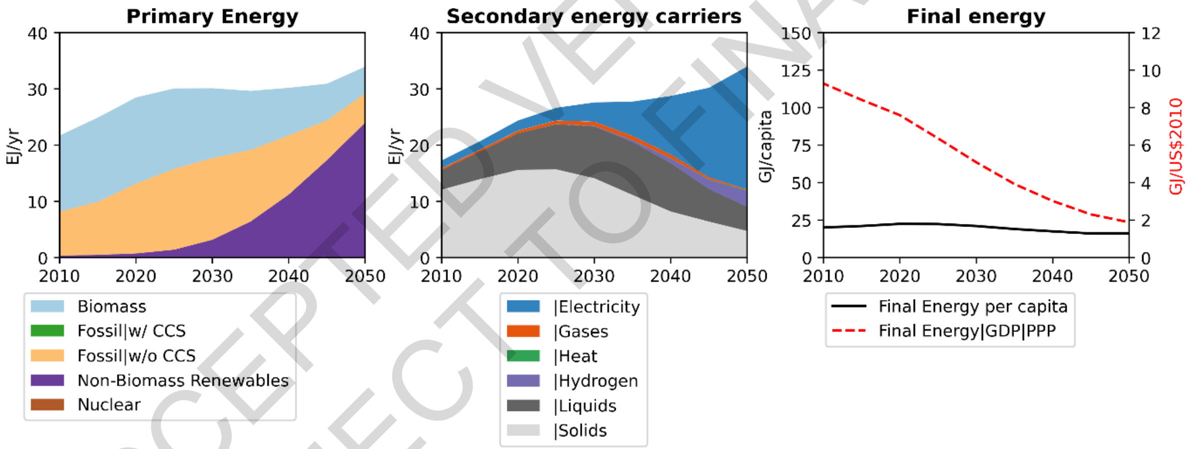
[START BOX 6.11 HERE]

Box 6.11 Illustrative Low-Carbon Energy System Transitions

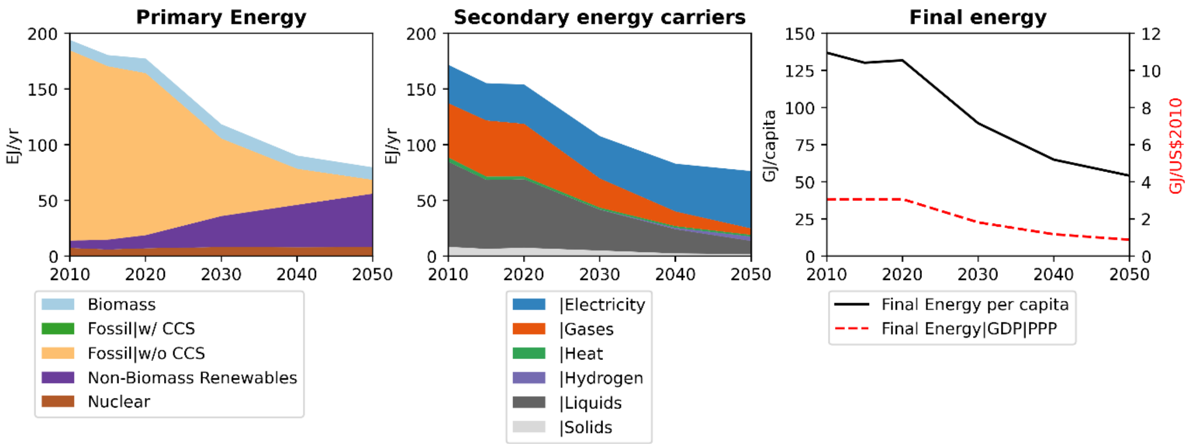
There are multiple possible strategies to transform the energy system to reach net zero CO_2 emissions and to limit likely warming to 2°C or below. All pathways rely on the strategies for net zero CO_2 energy systems highlighted in Section 6.6.2, but they vary in the emphasis that they put on different aspects of these strategies and the pace at which they approach net zero emissions. The pathway that any country or region might follow will depend on a wide variety of factors (Section 6.6.4), including, for example, resource endowments, trade and integration with other countries and regions, carbon sequestration potential, public acceptability of various technologies, climate, the nature of domestic industries, the degree of urbanization, and the relationship with other societal priorities such as energy access, energy security, air pollution, and economic competitiveness. The illustrative mitigation pathways presented in this box demonstrate four distinct strategies for energy system transformations and how each plays out for a different region, aligned with global strategies that would contribute to limiting warming to 1.5°C. Each pathway represents a very different vision of a net zero energy system. Yet, all these pathways share the common characteristic of a dramatic system-wide transformation over the coming decades.



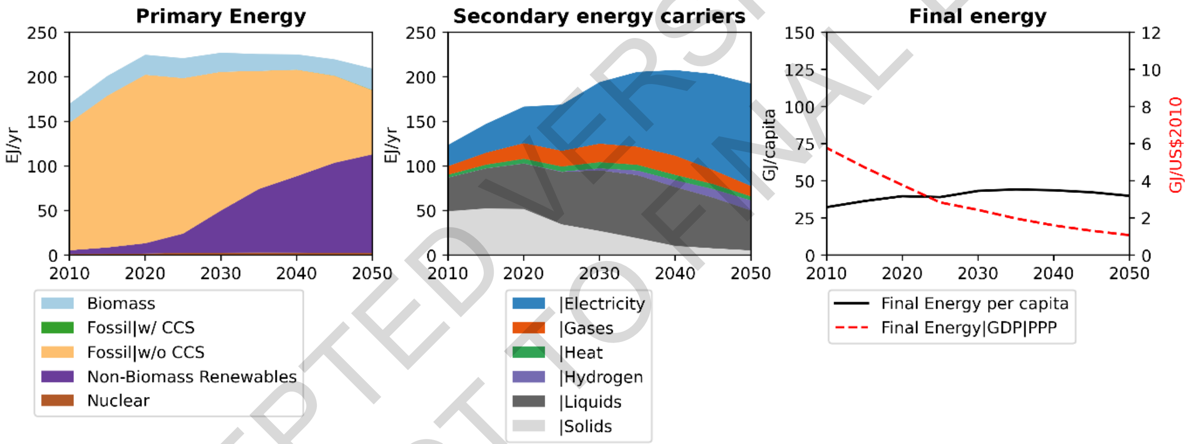
Box 6.11, Figure 1 Illustrative Mitigation Pathway 2.0-Neg: Latin America & Caribbean (LAM) in a likely below 2°C scenario (LAM net-zero economy 2040-2045, net zero energy system 2045-2050). Supply side focus with growing dependency on carbon dioxide removal and AFOLU, thus achieves net-zero CO_2 relatively early.



Box 6.11, Figure 2 Illustrative Mitigation Pathway 1.5-Renewables: Africa (AF) in a 1.5°C scenario (AF net-zero economy, 2055-2060, AF net zero energy system 2055-2060). Rapid expansion of non-biomass renewables, high electrification, and a fossil fuel phaseout.



Box 6.11, Figure 3 Illustrative Mitigation Pathway 1.5-Low Demand: Developed Countries (DEV) in a 1.5°C scenario (DEV net-zero economy, 2055-2060, net zero energy system 2075-2080). Major reduction of energy demand, high electrification, and gradual fossil fuel phaseout.



Box 6.11, Figure 4 Illustrative Mitigation Pathway 1.5-Shifting Pathways: Asia and Developing Pacific (APC) in a 1.5°C scenario (APC net-zero economy, 2075-2080, net-zero energy system 2090-2095). Renewables, high electrification, fossil fuel phaseout and low AFOLU emissions. Reaches net-zero CO_2 relatively late.

Box 6.11, Table 1. Summary of selected Illustrative Mitigation Pathways energy system characteristics in 2050 for the chosen regions.

		Energy sector CO_2 Reduction 2020-2050	Energy intensity	Variable renewable electricity generation	Low carbon electricity capacity additions	CO_2 Removal BECCS, AFOLU, Total	GDP per capita	Year net-zero CO2 emissions

		%	MJ / PPP USD2010		EJ/yr (%)		GW/yr		Gt CO_2 yr^{-1}	PPP USD2010/person		Full economy	Energy sector	Electricity
	Region	2050	2020	2050	2020	2050	2020	2050	2050	2020	2050			
Neg	LAM	124	3	2.1	0.5 (9)	7.7 (53)	15.4	21.5	1.1, 0.2, 1.9	12952	24860	2040-2045	2045-2050	2025-2030
Ren	AF	85	7.6	1.9	0.1 (5)	18 (84)	5	217	0.1, 0, 0.1	2965	8521	2055-2060	2055-2060	2025-2030
LD	DEV	92	3.1	0.9	4.6 (13)	37 (72)	52	188	0, 0.6, 0.6	42945	61291	2055-2060	2075-2080	2045-2050
SP	APC	76	3.8	1.1	3 (7)	91 (79)	123	603	0.1, 0.4, 0.4	10514	37180	2075-2080	2085-2090	2085-2090

[END BOX 6.11 HERE]

Switching to Low-Carbon Energy Carriers. Switching to energy carriers produced from low-carbon sources will be an important strategy for energy sector decarbonization. Accelerated electrification of end uses such as light duty transport, space heating, and cooking is a critical near-term mitigation strategy (Waisman et al. 2019; Sugiyama 2012; Zou et al. 2015; Rockström et al. 2017; IEA 2019f; Tang et al. 2021a). Electricity supplies 48-58% (interquartile range) of the global final energy demand by 2050 in scenarios limiting warming to 1.5°C with no or limited overshoot and 36-47% in likely below 2°C scenarios (Figure 6.29). Globally, the current level of electrification is about 20%.

Indirect electrification encompasses the use of electricity to produce hydrogen and synthetic fuels (efuels or power fuels). The extent of indirect electrification of final energy will depend on resource endowments and other regionally specific circumstances. Although indirect electrification is less efficient compared to direct electrification, it allows low-carbon fuels to be imported from regions with abundant low carbon electricity generation resources (Fasihi and Breyer 2020; Fasihi and Bogdanov 2016; Lehtveer et al. 2019, Box 6.10 on regional integration).

While electrifying end uses is a key decarbonization strategy, some end uses such as long-distance transport (freight, aviation, and shipping) and energy-intensive industries will be harder to electrify. For these sectors, alternative fuels or energy carriers such as biofuels, hydrogen, ammonia or synthetic methane, may be needed (see Section 6.6 and Box 6.9). Most scenarios find that hydrogen consumption will grow gradually, becoming more valuable when the energy system has become predominantly low-carbon (Figure 6.31).

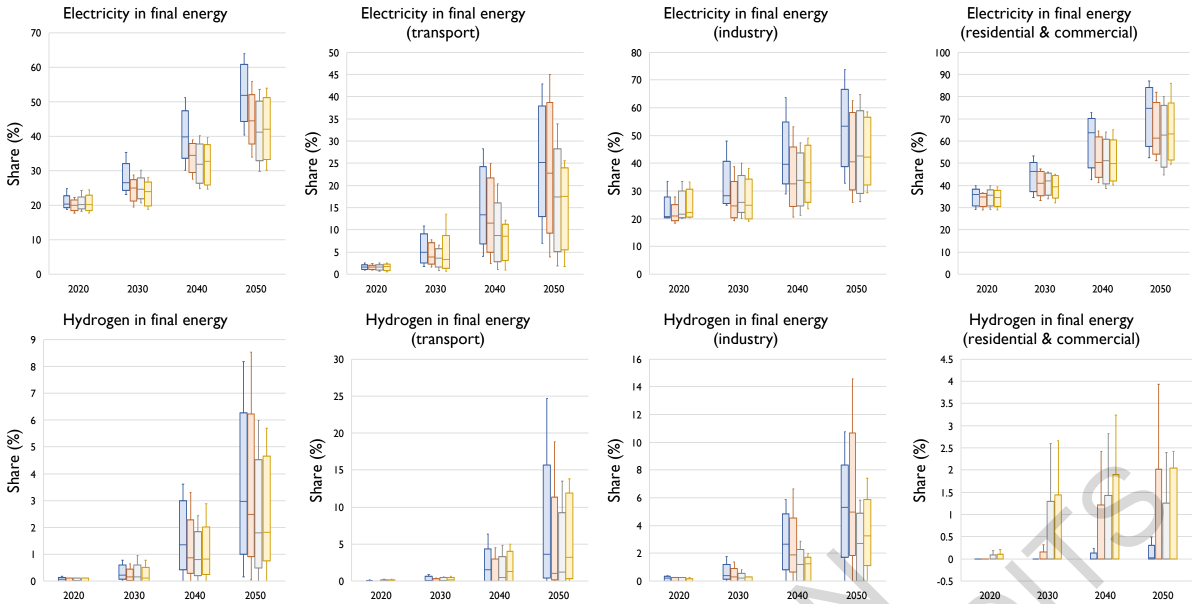


Figure 6.31 Shares of electricity and hydrogen in final energy for scenarios limiting warming to 1.5°C scenarios (without and with overshoot) and scenarios limiting likely warming to below 2°C (without and with delayed policy action) during 2020-2050 (Source: AR6 Scenario Database). Boxes indicate 25th and 75th percentiles while whiskers indicate 5th and 95th percentiles.

Reducing Energy Demand. Energy service demand is expected to continue to increase with growth of the economy, but there is great uncertainty about how much it will increase (Riahi et al. 2017; Bauer et al. 2017; Yu et al. 2018). Given the need to produce low-carbon energy, the scale of energy demand is a critical determinant of the mitigation challenge (Riahi et al. 2012). Higher energy demand calls for more low-carbon energy and increases the challenge; lower energy demand reduces the need for low-carbon sources and therefore can ease a low-carbon transtion. Recent studies have shown that tempering the growth of energy demand, while ensuring services and needs are still satisfied, can materially affect the need for technological CDR (see below) (Grubler et al. 2018; van Vuuren et al. 2018). Two of the Illustrative Mitigation Pathways (IMP-SP, IMP-LD) feature substantially lower final energy demand across buildings, transport, and industry than most other pathways in the literature. In some cases, energy demand levels are lower in 2050 (and later) than in 2019. These lower demands result in less reliance on bioenergy and a more limited role for CDR. [Ch. 3, Figure 3.18]

6.7.1.3 Technology options to offset residual emissions

CDR technologies can offset emissions from sectors that are difficult to decarbonize (Section 6.6), altering the timeline and character of energy sector transitions. A number of studies suggest that CDR is no longer a choice but rather a necessity to limit warming to 1.5°C (Luderer et al. 2018; Rogelj et al. 2015a; van Vuuren et al. 2018; Detz et al. 2018; Strefler et al. 2018). The reliance on CDR varies across scenarios and is tightly linked future energy demand and the rate of emission reductions in the next two decades: deeper near-term emissions reductions will reduce the need to rely on CDR to constrain cumulative CO_2 emissions. Some studies have argued that only with a transition to lower energy demands will it be possible to largely eliminate the need for engineered CDR options (Grubler et al. 2018; van Vuuren et al. 2018). Overall, the amount of CDR will depend on CO_2 capture costs, lifestyle changes, reduction in non-CO_2 GHGs, and utilization of zero-emission end-use fuels (van Vuuren et al. 2018)(Muratori et al, 2017; van Vuuren et al, 2018).

There is substantial uncertainty about the amount of CDR that might ultimately be deployed. In most scenarios that limit warming to 1.5°C, CDR deployment is fairly limited through 2030 at less than 1 Gt-CO_2 yr^{-1}. The key projected increase in CDR deployment (BECCS and DAC only) occurs between

2030 and 2050 with annual CDR in 2050 projected at 2.5-7.5 Gt-CO_2 yr^{-1} in 2050 (interquartile range) in scenarios limiting warming to 1.5°C with limited or no overshoot and 0.7-1.4 Gt-CO_2 yr^{-1} in 2050 in scenarios limiting warming to 2°C with limited or no overshoot. This characteristic of scenarios largely reflects substantial capacity addition of BECCS power plants. BECCS is also deployed in multiple ways across sectors. For instance, the contribution (interquartile range) of BECCS to electricity is 1-5% in 2050 in scenarios limiting warming to 1.5°C with limited or no overshoot and 0-5% in scenarios limiting likely warming to below 2°C . The contribution (interquartile range) of BECCS to liquid fuels is 9-21% in 2050 in scenarios limiting warming to 1.5°C with limited or no overshoot and 2-11% in scenarios limiting likely warming to below 2°C. Large-scale deployment of CDR allows flexibility in timing of emissions reduction in hard-to-decarbonize sectors.

CDR will influence the potential fossil-related stranded assets (Box 6.13). Availability of low-cost CDR can help reduce premature retirement for some fossil fuel infrastructure. CDR can allow countries to reach net zero emissions without phasing out all fossil fuels. Specific infrastructure could also be extended if it is used to burn biomass or other non-emitting sources. For example, existing coal-fired power plants, particularly those with CCS, could be co-fired with biomass (Pradhan et al, 2021; Woolf et al, 2016; Lu et al, 2019). In many scenarios, energy sector CDR is deployed to such an extent that energy sector CO_2 emissions become negative in the second half of the century (Chapter 3).

[START BOX 6.12 HERE]

Box 6.12 Taking Stock of the Energy System Transition

The Global Stocktake is a regularly occurring process under the UNFCCC in which efforts will be made to understand progress on, among other things, global mitigation. Collective progress of countries towards the Paris Agreement goal will be assessed and its outcome will inform Parties in updating and enhancing their NDCs. This box explores potential indicators to understand energy system mitigation progress.

CO_2 emissions from fuel combustion are the bottom line on energy system progress. Beyond CO_2 emissions, primary energy demand by energy sources, final energy consumption by sectors, and total electricity demand provide a first order assessment of energy system transitions. The year at which CO_2 emissions peak is also important. The Kaya Identity can be used to decompose energy system CO_2 emissions into carbon intensity of the energy system (CO_2 emissions from fossil-fuel combustion and industry divided by energy use), energy intensity (energy use divided by economic output), and economic output. The impacts of energy and climate policy are reflected in the changes of carbon intensity and energy intensity. Carbon intensity captures decarbonization of energy supply systems, for example through fuel switching from fossil fuels to non-fossil fuels, upscaling of low carbon energy sources, and deploying carbon dioxide removal technologies. The carbon intensity of electricity is specifically important, given the role of the electricity sector in near-term mitigation. Economy wide energy intensity represents efforts of demand-side energy, such as energy conservation, increase of energy performance of technologies, structural change of economy, and development of efficient urban infrastructure.

Beyond these aggregate indicators, a second order assessment would capture more details, such as the electrification rate, share of renewables, nuclear, CCS or other low carbon technologies in electricity generation, land area used for energy production, and numbers of EV or PHEV. Consumption of coal, oil and gas captures the underlying factors of CO_2 emissions. The emphasis of these indicators could differ across countries in the context of national specific circumstances. Technology- or project-based statistics are also useful to check the progress of the low-carbon transition, for example, the number of CCS facilities.

A critical challenge in the assessment of energy sector progress is how to measure societal, institutional, and political progress. These factors are difficult to quantify, yet they are fundamental determinants of the ability to reduce emissions. Public opinion, special interest politics, implications of mitigation for employment, energy subsidies, and energy policies are all critical indicators of progress. In addition, while much of the literature focuses on national level action, mitigation is increasingly being led by cities, states, provinces, businesses, and other subnational or non-national actors. Understanding the progress of these actors will be critical to assess energy system mitigation progress. New research is needed to better assess these "societal" indicators and the role of non-national actors.

[END BOX 6.12 HERE]

6.7.2. Investments in Technology and Infrastructure

Total global energy investment was roughly USD 1940 billion yr^{-1} in 2019 (IEA 2021f). This total can be broken down into the following main categories: fossil-related energy supply, including oil, gas, and coal extraction and fossil electricity generation (USD 990 billion yr^{-1}); renewable electricity, primarily solar and wind (USD 340 billion yr^{-1}); nuclear energy (USD 40 billion yr^{-1}); electricity networks (USD 270 billion yr^{-1}); and end-use energy efficiency (USD 270 billion yr^{-1}).

Energy investment needs are projected to rise going forward, according to investment-focused scenario studies found in the literature (Bertram et al. 2021; McCollum et al. 2018a; Zhou et al. 2019). While these increases are projected to occur in emissions-intensive pathways as well as low-carbon pathways, they are projected to be largest in low-carbon pathways. Average annual global energy investments over the 2016-2050 period range (across six models) from USD 2100 to 4100 billion yr^{-1} in pathways likely limiting warming to 2°C and from USD 2400 to 4700 billion yr^{-1} in pathways limiting warming to 1.5°C with no or limited overshoot (McCollum et al., 2018). Whatever the scenario, a significant and growing share of investments between now and 2050 will be channelled toward infrastructure build-out in emerging economies, particularly in Asia (Zhou et al. 2019).

More widespread electrification of buildings, transport, and industry means particularly substantial investment in the electricity system. According to C1-C3 pathways in the AR6 scenario database, such investments could be at the following average annual levels (inter-quartile range, USD_{2015}) over the 2023-2052 timeframe: USD 1670 to 3070 billion yr^{-1} (C1), 1600 to 2780 billion yr^{-1} (C2), and 1330-2680 billion yr^{-1} (C3). (See also 3.6.1.3)

Beyond these sector-wide numbers, a key feature of stringent mitigation pathways is a pronounced reallocation of investment flows across sub-sectors, namely from unabated fossil fuels (extraction, conversion, and electricity generation) and toward renewables, nuclear power, CCS, electricity networks and storage, and end-use energy efficiency (McCollum et al. 2018a; Bertram et al. 2021; IEA 2021f) (Figure 6.32). Investments in solar, wind, and electricity transmission, distribution, and storage increase the most in mitigation scenarios. Up to 2050, the bulk of these investments are made in OECD and Asian countries (Figure 6.33). While fossil fuel extraction investments exhibit a marked downscaling across all regions, compared to reference scenarios, the declines are especially strong in the Middle East, REF, and OECD.

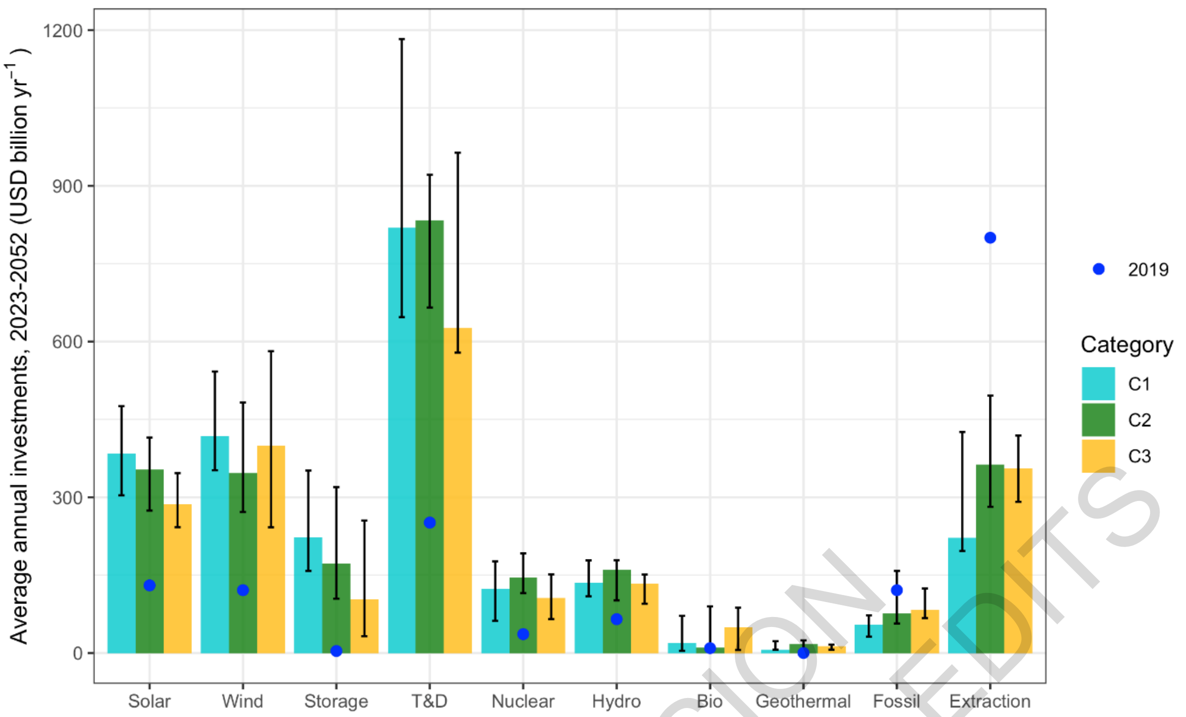


Figure 6.32 Global average annual investments from 2023 to 2052 (undiscounted, in USD billion yr^{-1}) for electricity supply sub-sectors and for extraction of fossil fuels in C1-C3 pathways (Source: AR6 Scenario Database and Chapter 3). Historical investments are also shown for comparison (Source: IEA, 2021; approximations are made for hydro and geothermal based on available data; solar and wind values are for 2020). 'T&D': transmission and distribution of electricity. Bars show median values across models-scenarios, and whiskers the inter-quartile ranges. See Chapters 3 and 15 for additional information on investments and finance.

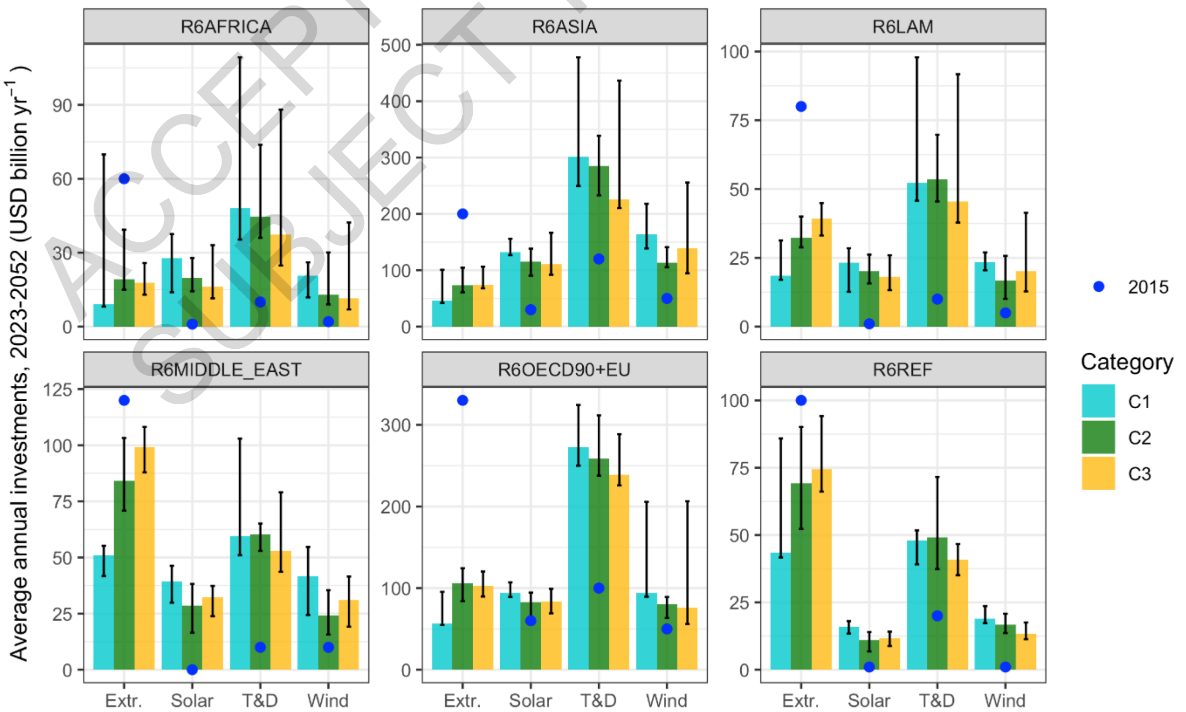


Figure 6.33 Regional average annual investments from 2023 to 2052 (undiscounted, in USD billion yr^{-1}) for four of the largest sub-sectors of the energy system in C1-C3 pathways (Source: AR6 Scenario Database and Chapter 3). Historical investments are also shown for comparison (Source: IEA, 2016). 'T&D': transmission and distribution of electricity. 'Extr.': extraction of fossil fuels. Bars show median values across models-scenarios, and whiskers the inter-quartile ranges. See Chapters 3 and 15 for additional information on investments and finance.

Investments into end-use energy efficiency are projected to also be substantial in mitigation pathways, potentially upwards of several hundred USD billion yr^{-1} on average to 2050, compared to USD 270 billion yr^{-1} in 2019 (McCollum et al. 2018a; IEA 2021f). However, the literature is inconsistent in how demand-side investments are calculated, as boundary conditions are less clear than for energy supply investments. Taking a broader definition can result in estimates that are an order-of-magnitude higher, meaning as large or larger than supply-side investments (IEA 2021f; Grubler et al. 2012).

Increasing low-carbon investment primarily requires shifting existing capital investment through regulation and incentives as well as removing existing investment barriers (McCollum et al. 2018a)(Ameli, N. et al., 2021: Hafner et al. 2020: McCollum et al. 2018). While there is a considerable amount of capital in the world, it is not always available to those wishing to invest in certain projects. Total annual global investment in fixed capital was USD 22.4 trillion in 2021, over an order-of-magnitude larger than energy sector investment (World Bank, 2021).

Future investment patterns will vary by region, as they do now, due to differences in risk profiles, resource endowments and economic and governance structures (Zhou et al. 2019)(6.6; Ameli, N. et al., 2021; Fizaine et al. 2016; Zhou et al., 2019). In rapidly growing countries, investments to support a low-carbon energy system transition will be integrated with those needed to meet rapidly increasing energy demands, irrespective of whether efforts are made to reduce emissions. In less-rapidly-growing countries (Sun et al. 2019), investments will focus on transitioning current energy systems to low-carbon configurations. Most current energy investments are concentrated in high- and upper-middle income countries (IEA 2021f), but this will change as investment needs continue to grow in today's lower-middle and low-income countries (Bertram et al. 2021; McCollum et al. 2018a; Zhou et al. 2019; IEA 2021f).

6.7.3 Energy System Lock-In and Path Dependence

Path dependence refers to resistance to change due to favourable socio-economic conditions with existing systems; decisions made in the past unduly shape future trajectories. Carbon lock-in is a specific type of path dependence (Seto et al. 2016). Given that energy system mitigation will require a major course change from recent history, lock-in is an important issue for emission reductions in the energy sector. While lock-in is typically expressed in terms of physical infrastructure that would need to be retired early to reach mitigation goals, it involves a much broader set of issues that go beyond physical systems and into societal and institutional systems (Table 6.11).

Table 6.11 Lock-in types and typical mechanisms (Kotilainen et al. 2020). Reproduced under Creative Commons 4.0 International License.

Type	Primary lock-in mechanisms	References
Technological (and infrastructural)	Economies of scale Economies of scope Learning effects Network externalities Technological interrelatedness	Arthur (1994), Hughes (1994), Klitkou et al. (2015) David (1985), Panzar and Willig (1981) Arthur (1994) David, (1985), Katz and Shapiro (1986) Arrow (1962), Arthur (1994), David (1985), Van den Bergh and Oosterhuis (2008)
Institutional	Collective action Complexity and opacity of politics Differentiation of power and institutions High density of institutions Institutional learning effects Vested interests	Seto et al. (2016) Foxon (2002), Pierson (2000) Foxon (2002) Pierson (2000) Foxon (2002), Boschma (2005) Boschma (2005), Lovio et al. (2011)
Behavioral	Habituation Cognitive switching costs Increasing informational returns	David (1985), Barnes et al. (2004), Zauberman (2003), Murray and Haubl (2007) Zauberman (2003), Murray and Haubl (2007), Van den Bergh and Oosterhuis (2008)

6.7.3.1 *Societal and Institutional Inertia*

A combination of factors - user, business, cultural, regulatory, and transnational - will hinder low-carbon energy transitions. Strong path dependencies, even in early formative stages, can have lasting impacts on energy systems, producing inertia that cuts across technological, economic, institutional and political dimensions (*high confidence*) (Vadén et al. 2019; Rickards et al. 2014) Chapter 5).

Energy systems exemplify the ways in which massive volumes of labor, capital, and effort become sunk into particular institutional configurations (Bridge et al. 2013, 2018). Several embedded factors affect large-scale transformation of these systems and make technological diffusion a complex process:

- **User environments** affect purchase activities and can involve the integration of new technologies into user practices and the development of new preferences, routines, habits and even values (Kanger et al. 2019).
- **Business environments** can shape the development of industries, business models, supply and distribution chains, instrument constituencies and repair facilities (Béland and Howlett 2016).
- **Culture** can encompass the articulation of positive discourses, narratives, and visions that enhance cultural legitimacy and societal acceptance of new technologies. Regulatory embedding can capture the variety of policies that shape production, markets and use of new technologies.
- **Transnational community** can reflect a shared understanding in a community of global experts related to new technologies that transcends the borders of a single place, often a country.

While low-carbon innovation involves systemic change (Geels et al. 2018), these are typically less popular than energy supply innovations among policymakers and the wider public. Managing low carbon transitions is therefore not only a techno-managerial challenge (based on targets, policies, and expert knowledge), but also a broader political project that involves the building of support coalitions that include businesses and civil society (moderate evidence, high agreement).

Low-carbon transitions involve cultural changes extending beyond purely technical developments to include changes in consumer practices, business models, and organizational arrangements. The development and adoption of low-carbon innovations will therefore require sustained and effective policies to create appropriate incentives and support. The implementation of such policies entails political struggles because actors have different understandings and interests, giving rise to disagreements and conflicts.

Such innovation also involves pervasive uncertainty around technical potential, cost, consumer demand, and social acceptance. Such uncertainty carries governance challenges. Policy approaches facing deep uncertainty must protect against and/or prepare for unforeseeable developments, whether it is through resistance (planning for the worst possible case or future situation), resilience (making sure you can recover quickly), or adaptation (changes to policy under changing conditions). Such uncertainty can be hedged in part by learning by firms, consumers, and policymakers. Social interactions and network building (e.g., supply and distribution chains, intermediary actors) and the articulation of positive visions, such as in long-term, low-emission development strategies, all play a crucial role. This uncertainty extends to the impacts of low carbon innovations on energy demand and other variables, where unanticipated and unintended outcomes are the norm. For instance, rapid investments in public transport networks could restrict car ownership from becoming common in developing countries (Du and Lin 2017).

6.7.3.2 Physical Energy System Lock-In

Current investments in fossil infrastructure have committed 500-700 Gt-CO_2 of emissions, creating significant risks for limiting warming to 1.5°C (Callaghan 2020) (*high confidence*). These current investments combined with emissions from proposed fossil infrastructure exceed the emissions required to limit warming to 1.5°C (*medium confidence*). Existing coal and gas fired electricity generation accounts for 200-300 Gt-CO_2 of committed emissions. Emissions from coal generation are larger than for gas plants (Tong et al. 2019; Smith et al. 2019). The lifetime of coal-fired power plants is 25-50 years, creating long lasting risks to climate goals (Erickson and Tempest 2015). Gas-fired power plants are generally younger than coal-fired power plants. Industry sector lock-in amounts for more than 100 Gt-CO_2, while buildings and transport sector together contribute another 50-100 Gt-CO_2 (Erickson and Tempest 2015).

Lock-in is also relevant to fossil resources. Both coal and gas exploration continue, and new permits are being issued, which may cause economic (Erickson et al. 2018) as well as non-economic issues (Boettcher et al. 2019).

The nature of lock in varies across the energy system. For example, lock-in in urban and transport sectors is different from the electricity sector. Broadly, urban environments involve infrastructural, institutional, and behavioural lock-in (Ürge-Vorsatz et al. 2018). Addressing lock-in in these sectors requires action by multiple stakeholders and is unlikely with just technological evolution (Table 6.11).

Committed carbon emissions are unevenly distributed. The disproportionate high share of committed emissions in emerging economies is the result of rapid growth in recent years, which has led to a comparably young fossil infrastructure with substantial remaining life (Shearer et al. 2017). Mature industrialized countries tend to have older infrastructures, part of which will be up for retirement in the near future (Tong et al. 2019). Coal-fired power plants currently planned or under construction are associated with 150-300 Gt-CO_2, of which ~75% and ~10% are located in Asia and the OECD respectively (Pfeiffer et al. 2018; Edenhofer et al. 2018). If implemented, these new fleets will further shorten all coal plants' lifetimes by another 10 years for meeting climate goals (Cui et al. 2019)

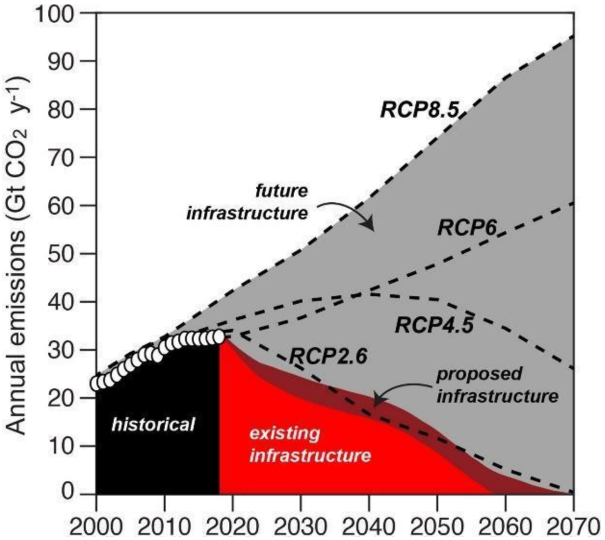


Figure 6.34 Annual emissions from existing, proposed, and future energy system infrastructure (Tong et al. 2019).

Despite the imperative to reduce use of fossil fuels and the multiple health and other benefits from closing coal-based infrastructure (Liu et al. 2019a; Portugal-Pereira et al. 2018; Rauner et al. 2020; Karlsson et al. 2020; Cui et al. 2021), coal power plants have continued to be commissioned globally (Jewell et al. 2019; Jakob et al. 2020), most notably in Asian countries. Gas power plants also continue to be built. In many regions, new fossil electricity generation exceeds needed capacity (Shearer et al. 2017).

Existing policies and the NDCs are insufficient to prevent an increase in fossil infrastructure and associated carbon lock in (*high confidence*) (Bertram et al. 2015; Johnson et al. 2015). Current investment decisions are critical because there is limited room within the carbon budget required to limit warming to well below 2°C (Rosenbloom 2019; Kalkuhl et al. 2019). Delays in mitigation will increase carbon lock-in and could result in large-scale stranded assets if stringency is subsequently increased to limit warming (Box 6.11). Near-term implementation of stringent GHG mitigation policies are likely to be most effective in reducing carbon lock-in (Haelg et al. 2018). Near-term mitigation policies will also need to consider different energy transition strategies as a result of different resources and carbon budgets between countries (Bos and Gupta 2018; Lucas 2016).

Near-term policy choices are particularly consequential for fast-growing economies. For example, Malik et al. (2020) found that 133 to 227 GW of coal capacity would be stranded after 2030 if India were to delay ambitious mitigation through 2030 and then pursue an ambitious, post-2030 climate strategy. (Cui et al. 2021)identified 18% of old, small, inefficient coal plants for rapid near-term retirement in China to help achieve air quality, health, water, and other societal goals and a feasible coal phaseout under climate goals. Comparable magnitudes of stranded assets may also be created in Latin America when adding all announced, authorized, and procured power plants up to 2060 (González-Mahecha et al. 2019). Options to reduce carbon lock in include reducing fossil fuels subsidies (Box 6.3), building CCS-ready facilities, or ensuring that facilities are appropriately designed for fuel switching (Budinis et al. 2018). Substantial lock-in may necessitate considerable deployment of CDR to compensate for high cumulative emissions.

Past and present energy sector investments have created technological, institutional, and behavioural path dependencies aligned towards coal, oil, and natural gas (*high confidence*). In several emerging economies, large projects are planned that address poverty reduction and economic development. Coal infrastructure may be the default choice for these investments without policies to invest in low-carbon infrastructure instead (Steckel et al. 2020; Joshua and Alola 2020). Path dependencies frequently have sustainability implications beyond carbon emissions. (Box 6.2 and Section 6.7.7). There are several SDG co-benefits associated with decarbonization of energy systems (Section 6.7.7; Sörgel et al. 2021). For example, coal mining communities frequently experience significant health and economic burdens from resource extraction.

[START BOX 6.13 HERE]

Box 6.13 Stranded Assets

Limiting likely warming to 2°C or below will result in stranded assets *(high confidence)*. Stranded assets can be broadly defined as assets which "suffer from unanticipated or premature write-offs, downward revaluations or [conversion] to liabilities." Stranded assets may create risks for financial market stability and macro-economic stability (Mercure et al. 2018, Battiston et al. 2017; Sen and von Schickfus 2020), and they will result in a rapid loss of wealth for the owners of affected assets (Vogt-Schilb and Hallegatte 2017; Ploeg and Rezai 2020).

There are two types of stranded assets: fossil-fuel resources that cannot be burned, and premature retirement of fossil infrastructure (e.g., power plants). About 30% of oil, 50% of gas, and 80% of coal reserves will remain unburnable if likely warming is limited to 2°C (Meinshausen et al. 2009; Leaton 2011; Leaton Ranger 2013; Pye et al. 2020; IRENA 2017b; Bauer et al. 2016; McGlade and Ekins 2015) (*high confidence*). Significantly more reserves are expected to remain unburned if warming is limited to 1.5°C. Countries with large oil, gas, and coal reserves are most at risk (Caldecott et al. 2017; Ansari and Holz 2020)

About 200 GW of fossil fuel electricity generation per year will likely need to be retired prematurely after 2030 to limit likely warming to 2°C, even if countries achieve their NDCs (Iyer et al. 2015; Johnson et al. 2015; Fofrich et al. 2020) (*medium confidence*). Limiting warming to 1.5°C will require significantly more rapid premature retirement of electricity generation capacity (Binsted et al. 2020). Coal- and gas-fired power plants will likely need to retire about 25 years earlier than in the past to limit likely warming to 2°C, and 30 years earlier to limit warming to 1.5°C (Cui et al. 2019; Fofrich et al. 2020). Coal-fired power plants are at significantly greater risk of stranding compared with gas-fired and oil-fired plants (Iyer et al. 2015; Johnson et al. 2015; Fofrich et al. 2020). The risks of stranded power plants are greatest in countries with newer fossil infrastructure.

If likely warming is limited to 2°C, the discounted economic impacts of stranded assets, including unburned fossil reserves, could be as high as USD 1-4 trillion from 2015 through 2050 (USD 10-20 trillion in undiscounted terms) (Mercure et al. 2018), IRENA, 2017) (*medium confidence*). About 40% of these impacts correspond to unburned fossil reserves (IRENA 2017b). If warming is limited to 1.5°C, the economic impacts of stranded assets are expected to be significantly higher (Binsted et al. 2020)

Stronger near-term mitigation will reduce premature retirements of fossil infrastructure, because more rapid mitigation will decrease new builds of fossil infrastructure that might later be stranded (Johnson et al. 2015; Bertram et al. 2018) (*high confidence*). For example, if likely warming is limited to 2°C, strengthening the NDC pledges beyond their 2015 levels could decrease stranded electricity sector assets by more than 50% (Iyer et al. 2015). By contrast, if countries fail to meet their NDCs and continue to build fossil infrastructure, mitigation will need to be accelerated beyond 2030, resulting up to double the amount of stranded electricity generation capacity (Iyer et al. 2015). This corresponds to a total undiscounted cost of about USD 2 trillion from electricity infrastructure alone, from the period 2015 to 2050 (IRENA 2017). CCS (6.4) could potentially help reduce hundreds of gigawatts stranded power plant capacity along with other fossil-based capital (Clark and Herzog 2014; Fan et al. 2018; Iyer et al. 2017).

[END BOX 6.13 HERE]

6.7.4 Fossil fuels in a low-carbon transition

Global fossil fuel use will need to decline substantially by 2050 to limit likely warming to 2°C or below, and it must decline substantially by 2030 to limit warming to 1.5°C with no or limited overshoot *(high confidence)*. Failing to reduce global fossil fuel use below today's levels by 2030 will make it more challenging to limit likely warming to below 2°C. *(high confidence)*. Fossil fuel use declines by 260-330 EJ (52-73% from 2020 levels, interquartile range) through 2050 to limit warming to 1.5°C with no or limited overshoot and 124-231 EJ (23-51% reduction compared to 2020 levels) to limit likely warming to 2°C; this will require a significant reduction in coal, oil and gas investments. Fossil fuels account for about 80% of primary energy today. In scenarios limiting warming to 1.5°C with limited or no overshoot, fossil energy provides 59-69% (interquartile range) primary energy in 2030 and 25-40s% primary energy in 2050 (AR6 database). In scenarios limiting likely warming to 2°C or below, fossil energy provides 71-75% (interquartile range) primary energy in 2030 and 41-57% primary energy in 2050 (AR6 database). The timeline for reducing production and usage varies across coal, oil, and gas due to their differing carbon intensities and their differing uses.

Global coal consumption without CCS needs to be largely eliminated by 2040-2050 to limit warming to 1.5°C, and 2050-2060 to limit likely warming to 2°C (*high confidence*). New investments in coal-fired electricity without CCS are inconsistent with limiting likely warming to 2°C or below (*high confidence*) (Spencer et al. 2018; Pfeiffer et al. 2018; Edenhofer et al. 2018; Cui et al. 2019). Coal consumption declines 130 EJ yr^{-1} to 140 EJ yr^{-1} in 2050 (79% to 99% compared to 2020 levels, interquartile range) in scenarios limiting warming to 1.5°C and 118 EJ yr^{-1} to 139 EJ yr^{-1} (66% to 98% compared to 2020 levels) in scenarios limiting likely warming to 2°C. Coal consumption without CCS falls by 67% to 82% (interquartile range) in 2030 in scenarios limiting warming to 1.5°C with no or limited overshoot. Studies indicate that coal use may decline substantially in the US and Europe over the coming decade based on the increasing competitiveness of low-carbon sources and near-term policy actions (Oei et al. 2020; Grubert and Brandt 2019). In several developing economies, the relative youth of the coal-fired electricity fleet will make a complete phaseout before 2050 difficult (Garg and Shukla 2009; Jewell et al. 2016). There are considerable differences in projected coal phaseout timelines in major Asian economies. Some studies suggest that coal may continue to be a part of the Chinese energy mix composing around a third of the total primary energy consumption by 2050 even if emissions are reduced by 50% by 2030 (He et al. 2020). Others indicate that a strategic transition would decrease the risk of stranded assets and enable a near-complete phaseout by 2050 (Wang et al. 2020a; Cui et al. 2021). This would entail prioritizing earlier retirements of plants based on technical (efficiency), economic (profitability, local employment) and environmental considerations (e.g., water scarcity for cooling).

Natural gas may remain part of energy systems through mid-century, both for electricity generation and use in industry and buildings, and particularly in developed economies, even if likely warming is limited to 2°C or less *(medium confidence)*. The decline in natural gas use in from 2020 to 2050 is 38 EJ yr^{-1} to 78 EJ yr^{-1} (21% to 61% decline from 2020 levels, interquartile range) in scenarios limiting warming to 1.5°C with no or limited overshoot and -22 EJ yr^{-1} to 46 EJ yr^{-1} (-13% to 36% decline from 2020 levels) in scenarios limiting likely warming to 2°C. Scenarios indicate that gas use in electricity will likely peak around 2035 and 2050 if warming is limited to 1.5°C with limited or no overshoot or likely below 2°C, respectively. There is variability in the role gas would play in future scenarios based on national climate commitments and availability of cheap renewable (Vrontisi et al. 2020, (Vishwanathan and Garg 2020; Malik et al. 2020). Note that these differences are not only present in the electricity sector but also in other end-uses.

While oil use is anticipated to decline substantially, due to changes in the transport sector, its use will likely continue through the mid-century, even if likely warming is limited to 2°C or less *(medium confidence).* Oil use declines by 43 EJ yr^{-1} to 91 EJ yr^{-1} (19% to 54% from 2020 levels, interquartile range) in scenarios that limit warming to 1.5°C with no or limited overshoot and 46 EJ yr^{-1} to 109 EJ yr^{-1} (21% 60% from 2020 levels) by 2050 in scenarios that limit likely warming to 2°C. While oil use is anticipated to decline immediately in scenarios limiting warming to 1.5°C, it is likely to continue to be used through 2050. Oil use continues to be a significant source of transport fuels in most scenarios limiting likely warming to 2°C (Welsby et al, 2021). Oil use may reduce to about half of the current levels as a transport fuels (Feijoo et al. 2020) if likely warming is limited to 2°C, because of the availability of other options (biofuels, green hydrogen) and rapid deployment of EVs. In the absence of rapid transport electrification, the decline is slower with some studies projecting peak oil use around 2035 (Delgado et al. 2020; Pan et al. 2020).

There is a lack of consensus about how CCS might alter fossil fuel transitions for limiting likely warming to 2°C or below. CCS deployment will increase the shares of fossil fuels associated with limiting warming, and it can ease the economic transition to a low-carbon energy system (Muratori et al. 2016; Marcucci et al. 2019).While some studies find a significant role for fossil fuels with CCS by 2050 (Koelbl et al. 2014; Eom et al. 2015; Vishwanathan and Garg 2020), others find that retirement of unabated coal far outpaces the deployment of coal with CCS (McJeon et al, 2021; Budinis et al. 2018; Xie et al. 2020) Moreover, several models also project that with availability of CO_2 capture technology, BECCS might become significantly more appealing than fossil CCS even before 2050 (Luderer et al. 2018b; Muratori et al, 2017).

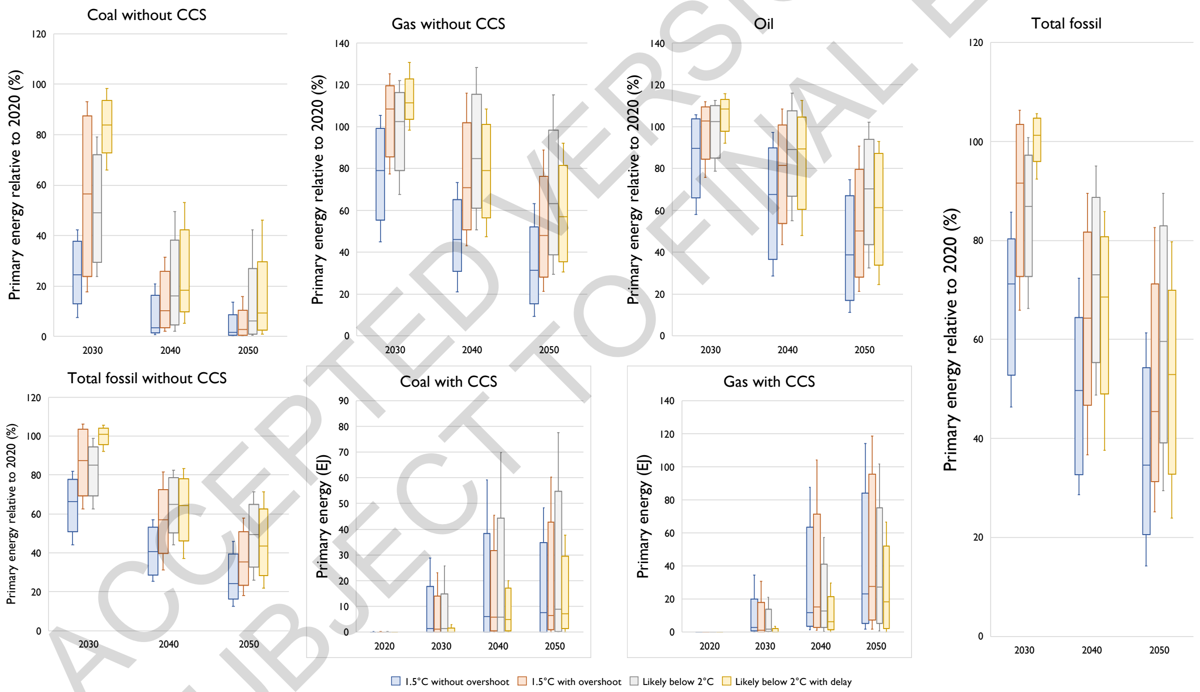


Figure 6.35 Global fossil fuel pathways for the 1.5°C scenarios (without and with overshoot), and likely 2°C scenarios (without and with delayed policy action) during 2020-2050 (Source: AR6 Scenario Database). Results for total consumption are expressed as a percentage relative to 2020 consumption. Results for fossil energy with CCS are expressed in total energy consumption. Boxes indicate 25th and 75th percentiles while whiskers indicate 5th and 95th percentiles. Oil use with CCS is not shown here as it remains below 5% of total use.

6.7.5 Policy and Governance

Policy and governance frameworks are essential for shaping near- and medium-term low-emissions energy system transitions (*high confidence*). While policy interventions are necessary to achieve low-carbon energy system transitions, appropriate governance frameworks are crucial to ensure policy implementation (*high confidence*). The policy environment in energy transition pathways relate to climate policy goals, the characteristics of the policy regimes and measures to reach the policy goals including implementation limits and obstacles, and the timing of the climate instrument (Kriegler et al. 2014b)

The literature discusses a broad set of policy approaches. Environmental economics focuses mainly on market-based approaches as the least-cost policy to achieve emission reductions (Kube et al. 2018). Many countries, however, have implemented policy mixes with a diverse set of complementary policies to achieve energy and climate policy targets. One example is the German Energiewende, which includes substantial support for renewables, an action plan for energy efficiency, and phase-out processes for nuclear- and coal-based power generation next to carbon pricing (Löschel et al. 2019). The halving of CO_2 emissions in UK power generation reflects multiple policies, particularly within the UK's Climate Change Act 2008 (Grubb and Newbery 2018). More generally, the implementation of the NDCs under the Paris Agreement are all characterized by diverse climate policy mixes.

These policy mixes (or policy packages) are shaped by different factors, including policy goals and objectives (including political, social and technological influences), multiple market, governance or behavioural failures or previous policy choices of earlier policy eras (Rogge 2017). When pursuing multiple policy goals or targeting some type of imperfection, well designed policy mixes can in principle reduce mitigation costs (Corradini et al. 2018) or address distributional concerns, especially vulnerable populations. For example, the interaction between carbon pricing and the support for clean energy technologies in the EU clean low-carbon strategy for 2050 can reduce mitigation costs and allow for the early adoption of more stringent climate targets (Vandyck et al. 2016). Policy efforts to promote adoption of low-carbon technologies are more successful if they focus not only on economic incentives but include behavioural interventions that target relevant cognitive and motivational factors (Khanna et al. 2021; Mundaca et al. 2019; see also Section 6.7.6). Overlapping nudges might not necessarily lead to lower effectiveness (Brandon et al. 2019).

Well-designed policy mixes can support the pursuit of multiple policy goals, target effectively different types of imperfections and framework conditions and take into account the technological, economical, and societal situation (*high confidence*). Accounting for the different development stages of new technologies will enhance low-emissions transitions (Graaf and Sovacool 2020). For prototype technologies and technologies in the demonstration phase, research subsidies and demonstration projects are most important. For technologies experiencing early adoption, infrastructure development and strengthening of markets are increasingly important, while retiring or repurposing of existing assets is important for mature technologies (IEA 2020h) Effective policy mixes will address different market frictions and deal with various uncertainties, for example, those pertaining to technological, climate, and socio-economic developments (Aldy 2020), but also with respect to outcomes of individual policies (e.g. Borenstein et al. 2019). Therefore, policy mixes may balance the trade-off between stability and the flexibility to change individual policies (Gawel and Lehmann 2019) and the policy mix over time (Rayner et al. 2017). Some policy instruments may become feasible over time, for example, as technological advancements reduce the transaction costs of comprehensive market-based approaches (Andoni et al. 2019; Di Silvestre et al. 2020), or as weakened barriers to stringency enable policy sequencing (Pahle et al. 2018) . Energy system policy mixes often include sector-specific regulation. Compared to economy-wide approaches, sectoral policies may be able to directly target specific sectors or mitigation options. However, uncoordinated implementation or limited coordination across sectors may lead to efficiency losses (e.g. Rosendahl et al. 2017). These losses also depend on other policies, such as pre-existing taxes (Goulder et al. 2016; Marten et al. 2018) or research and development policies (Acemoglu et al. 2016). Moreover, unilateral policies – those taken by individual countries in the absence of coordination with other countries – could raise carbon leakage risks, while balancing potential issues of (industrial) competitiveness (Martin et al. 2014; Rosendahl et al. 2017). Energy leakage may become more important during low-carbon energy systems. Numerous studies have identified pathways for carbon leakage in electricity markets with incomplete emission markets (Caron et al. 2015; Thurber et al. 2015; Murray and Maniloff 2015; Fell and Maniloff 2017; Duan et al. 2017; Qian et al. 2018). Well-designed policy mixes will need to target the whole life-cycle or value chains, for example, through policies on limiting fossil fuel extraction (Asheim et al. 2019), or they will need to include measures to limit carbon leakage (e.g. Cosbey et al. 2019).

Interactions between policy measures including their scope, stringency, and timing, influence the costs of reducing emissions (Corradini et al. 2018). In particular, some policy instruments may lead to lock-in effects (Section 6.7.3.), compete with other regulations (Graaf and Sovacool 2020), or trigger negative policy interactions (Perino 2015; Jarke-Neuert and Perino 2020). Existing policy mixes often reflect different political economy constraints and sometimes not well coordinated goals. The resulting policy mixes are often economically inefficient. However, comprehensive evaluation of policy mixes requires a broader set of criteria that reflect different considerations, such as broader goals (e.g., SDGs) and the feasibility of policies (*high confidence*).

Policy mixes might rather emerge piece-by-piece over time out of individual policy interventions rather than be designed as a whole from the outset (Howlett 2014; Rogge 2017) and may reflect differences across jurisdictions and sectors (Howlett 2014). For example, taking into account country-specific objectives, failures, and limitations, carbon prices may be only one part of a broader policy mix and thereby may not be uniform across countries (Bataille 2020). This lack of consistency makes it more difficult to assess economic outcomes since costs of complementary policies are often less visible and are often targeted at high-cost mitigation options (Borenstein et al. 2019).

Effective assessment of policy mixes requires comprehensive, validated international data, methodologies, and indicators. Existing policy mixes are difficult to evaluate because they target multiple objectives, and the evaluation must consider various criteria (Chapter 13, 6.7.7), such as environmental and economic effectiveness, distributional effects, transformative potential, institutional requirements, and feasibility. Economic outcomes depend on policy goals and implementation. Existing studies on policy mixes suggest the benefits of a comprehensive approach (Rosenow et al. 2017), while also highlighting that an "excessive" number of instruments may reduce overall effectiveness (Costantini et al. 2017). Combining environmental regulation and innovation policies may be of particular importance to tackle both emissions and innovation market failures (Fabrizi et al. 2018). The consistency and credibility of policy mixes is positively associated with green innovation (Rogge and Schleich 2018).

Potential future policies are difficult to evaluate due to methodological challenges (*high confidence*). Recent model-based analyses of future policy mixes based on "current policy scenarios" try to implement existing policies besides explicit or implicit carbon prices (den Elzen et al. 2016; Roelfsema et al. 2020; van Soest et al. 2017; Rogelj et al. 2016). Many assessments of future low-carbon energy transitions are still based on cost-optimal evaluation frameworks and include only limited analysis of interactions between policy measures. Hence they are often not describing real-world energy transitions properly, but rather differences in implied carbon prices, constraints in technology deployment, and timing of policies (Trutnevyte 2016).

6.7.6 Behaviour and Societal Integration

Members of societies, including individuals, civil society, and businesses, will all need to engage with and be affected by low-carbon energy system transitions (*high confidence*). This raises questions about the extent to which different strategies and policy would effectively promote mitigation behaviours and the factors that increase the social acceptability of mitigation options, policies, and system changes.

6.7.6.1 Strategies to encourage climate mitigation actions

Climate policy will be particularly effective if it targets key factor inhibiting, enabling, and motivating mitigation behaviours. As barriers differ across mitigation options, regions, and groups, tailored approaches are more effective (Grubb et al. 2017). When people face important barriers to change (e.g., high costs, legal barriers), policy would be needed make low carbon actions more attractive, or to make high carbon actions less attractive. As people generally face multiple barriers for change, combinations of policies would be more effective (Rosenow et al. 2017).

Financial incentives can motivate mitigation actions (Santos 2008; Thøgersen 2009; Eliasson 2014; Maki et al. 2016; Bolderdijk et al. 2011), particularly when actions are costly (Mundaca 2007). In many countries, more residential solar PV were installed after the introduction of favourable financial schemes such as feed-in-tariffs, federal income tax credits, and net metering (Wolske and Stern 2018). Similarly, a subsidy promoted the installation of solar water heaters in Asia (Chang et al. 2009). Yet, financial incentives may underperform expectations when other factors are overlooked. For example, people may not respond to financial incentives when they do not trust the organization sponsoring the program or when it takes too much effort to receive the incentive (Mundaca 2007; Stern et al. 2016a). Financial incentives are more effective if combined with strategies addressing non-financial barriers.

Communicating financial consequences of behaviour seems less effective than emphasizing social rewards (Handgraaf et al. 2013) or benefits of actions for people (e.g., public health, comfort) and the environment (Asensio and Delmas 2015, 2016; Schwartz et al. 2015; Ossokina 2020; Bolderdijk et al. 2013). Financial appeals may have limited effects because they reduce people's focus on environmental consequences, weaken intrinsic motivation to engage in mitigation actions, provide a license to pollute (Agrawal et al. 2015; Bolderdijk and Steg 2015; Schwartz et al. 2015), and because pursuing small financial gains is perceived not worth the effort (Dogan et al. 2014; Bolderdijk et al. 2013).

Providing information on the causes and consequences of climate change or on effective mitigation actions increases people's knowledge and awareness, but generally does not promote mitigation actions by individuals (Abrahamse et al. 2005) or organizations (Anderson and Newell 2004). Fear-inducing representations of climate change may inhibit action when they make people feel helpless (O´Neill and Nicholson-Cole 2009). Energy-related advice and feedback can promote energy savings, load shifting in electricity use and sustainable travel, particularly when framed in terms of losses rather than gains (Gonzales et al. 1988; Wolak 2011; Bradley et al. 2016; Bager and Mundaca 2017). Also, credible and targeted information at the point of decision can promote action (Stern et al. 2016a). Information is more effective when delivered by a trusted source, such as peers (Palm 2017), advocacy groups (Schelly 2014), and community organizations (Noll et al. 2014), and when tailored to actors' personal situation and core values (Abrahamse et al. 2007; Boomsma and Steg 2014; van den Broek et al. 2017; Daamen et al. 2001; Wolsko et al. 2016; Bolderdijk et al. 2013). This explains why home energy audits promoted energy savings (Delmas et al. 2013; Alberini and Towe 2015), and investments in resource efficiency and renewable energy generation (Kastner and Stern 2015).

Energy use feedback can promote energy saving behaviour within households (Grønhøj and Thøgersen 2011; Fischer 2008; Karlin et al. 2015; Delmas et al. 2013; Zangheri et al. 2019) and at work (Young et al. 2015), particularly when provided in real-time or immediately after the action so that people learn the impact of different actions (Faruqui et al. 2009; Delmas et al. 2013; Abrahamse et al. 2005; Tiefenbeck et al. 2016; Stern et al. 2016a; Yu et al. 2015). Energy labels (Banerjee and Solomon 2003; Stadelmann 2017), visualization techniques (Pahl et al. 2016), and ambient persuasive technology (Midden and Ham 2012) can encourage energy savings as they immediately make sense and hardly require users' conscious attention. Feedback can make people aware of their previous mitigation behaviours, which can strengthen their environmental self-identity, and motivate them to engage in other mitigation actions as well as to act in line with their self-image (Van der Werff et al. 2014).

Social influence approaches that communicate what other people do or think can encourage mitigation actions (Clayton et al. 2015), as can social models of desired actions (Osbaldiston and Schott 2012; Abrahamse and Steg 2013; Wolske et al. 2020; Sussman and Gifford 2013). Feedback on one's own energy use relative to others can be effective (Nolan et al. 2008; Allcott 2011; Schultz et al. 2015), although not always, and effect sizes are small (Abrahamse and Steg 2013) compared to other types of feedback (Karlin et al. 2015).

Interventions that capitalize on people's motivation to be consistent can promote mitigation actions (Steg 2016). Examples are commitment strategies where people pledge to act (Abrahamse and Steg 2013; Lokhorst et al. 2013), implementation intentions where they additionally explicate how and when they will perform the relevant action and how they would cope with possible barriers (Rees et al. 2018; Bamberg 2000, 2002), and hypocrisy-related strategies that make people aware of inconsistencies between their attitudes and behaviour (Osbaldiston and Schott 2012).

Bottom-up approaches can promote mitigation action (Abrahamse and Steg 2013). Indeed, community energy initiatives can encourage members' low carbon behaviour (Middlemiss 2011; Seyfang and Haxeltine 2012; Abrahamse and Steg 2013; Sloot et al. 2018). Organizations can promote mitigation behaviour among their employees and customers by communicating their mission and strategies to mitigate climate change (van der Werff et al. 2021; Ruepert et al. 2017).

Default options, where a preset choice is implemented if users do not select another option, can promote mitigation actions such as energy savings, green electricity uptake, and meat-free meals options (Liebe et al. 2021; Pichert and Katsikopoulos 2008; Ölander and Thøgersen 2014; Kunreuther and Weber 2014; Bessette et al. 2014; Ebeling and Lotz 2015; Liebe et al. 2018; Campbell-Arvai et al. 2014).

6.7.6.2 Acceptability of policy, mitigation options and system changes

Public acceptability reflects the extent to which the public evaluates climate policy, mitigation options, and system changes (un)favourably, which can shape, enable, or prevent low-carbon energy system transitions. Public acceptability of policy and mitigation options is higher when people expect these have more positive and less negative consequences for self, others, and the environment (Demski et al. 2015; Drews and Van den Bergh 2016; Perlaviciute and Steg 2014). Public opposition may result when a culturally valued landscape is affected by renewable energy development (Warren et al. 2005; Devine-Wright and Howes 2010), particularly place-based identities are threatened (Devine-Wright 2009, 2013; Boudet 2019). Acceptability can increase after a policy or change has been implemented and the consequences appear to be more positive than expected (Carattini et al. 2018; Schuitema et al. 2010; Eliasson 2014; Weber 2015); effective policy trials can thus build public support.

Next, climate policy and low carbon options are evaluated as more fair and acceptable when costs and benefits are distributed equally, and when nature, the environment and future generations are protected (Schuitema et al. 2011; Drews and Van den Bergh 2016). Compensating affected groups for losses due to policy or systems changes enhanced public acceptability in some cases (Perlaviciute and Steg 2014), but people may disagree on which compensation would be worthwhile (Aitken 2010b; Cass et al. 2010), on the distribution of compensation (Devine-Wright and Sherry-Brennan 2019; Leer Jørgensen et al. 2020), or feel they are being bribed (Perlaviciute and Steg 2014; Cass et al. 2010). Pricing policies are more acceptable when revenues are earmarked for environmental purposes (Steg et al. 2006; Sælen and Kallbekken 2011) or redistributed towards those affected (Schuitema and Steg 2008).

Climate policy and mitigation options, such as renewable energy projects, are also perceived as more fair and acceptable when the public (Dietz 2013; Bidwell 2014; Bernauer et al. 2016b) or public society organizations (Terwel et al. 2010; Bernauer et al. 2016b) could participate in the decision making (Devine-Wright 2005; Terwel et al. 2012; Perlaviciute and Squintani 2020; Arvai 2003; Walker and Baxter 2017). People are more motivated to participate in decision making on local projects than on national or general policy goals (Perlaviciute and Squintani 2020). Public acceptability is also higher when people can influence major rather than only minor decisions, particularly when trust in responsible parties is low (Liu et al. 2019a). Public participation can enhance the quality and legitimacy of decisions by including local knowledge and views that may otherwise be missed (Bidwell 2016; Dietz 2013).

Public support is higher when people trust responsible parties (Perlaviciute and Steg 2014; Jiang et al. 2018; Drews and Van den Bergh 2016; Michaels and Parag 2016; Liu et al. 2019a). Public support for unilateral climate policy is rather strong and robust (Bernauer et al. 2016a), even in the absence of reciprocal commitments by other states (Bernauer and Gampfer 2015).

Public acceptability of climate policy and low carbon options differs across individuals. Climate policy and low carbon options are more acceptable when people strongly value protecting other people and the environment, and support egalitarian worldviews, left-wing or green political ideologies, while acceptability is lower when people strongly endorse self-centered values, and support individualistic worldviews (Dietz et al. 2007; Perlaviciute and Steg 2014; Drews and Van den Bergh 2016). Similarly, public decision makers support climate policy more when they endorse environmental values (Nilsson et al. 2016). Climate and energy policy is more acceptable when people are more concerned about climate change (Hornsey et al. 2016), when they believe their actions would help mitigating climate change, and feel responsible to mitigate climate change (Steg 2005; Jakovcevic and Steg 2013; Ünal et al. 2019; Eriksson et al. 2006; Drews and Van den Bergh 2016; Kim and Shin 2017).

6.7.7 The Costs and Benefits of Low-Carbon Energy System Transitions in the Context of Sustainable Development

The attractiveness of energy sector mitigation ultimately depends on the way that it provides benefits and reduces the costs for the many different priorities that societies value(Wei et al. 2018, 2020; Yang et al. 2018a). While costs and benefits of climate mitigation are often considered in the context of pure economic outcomes – for example, GDP effects or changes in value of consumption – costs and benefits should be viewed with a broader lens that accounts for the many ways that the energy system interacts with societal priorities (Karlsson et al. 2020). Climate mitigation is not separate from countries' broader growth and development strategies, but rather as a key element of those strategies.

Cost reductions in key technologies, particularly in electricity and light-duty transport, have increased the economic attractiveness of near-term low-carbon energy system transitions (*high confidence*). The near-term, economic outcomes of low-carbon energy system transitions in some sectors and regions may be on par with or superior to those of an emissions-intensive future (*high confidence*). Even in cases when system costs are higher for low-carbon transitions, these transitions may still be economically favourable when accounting for health impacts and other co-benefits (Gielen et al. 2019). Past assessments have quantified the aggregate economic costs for climate change mitigation using different metrics, for example carbon prices, GDP losses, investments in energy infrastructure, and energy system costs. Assessments of mitigation costs from integrated assessment and energy system models vary widely. For example, scenarios include carbon prices in 2030 of less than USD 20/t-CO_2, but also more than USD 400/t-CO_2 depending on the region, sector boundary, and methodology (e.g. (Bauer et al. 2016; Oshiro et al. 2017; Vaillancourt et al. 2017; Chen et al. 2019; Brouwer et al. 2016). Those arise both from different methodologies (Guivarch and Rogelj 2017) and assumptions about uncertainties in key factors that drive costs (Meyer et al. 2021)

Recent developments, however, raise the prospect that economic outcomes could be substantially superior to prior estimates, particularly if key technologies continue to improve rapidly. In some regions and circumstances, particularly in the electricity sector, near-term mitigation may well lead to superior economic outcomes than continuing to invest in and utilize emissions-intensive infrastructure (e.g. (Brown et al. 2017; Kumar et al. 2020). Given the importance of electricity decarbonization in near-term mitigation strategies (see Section 6.7.1), decreasing costs of solar PV, wind power, and batteries to support their integration, have an outsized influence on near-term economic outcomes from mitigation. At the same time, economic outcomes may vary across regions depending, among other things, on the characteristics of the current energy systems, energy resources, and needs for integrating VRE technologies.

The long-term economic characteristics of low-emissions energy system transitions are not well understood and depend on policy design and implementation along with future costs and availability of technologies in key sectors (e.g., process heat, long-distance transport), and the ease of electrification in end-use sectors (*high confidence*). The long-term aggregate economic outcomes from a low-emissions future are not likely to be substantially worse than in an emissions-intensive future and may prove superior (see, e.g., Bogdanov et al. 2021, Child et al. 2019, Farmer et al. 2020) (*medium confidence*). For the whole economy, the interquartile range of estimated mitigation costs is between USD_{2015} 140 and USD_{2015} 340/t-CO_2 in 2050 in scenarios limiting likely warming to 2°C and between USD_{2015} 430 and USD_{2015} 990/tCO_2 in scenarios limiting likely warming to 1.5°C (Chapter 3). For energy sectors in various regions and globally, different scenarios show a wide range of implied carbon prices in 2050 to limit warming to 1.5°C, from below USD 50/t-CO_2 to more than USD 900/t-CO_2 (Brouwer et al. 2016; Rogelj et al. 2018a). Mitigation costs for scenarios limiting likely warming to 2°C were 3-11% in consumption losses in AR5, but the median in newer studies is about 3% in GDP losses (Su et al. 2018; Gambhir et al. 2019).

Estimates of long run mitigation costs are highly uncertain and depend on various factors. Both faster technological developments and international cooperation are consistently found to improve economic outcomes (Paroussos et al. 2019). Long-term mitigation is likely to be more challenging than near-term mitigation because low-cost opportunities get utilized first and efforts after that would require mitigation in more challenging sectors (Section 6.6). Advances in low-carbon energy resources and carriers such as next-generation biofuels, hydrogen produced from electrolysis, synthetic fuels, and carbon-neutral ammonia would substantially improve the economics of net zero energy systems *(high confidence)*. Current estimates of cumulative mitigation costs are comparably high for developing countries, amounting to up to 2-3% of GDP, indicating difficulties for mitigation without adequate support from developed countries (Fujimori et al. 2020; Dorband et al. 2019). In scenarios involving large amounts of stranded assets, the overall costs of low-carbon transitions also include the additional costs of early retirements (Box 6.11).

Focusing only on aggregate economic outcomes neglects distributional impacts, impacts on broader SDGs, and other outcomes of broad societal importance. Strategies to increase energy efficiency and energy conservation are, in most instances, mutually reinforcing with strategies to support sustainable development. Improving efficiency and energy conservation will promote sustainable consumption and production of energy and associated materials (SDG-12) (*high confidence*). Contrastingly, successful implementation of demand-side options requires sustainable partnerships (SDG-17) between different actors in energy systems, for example governments, utilities, distributors, and consumers. Many authors have argued that energy efficiency has a large untapped potential in both supply and demand (Lovins 2018; Méjean et al. 2019). For example, improved fossil power plant efficiency has been estimated to lower the costs of CCS from USD 80-100/t-CO_2 for a subcritical plant to <USD 40/t-CO_2 for a high efficiency plant (Hu and Zhai 2017; Singh et al. 2017). This could enhance energy access and affordability. Eliminating electricity transmission losses has been estimated to mitigate 500 Mt-CO_2 per year globally (Surana and Jordaan 2019). For several other options, such as methane mitigation from the natural gas sector, the costs of infrastructure refurbishing could be offset with the value of the recovered natural gas (Kang et al. 2019).

Efficient end use technologies are likely to be particularly cost-effective in developing countries where new infrastructure is rapidly getting built and there is an opportunity to create positive path dependencies (Section 6.7.3). Aside from reducing energy consumption, efficient end use technologies reduce the need for resource extraction, for example, fossil fuel extraction or mining for materials used in wind turbines or solar PV cells (Luderer et al. 2019). Reduced resource extraction is an important precursor to SDG-12 on sustainable consumption and production of minerals. End use efficiency strategies also reduce the need for, and therefore SDG tradeoffs associated with, CDR towards the end of the century and avoid temperature overshoot (van Vuuren et al. 2018). But fully leveraging the demand-side efficiency would entail behavioural changes and thus rely on strong partnerships with communities (SDG-17). For instance, approaches that inform households of the economic value of conservation strategies at home could be particularly useful (Niamir et al. 2018). Improved energy efficiency is interlinked with higher economic growth in Africa (Ohene-Asare et al. 2020; Lin and Abudu 2020). An important distinction here between SDGs focusing on infrastructural and behavioural interventions is the temporal context. Improving building heat systems or the electricity grid with reduced T&D losses would provide climate mitigation with one-time investments and minor maintenance over decades. On the other hand, behavioural changes would be an ongoing process involving sustained, long-term societal interactions.

Increasing electrification will support and reduce the costs of key elements of human development, such as education, health, and employment) (*high confidence*). Greater access to electricity might offer greater access to irrigation opportunities for agricultural communities (Peters and Sievert 2016) which could have the potential increasing farmer incomes in support of SDG-1. Coordinated electrification policies also improve enrolment for all forms of education (Kumar and Rauniyar 2018; López-González et al. 2020). Empirical evidence from India suggests that electrification reduced the time for biomass collection thus improved the time children have available for schooling (SDG-4/5) (Khandker et al. 2014). Reduced kerosene use in developing countries has improved indoor air quality (SDG-3) (Barron and Torero 2017; Lewis and Severnini 2020). These positive linkages between climate change mitigation and other goals have improved perceptions of solar PV among the public and policymakers. "Goodwill" towards solar PV is the highest among all the major mitigation options considered in this chapter (Section 6.4.2).

Past trends have also indicated that in some Asian countries, electrification has been obtained at lower income levels as compared to developed countries (Rao and Pachauri 2017), with corresponding impacts for development goals For example, a human development index (HDI) greater than 0.7 (Figure 6.36) which signifies high development is now possible at close to 30 GJ yr^{-1} per person. This was attainable only at the energy consumption of 50 GJ yr^{-1} per person in preceding decades.

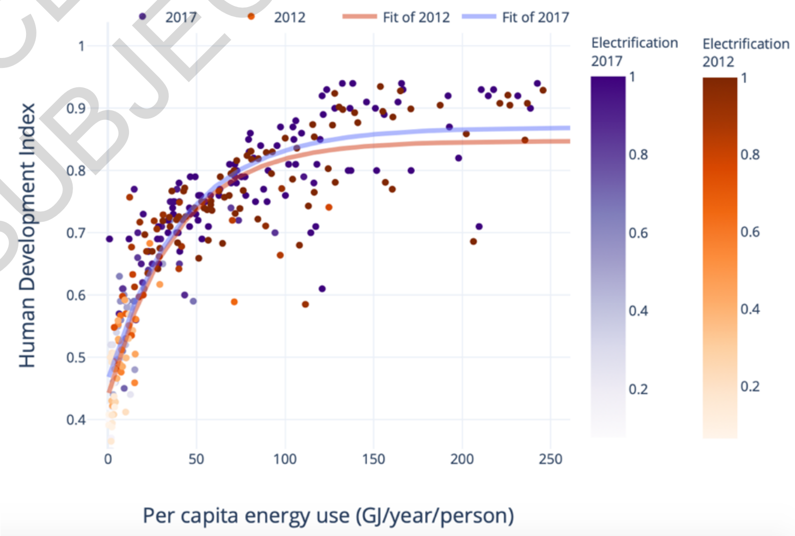


Figure 6.36 The relationship between total per capita energy use, rate of electrification and human development index. Improved efficiency has lowered the energy demand required for meeting a threshold HDI during 2012-2017

Electrification also improves energy efficiency, with corresponding implications for development goals For example, the availability of electric cooking may reduce the cooking primary energy requirement considerably compared to traditional stoves (Batchelor et al. 2019; Yang and Yang 2018; Khan and Alam 2020) while also promoting improved indoor air quality (SDG-3). Similarly, PV-powered irrigation and water pumping reduces pumping energy demands, which has the added advantage of promoting SDG-6 on clean water (Elkadeem et al. 2019; Rathore et al. 2018).

Phasing out fossil fuels in favour of low-carbon sources, is likely to have considerable SDG benefits, particularly if tradeoffs such as unemployment to fossil fuel workers are minimized (*high confidence*). A phaseout of coal (Box 6.2, Section 6.3) will support SDGs 3, 7 and 14, but it is also anticipated to create large job losses if not properly managed. At the same time, there are large potential employment opportunities that may be created in alternative sectors such as renewables and bioenergy for both skilled and unskilled workers. "Sustainable transition" pathways have indicated a complete fossil phaseout which could entail numerous other co-benefits. For instance, fossil fuels are estimated to generate only 2.65 jobs per USD 1M as compared to projected 7.49 from renewables (Garrett-Peltier 2017). Similar synergies may also emerge for nuclear power in the long-term though the high costs create tradeoffs in developing country contexts (Castor et al. 2020; Agyekum et al. 2020). While bioenergy production may create jobs, it may also be problematic for SDG-2 on zero hunger by affecting the supplies and prices of food. Phasing out of fossil fuels will also improve air quality (SDG-3) and premature deaths by reducing PM2.5 emissions, (He et al. 2020; Li et al. 2020c). Energy transitions from fossil fuels to renewables, as well as within fossil fuels (coal to gas switching), are already occurring in some regions, spurred by climate concerns, health concerns, market dynamics, or consumer choice (for example in the transport sector).

CDR and CCS can create significant land and water tradeoffs (*high confidence*). For large-scale CDR and CCS deployment to not conflict with development goals requires efforts to reduce implications on water and food systems. The water impacts of carbon capture are large, but these impacts can be strategically managed (Giannaris et al. 2020c; Magneschi et al. 2017; Realmonte et al. 2019; Liu et al. 2019a). In addition, high-salinity brines are produced from geologic carbon storage, which may be a synergy or tradeoff depending on the energy intensity of the treatment process and the reusability of the treated waters (Arena et al. 2017; Klapperich et al. 2014); if the produced brine from geologic formations can be treated via desalination technologies, there is an opportunity to keep the water intensity of electricity as constant (section 6.4.2.5). Both implications of CCS and CDR are related to SDG-6 on clean water. CDR discussions in the context of energy systems frequently pertains to BECCS which could affect food prices based on land management approaches (Daioglou et al. 2020a). Several CDR processes also require considerable infrastructure refurbishment and electrification to reduce upstream CO_2 emissions (Singh and Colosi 2021). Large-scale CDR could also open the potential for low-carbon transport and urban energy (by offsetting emissions in these sectors) use that would create synergies with SDG-11 (sustainable cities and communities). Effective siting of CDR infrastructure therefore requires consideration of tradeoffs with other priorities. At the same time, several SDG synergies have also been reported to accompany CCS projects such as with reduced air pollution (SDG-3) (Mikunda et al. 2021).

Greater energy system integration (Section 6.4.3, Section 6.6.2) would enhance energy-SDG synergies while eliminating tradeoffs associated with deploying mitigation options (*high confidence*). Energy system integration strategies focus on codependence of individual technologies in ways that optimize system performance. Accordingly, they can improve economic outcomes and reduce negative implications for SDG. For example, VRE electricity options raise intermittency concerns and hydrogen can be expensive due to the costs of electricity. Both are relevant to SDG-7 on affordable and reliable energy access. Routing excess solar generation during daytime for hydrogen production will improve grid stability as lower hydrogen costs (Tarroja et al. 2015). Due to the varying patterns of solar and wind energy, these two energy sources could be operated in tandem, thus reducing the material needs for their construction and for storage, thus promoting SDG-12 on sustainable production (Weitemeyer et al. 2015; Wang et al. 2019d). For CCS facilities, co-firing of fossil fuels and biomass could enable a more gradual, near-term low-carbon transition (Lu et al. 2019). This could enable early retirements (associated with SDG-1) while also providing air pollution reductions (associated with SDG-3).

Overall, the scope for positive interactions between low-carbon energy systems and SDGs is considerably larger than the tradeoffs (Figure 6.37) (McCollum et al. 2018b). Some critical tradeoffs include impact to biodiversity due to large-scale mineral mining needed for renewable infrastructure (Sonter et al. 2020).

Figure 6.37 Nature of the interactions between SDG7 (Energy) and the non-energy SDGs (McCollum et al. 2018b). Reproduced under Creative Commons 3.0 License.

Frequently Asked Questions

FAQ 6.1. Will energy systems that emit little or no CO_2 be different than those of today?

Low-carbon energy systems will be similar to those of today in that they will provide many of the same services as today – for example, heating and cooling homes, travelling to work or on vacation, transporting goods and services, and powering manufacturing. But future energy systems may be different in that people may also demand new services that aren't foreseen today, just as people now use energy for many information technology uses that were not anticipated 50 years ago. More importantly, low-carbon energy systems will be different in the way that energy is produced, transformed, and used to provide these services. In the future, almost all electricity will be produced from sources that emit little or no CO_2, such as solar power, wind power, nuclear power, bioenergy, hydropower, geothermal power, or fossil energy in which the CO_2 is captured and stored. Electricity, hydrogen, and bioenergy will be used in many situations where fossil fuels are used today, for example, in cars or heating homes. And energy is likely to be used more efficiently than today, for example, through more efficient cars, trucks, and appliances, buildings that use very little energy, and greater use or public transportation. All of these changes may require new policies, institutions, and even new ways for people to live their lives. And fundamental to all of these changes is that low-carbon energy systems will use far less fossil fuel than today.

FAQ 6.2. Can renewable sources provide all the energy needed for energy systems that emit little or no CO_2?

Renewable energy technologies harness energy from natural sources that are continually replenished, for example, from the sun (solar energy), the wind (wind energy), plants (bioenergy), rainfall (hydropower), or even the ocean. The energy from these sources exceeds the world's current and future energy needs many times. But that does not mean that renewable sources will provide all energy in future low-carbon energy systems. Some countries have a lot of renewable energy, whereas others do not, and other energy sources, such as nuclear power or fossil energy in which CO_2 emissions are captured and stored (carbon dioxide capture and storage, or CCS) can also contribute to low-carbon energy systems. The energy from sources such as solar energy, wind energy, and hydropower can vary throughout the day or over seasons or years. All low-carbon energy sources have other implications for people and countries, some of which are desirable, for example, reducing air pollution or making it easy to provide electricity in remote locations, and some of which are undesirable, for example decreasing biodiversity or mining of minerals to produce low-emissions technologies. For all of these reasons, it is unlikely that all low-carbon energy systems around the world will rely entirely on renewable energy sources.

FAQ 6.3. What are the most important steps to decarbonize the energy system?

To create a low-carbon energy system, emissions must be reduced across all parts of the system, and not just one or two. This means, for example, reducing the emissions from producing electricity, driving cars, hauling freight, heating and cooling buildings, powering data centers, and manufacturing goods. There are more opportunities to reduce emissions over the next decade in some sectors compared to others. For example, it's possible to substantially reduce electricity emissions over the next decade by investing in low-carbon electricity sources, while at the same time halting the construction of new coal-fired power plants, retiring existing coal-fired power plants or retrofitting them with CCS, and limiting the construction of new gas-fired power plants. There are also opportunities to increase the number of electric cars, trucks, and other vehicles on the road, or to use electricity rather than natural gas or coal to heat homes. And across the whole energy system, emissions can be reduced by using more efficient technologies. While these and other actions will be critical over the coming decade, it is also important to remember that the low-carbon energy transition needs to extend for many decades into the future to limit warming. This means that it is important now to improve and test out options that could be useful later on, for example, producing hydrogen from low-carbon sources or producing bioenergy from crops that require less land than those of today.

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Chapter 7: Agriculture, Forestry and Other Land Uses (AFOLU)

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Executive summary

The Agriculture, Forestry and Other Land Uses[1] (AFOLU) sector encompasses managed ecosystems and offers significant mitigation opportunities while delivering food, wood and other renewable resources as well as biodiversity conservation, provided the sector adapts to climate change. Land-based mitigation measures represent some of the most important options currently available. They can both deliver carbon dioxide removal (CDR) and substitute for fossil fuels, thereby enabling emissions reductions in other sectors. The rapid deployment of AFOLU measures is essential in all pathways staying within the limits of the remaining budget for a 1.5◦C target *(high confidence)*. Where carefully and appropriately implemented, AFOLU mitigation measures are uniquely positioned to deliver substantial co-benefits and help address many of the wider challenges associated with land management. If AFOLU measures are deployed badly then, when taken together with the increasing need to produce sufficient food, feed, fuel and wood, they may exacerbate trade-offs with the conservation of habitats, adaptation, biodiversity and other services. At the same time the capacity of the land to support these functions may be threatened by climate change itself (*high confidence*). {WGI, Figure SPM7; WGII, 7.1, 7.6}

The AFOLU (managed land) sector, on average, accounted for 13-21% of global total anthropogenic greenhouse gas (GHG) emissions in the period 2010-2019 (*medium confidence*). At the same time managed and natural terrestrial ecosystems were a carbon sink, absorbing around one third of anthropogenic CO_2 emissions (*medium confidence*). Estimated anthropogenic net CO_2 emissions from AFOLU (based on bookkeeping models) result in a net source of +5.9 ± 4.1 $GtCO_2$ yr^{-1} between 2010 and 2019 with an unclear trend. Based on FAOSTAT or national GHG inventories, the net CO_2 emissions from AFOLU were 0.0 to +0.8 $GtCO_2$ yr^{-1} over the same period. There is a discrepancy in the reported CO_2 AFOLU emissions magnitude because alternative methodological approaches that incorporate different assumptions are used. If the managed and natural responses of all land to both anthropogenic environmental change and natural climate variability, estimated to be a gross sink of -12.5 ± 3.2 $GtCO_2$ yr^{-1} for the period 2010–2019, are included with land use emisisons, then land overall, constituted a net sink of -6.6 ± 5.2 $GtCO_2$ yr^{-1} in terms of CO_2 emissions (*medium confidence*). {WGI; 7.2, 7.2.2.5, Table 7.1}

AFOLU CO_2 emission fluxes are driven by land use change. The rate of deforestation, which accounts for 45% of total AFOLU emissions, has generally declined, while global tree cover and global forest growing stock levels are likely increasing (*medium confidence*). There are substantial regional differences, with losses of carbon generally observed in tropical regions and gains in temperate and boreal regions. Agricultural CH_4 and N_2O emissions are estimated to average 157 ± 47.1 $MtCH_4$ yr^{-1} and 6.6 ± 4.0 MtN_2O yr^{-1} or 4.2 ± 1.3 and 1.8 ± 1.1 $GtCO_2$-eq yr^{-1} (using IPCC AR6 GWP_{100} values for CH_4 and N_2O) respectively between 2010 and 2019. AFOLU CH_4 emissions continue to increase (*high confidence*), the main source of which is enteric fermentation from ruminant animals (*high confidence*). Similarly, AFOLU N_2O emissions are increasing, dominated by agriculture, notably from manure application, nitrogen deposition, and nitrogen fertiliser use (*high confidence*). In addition to being a source and sink for GHG emissions, land plays an important role in climate through albedo effects, evapotranspiration and volatile organic compounds (VOCs) and their mix, although the

FOOTNOTE [1] For the AFOLU Sector, anthropogenic greenhouse gas emissions and removals by sinks are defined as all those occurring on 'managed land'. Managed land is land where human interventions and practices have been applied to perform production, ecological or social functions.

combined role in total climate forcing is unclear and varies strongly with bioclimatic region and management type. {2.4.2.5, 7.2, 7.2.1, 7.2.3, 7.3}

The AFOLU sector offers significant near-term mitigation potential at relatively low cost but cannot compensate for delayed emission reductions in other sectors. (*high evidence, medium agreement*). The AFOLU sector can provide 20–30% (interquartile range) of the global mitigation needed for a 1.5 or 2ºC pathway towards 2050 (*robust evidence, medium agreement*), though there are highly variable mitigation strategies for how AFOLU potential can be deployed for achieving climate targets. The estimated *likely* economic (< USD100 tCO_2-eq^{-1}) AFOLU sector mitigation potential is 8 to 14 $GtCO_2$-eq yr^{-1} between 2020-2050, with the bottom end of this range representing the mean from integrated assessment models (IAMs) and the upper end representing the mean estimate from global sectoral studies. The economic potential is about half of the technical potential from AFOLU, and about 30-50% could be achieved under USD20 tCO_2-eq^{-1}. The implementation of robust measurement, reporting and verification processes is paramount to improving the transparency of net-carbon-stock-changes per land unit to prevent misleading assumptions or claims on mitigation. {7.1, 7.4, 7.5}

Between 2020 and 2050, mitigation measures in forests and other natural ecosystems provide the largest share of the economic (up to USD100 tCO_2-eq^{-1}) AFOLU mitigation potential, followed by agriculture and demand-side measures (*high confidence*). In the global sectoral studies, the protection, improved management, and restoration of forests, peatlands, coastal wetlands, savannas and grasslands have the potential to reduce emissions and/or sequester 7.3 mean (3.9–13.1 range) $GtCO_2$-eq yr^{-1}. Agriculture provides the second largest share of the mitigation potential, with 4.1 (1.7–6.7) $GtCO_2$-eq yr^{-1} (up to USD100 tCO_2-eq^{-1}) from cropland and grassland soil carbon management, agroforestry, use of biochar, improved rice cultivation, and livestock and nutrient management. Demand-side measures including shifting to sustainable healthy diets, reducing food waste, and building with wood and biochemicals and bio-textiles have a mitigation potential of 2.2 (1.1–3.6) $GtCO_2$-eq yr^{-1} . Most mitigation options are available and ready to deploy. Emissions reductions can be unlocked relatively quickly, whereas CDR needs upfront investment. Sustainable intensification in agriculture, shifting diets, and reducing food waste could enhance efficiencies and reduce agricultural land needs, and are therefore critical for enabling supply-side measures such as reforestation, restoration, as well as decreasing CH_4 and N_2O emissions from agricultural production. In addition, emerging technologies (e.g., vaccines or inhibitors) have the potential to substantially increase CH_4 mitigation potential beyond current estimates. AFOLU mitigation is not only relevant in countries with large land areas. Many smaller countries and regions, particularly with wetlands, have disproportionately high levels of AFOLU mitigation potential density. {7.4, 7.5}

The economic and political feasibility of implementing AFOLU mitigation measures is hampered by persistent barriers. Assisting countries to overcome barriers will help to achieve significant short-term mitigation (*medium confidence*). Finance forms a critical barrier to achieving these gains as currently mitigation efforts rely principally on government sources and funding mechanisms which do not provide sufficient resources to enable the economic potential to be realised. Differences in cultural values, governance, accountability and institutional capacity are also important barriers. Climate change could also emerge as a barrier to AFOLU mitigation, although the IPCC WGI contribution to AR6 indicated that an increase in the capacity of natural sinks may occur, despite changes in climate (*medium confidence*). The continued loss of biodiversity makes ecosystems less resilient to climate change extremes and this may further jeopardise the achievement of the AFOLU mitigation potentials indicated in this chapter (WGII and IPBES) (*high confidence*). {WGI Figure SPM7; 7.4, 7.6}

Bioenergy and other biobased options represent an important share of the total mitigation potential. The range of recent estimates for the technical bioenergy potential when constrained by food security and environmental considerations is 5–50 and 50–250 EJ yr^{-1} by 2050 for residues and dedicated biomass production system respectively. These estimates fall within previously estimated ranges (*medium agreement*). Poorly planned deployment of biomass production and afforestation options for in-forest carbon sequestration may conflict with environmental and social dimensions of sustainability (*high confidence).* The global technical CDR potential of BECCS by 2050 (considering only the technical capture of CO_2 and storage underground) is estimated at 5.9 mean (0.5-11.3) $GtCO_2$ yr^{-1}, of which 1.6 (0.8-3.5) $GtCO_2$ yr^{-1} is available at below USD100 tCO_2^{-1} (*medium confidence*). Bioenergy and other bio-based products provide additional mitigation through the substitution of fossil fuels fossil based products (*high confidence*). These substitution effects are reported in other sectors. Wood used in construction may reduce emissions associated with steel and concrete use. The agriculture and forestry sectors can devise management approaches that enable biomass production and use for energy in conjunction with the production of food and timber, thereby reducing the conversion pressure on natural ecosystems (*medium confidence*). {7.4}

The deployment of all land-based mitigation measures can provide multiple co-benefits, but there are also risks and trade-offs from misguided or inappropriate land management (*high confidence*). Such risks can best be managed if AFOLU mitigation is pursued in response to the needs and perspectives of multiple stakeholders to achieve outcomes that maximize synergies while limiting trade-offs (*medium confidence*). The results of implementing AFOLU measures are often variable and highly context specific. Depending on local conditions (e.g., ecosystem, climate, food system, land ownership) and management strategies (e.g., scale, method), mitigation measures have the potential to positively or negatively impact biodiversity, ecosystem functioning, air quality, water availability and quality, soil productivity, rights infringements, food security, and human wellbeing. Mitigation measures addressing GHGs may also affect other climate forcers such as albedo and evapotranspiration. Integrated responses that contribute to mitigation, adaptation, and other land challenges will have greater likelihood of being successful (*high confidence*); measures which provide additional benefits to biodiversity and human well-being are sometimes described as 'Nature-based Solutions'. {7.1, 7.4, 7.6}

AFOLU mitigation measures have been well understood for decades but deployment remains slow and emissions trends indicate unsatisfactory progress despite beneficial contributions to global emissions reduction from forest-related options (*high confidence*). Globally, the AFOLU sector has so far contributed modestly to net mitigation, as past policies have delivered about 0.65 $GtCO_2$ yr^{-1} of mitigation during 2010–2019 or 1.4% of global gross emissions (*high confidence*). The majority (>80%) of emission reduction resulted from forestry measures (*high confidence*). Although the mitigation potential of AFOLU measures is large from a biophysical and ecological perspective, its feasibility is hampered by lack of institutional support, uncertainty over long-term additionality and trade-offs, weak governance, fragmented land ownership, and uncertain permanence effects. Despite these impediments to change, AFOLU mitigation options are demonstrably effective and with appropriate support can enable rapid emission reductions in most countries. {7.4, 7.6}

Concerted, rapid and sustained effort by all stakeholders, from policy makers and investors to land owners and managers is a pre-requisite to achieving high levels of mitigation in the AFOLU sector (*high confidence*). To date USD0.7 billion yr^{-1} is estimated to have been spent on AFOLU mitigation. This is well short of the more than USD400 billion yr^{-1} that is estimated to be necessary to deliver the up to 30% of global mitigation effort envisaged in deep mitigation scenarios (*medium confidence)*. This estimate of the global funding requirement is smaller than current subsidies provided to agriculture and forestry. Making this funding available would require a change in flows of money and determination of who pays. A gradual redirection of existing agriculture and forestry subsidies would greatly advance mitigation. Effective policy interventions and national (investment) plans as part of Nationally Dertermined Contributions (NDCs), specific to local circumstances and needs, are urgently needed to accelerate the deployment of AFOLU mitigation options. These interventions are effective when they include funding schemes and long-term consistent support for implementation with governments taking the initiative together with private funders and non-state actors. {7.6}

Realizing the mitigation potential of the AFOLU sector depends strongly on policies that directly address emissions and drive the deployment of land-based mitigation options, consistent with carbon prices in deep mitigation scenarios (*high confidence*). Examples of successful policies and measures include establishing and respecting tenure rights and community forestry, improved agricultural management and sustainable intensification, biodiversity conservation, payments for ecosystem services, improved forest management and wood chain usage, bioenergy, voluntary supply chain management efforts, consumer behaviour campaigns, private funding and joint regulatory efforts to avoid e.g., leakage. The efficacy of different policies, however, will depend on numerous region-specific factors. In addition to funding, these factors include governance, institutions, long-term consistent execution of measures, and the specific policy setting (*high confidence*). {7.6}

There is a discrepancy, equating to 5.5 $GtCO_2$ yr^{-1} between alternative methods of accounting for anthropogenic land CO_2 fluxes. Reconciling these methods greatly enhances the credibility of AFOLU-based emissions offsetting. It would also assist in assessing collective progress in a global stocktake (*high confidence*). The principal accounting approaches are National GHG inventories (NGHGI) and global modelling approaches. NGHGI, based on IPCC guidelines, consider a much larger area of forest to be under human management than global models. NGHGI consider the fluxes due to human-induced environmental change on this area to be anthropogenic and are thus reported. Global models[2], in contrast, consider these fluxes to be natural and are excluded from the total reported anthropogenic land CO_2 flux. To enable a like-with-like comparison, the remaining cumulative global CO_2 emissions budget can be adjusted (*medium confidence*). In the absence of these adjustments, collective progress would appear better than it is. {Cross-Chapter Box 6 in this Chapter, 7.2}

Addressing the many knowledge gaps in the development and testing of AFOLU mitigation options can rapidly advance the likelihood of achieving sustained mitigation (*high confidence*). Research priorities include improved quantification of anthropogenic and natural GHG fluxes and emissions modelling, better understanding of the impacts of climate change on the mitigation potential, permanence and additionality of estimated mitigation actions, and improved (real time & cheap) measurement, reporting and verification. There is a need to include a greater suite of mitigation measures in IAMs, informed by more realistic assessments that take into account local circumstances and socio-economic factors and cross-sector synergies and trade-offs. Finally, there is a critical need for more targeted research to develop appropriate country-level, locally specific, policy and land management response options. These options could support more specific NDCs with AFOLU measures that enable mitigation while also contributing to biodiversity conservation, ecosystem functioning, livelihoods for millions of farmers and foresters, and many other Sustainable Development Goals (SDGs) (*high confidence*). {7.7}

FOOTNOTE [2] Book keeping models and dynamic global vegetation models

7.1 Introduction

7.1.1 Key findings from previous reports

Agriculture, Forestry and Other Land Uses (AFOLU) is unique due to its capacity to mitigate climate change through greenhouse gas (GHG) emission reductions, as well as enhance removals (IPCC 2019). However, despite the attention on AFOLU since early 1990s it was reported in the SRCCL as accounting for almost a quarter of anthropogenic emission (IPCC (2019a), with three main GHGs associated with AFOLU; carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Overall emission levels had remained similar since the publication of AR4 (Nabuurs et al. 2007). The diverse nature of the sector, its linkage with wider societal, ecological and environmental aspects and the required coordination of related policy, was suggested to make implementation of known and available supply- and demand-side mitigation measures particularly challenging (IPCC 2019a). Despite such implementation barriers, the considerable mitigation potential of AFOLU as a sector on its own and its capacity to contribute to mitigation within other sectors was emphasised, with land-related measures, including bioenergy, estimated as capable of contributing between 20 and 60% of the total cumulative abatement to 2030 identified within transformation pathways (IPCC 2018). However, the vast mitigation potential from AFOLU initially portrayed in literature and in Integrated Assessment Models (IAMs), as explored in SR1.5, is being questioned in terms of feasibility (Roe et al. 2021) and a more balanced perspective on the role of land in mitigation is developing, while at the same time, interest by private investors in land-based mitigation is increasing fast.

The SRCCL (IPCC 2019a) outlined with *medium evidence* and *medium agreement* that supply-side agriculture and forestry measures had an economic (at USD100 tCO_2-eq^{-1}) mitigation potential of 7.2-10.6 $GtCO_2$-eq^{-1} in 2030 (using GWP_{100} and multiple IPCC values for CH_4 and N_2O) of which about a third was estimated as achievable at < USD20 tCO_2-eq^{-1}. Agricultural measures were reported as sensitive to carbon price, with cropland and grazing land soil organic carbon management having the greatest potential at USD20 tCO_2-eq^{-1} and restoration of organic soils at USD100 tCO_2-eq^{-1}. Forestry measures were less sensitive to carbon price, but varied regionally, with reduced deforestation, forest management and afforestation having the greatest potential depending on region. Although demand-side measures related to food could in theory make a large contribution to mitigation, in reality the contribution has been very small. Overall, the dependency of mitigation within AFOLU on a complex range of factors, from population growth, economic and technological developments, to the sustainability of mitigation measures and impacts of climate change, was suggested to make realisation highly challenging (IPCC 2019a).

Land can only be part of the solution alongside rapid emission reduction in other sectors (IPCC 2019a). It was recognised that land supports many ecosystem services on which human existence, wellbeing and livelihoods ultimately depend. Yet over-exploitation of land resources was reported as driving considerable and unprecedented rate of biodiversity loss, and wider environmental degradation (IPCC 2019a;IPBES 2019a). Urgent action to reverse this trend was deemed crucial in helping to accommodate the increasing demands on land and enhance climate change adaptation capacity. There was *high confidence* that global warming was already causing an increase in the frequency and intensity of extreme weather and climate events, impacting ecosystems, food security, disturbances and production processes, with existing (and new) carbon stocks in soils and biomass at serious risk. The impact of land cover on regional climate (through biophysical effects) was also highlighted, although there was *no confidence* regarding impacts on global climate.

Since AR5, the share of AFOLU to anthropogenic GHG emissions had remained largely unchanged at 13-21% of total GHG emissions (*medium confidence*), though uncertainty in estimates of both sources and sinks of CO_2, exacerbated by difficulties in separating natural and anthropogenic fluxes, was emphasised. Models indicated land (including the natural sink) to have *very likely* provided a net removal of CO_2 between 2007 and 2016. As in AR5, land cover change, notably deforestation, was identified as a major driver of anthropogenic CO_2 emissions whilst agriculture was a major driver of the increasing anthropogenic CH_4 and N_2O emissions.

In terms of mitigation, without reductions in overall anthropogenic emissions, increased reliance on large-scale land-based mitigation was predicted, which would add to the many already competing demands on land. However, some mitigation measures were suggested to not compete with other land uses, while also having multiple co-benefits, including adaptation capacity and potential synergies with some Sustainable Development Goals (SDGs). As in AR5, there was large uncertainty surrounding mitigation within AFOLU, in part because current carbon stocks and fluxes are unclear and subject to temporal variability. Additionally, the non-additive nature of individual measures that are often inter-linked and the highly context specific applicability of measures, causes further uncertainty. Many AFOLU measures were considered well-established and some achievable at low to moderate cost, yet contrasting economic drivers, insufficient policy, lack of incentivisation and institutional support to stimulate implementation among the many stakeholders involved, in regionally diverse contexts, was recognised as hampering realisation of potential.

None the less, the importance of mitigation within AFOLU was highlighted in all IPCC reports, with modelled scenarios demonstrating the considerable potential role and land-based mitigation forming an important component of pledged mitigation in Nationally Determined Contributions (NDCs) under the Paris Agreement. The sector was identified as the only one in which large-scale Carbon Dioxide Removal (CDR) may currently and at short term be possible (e.g. through afforestation/reforestation or soil organic carbon management). This CDR component was deemed crucial to limit climate change and its impacts, which would otherwise lead to enhanced release of carbon from land. However, the SRCCL emphasised that mitigation cannot be pursued in isolation. The need for integrated response options, that mitigate and adapt to climate change, but also deal with land degradation and desertification, while enhancing food and fibre security, biodiversity and contributing to other SDGs has been made clear (IPCC 2019a; Díaz et al. 2019; IPBES-IPCC 2021).

7.1.2 Boundaries, scope and changing context of the current report

This chapter assesses GHG fluxes between land and the atmosphere due to AFOLU, the associated drivers behind these fluxes, mitigation response options and related policy, at time scales of 2030 and 2050. Land and its management has important links with other sectors and therefore associated chapters within this report, notably concerning the provision of food, feed, fuel or fibre for human consumption and societal wellbeing (Chapter 5), for bioenergy (Chapter 6), the built environment (Chapter 9), transport (Chapter 10) and industry (Chapter 11). Mitigation within these sectors may in part, be dependent on contributions from land and the AFOLU sector, with interactions between all sectors discussed in Chapter 12. This chapter also has important links with IPCC WGII regarding climate change impacts and adaptation. Linkages are illustrated in Figure 7.1.

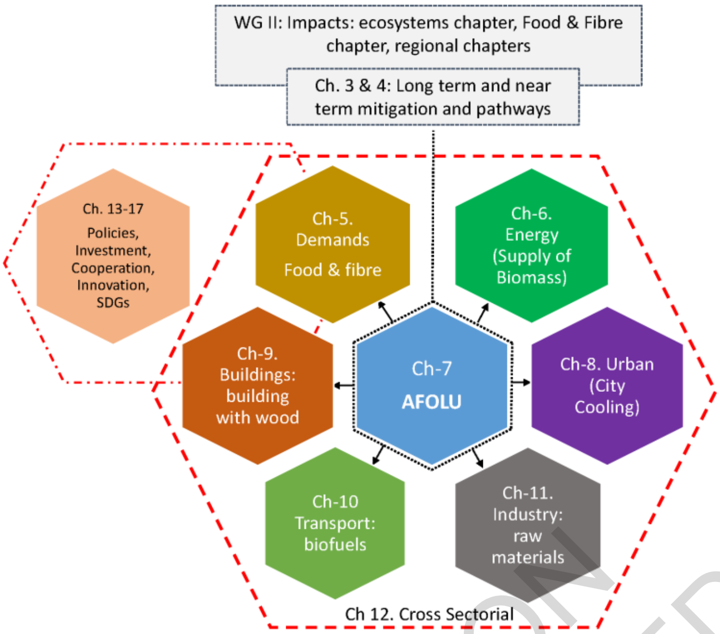

Figure 7.1 Linkage between Chapter 7 and other chapters within this report as well as to WGII. Mitigation potential estimates in this chapter consider potential emission reductions and removals only within the AFOLU sector itself, and not the substitution effects from biomass and biobased products in sectors such as Energy, Transport, Industry, Buildings, nor biophysical effects of e.g. cooling of cities. These are covered in their respective chapters.

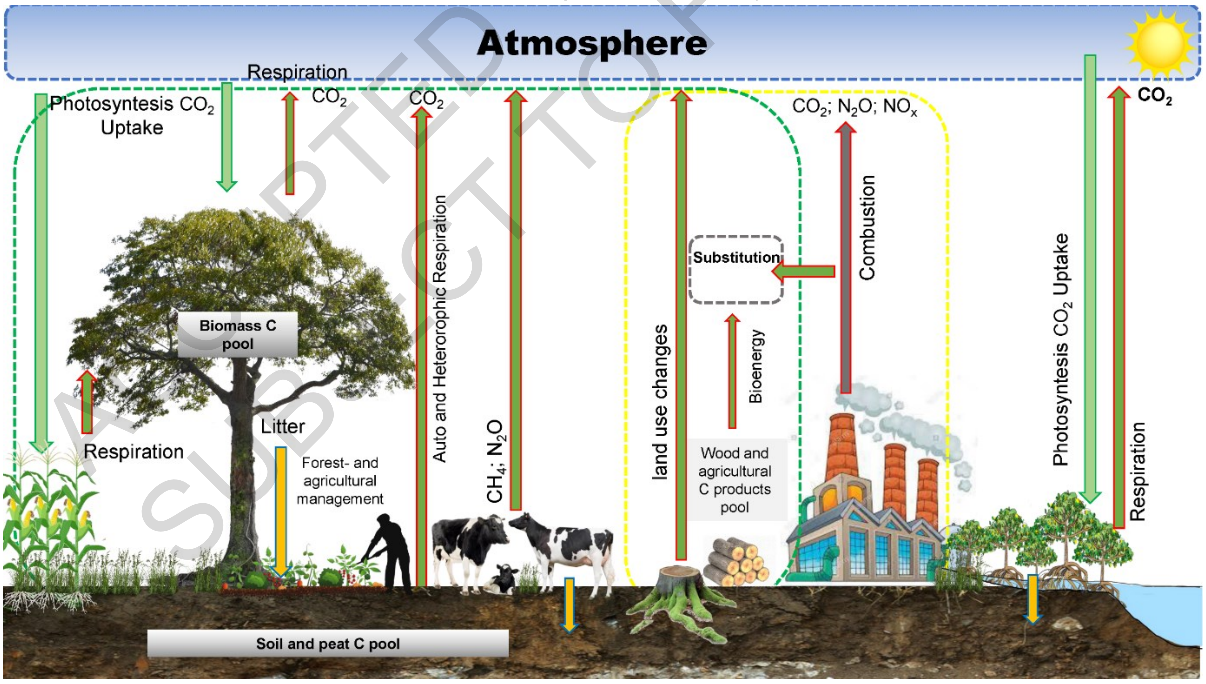

Figure 7.2 Summarised representation of interactions between land management, its products in terms of food and fibre, and land - atmospheric GHG fluxes. For legibility reasons only a few of the processes and management measures are depicted.

As highlighted in both AR5 and the SRCCL, there is a complex interplay between land management and GHG fluxes as illustrated in Figure 7.2, with considerable variation in management regionally, as a result of geophysical, climatic, ecological, economic, technological, institutional and socio-cultural diversity. The capacity for land-based mitigation varies accordingly. The principal focus of this chapter is therefore, on evaluating regional land-based mitigation potential, identifying applicable AFOLU mitigation measures, estimating associated costs and exploring policy options that could enable implementation.

Mitigation measures are broadly categorised as those relating to (1) forests and other ecosystems (2) agriculture (3) biomass production for products and bioenergy and (4) demand-side levers. Assessment is made in the context that land-mitigation is expected to contribute roughly 25% of the 2030 mitigation pledged in Nationally Determined Contributions (NDCs) under the Paris Agreement (Grassi et al. 2017), yet very few countries have provided details on how this will be achieved. In light of AR5 and the SRCCL findings, that indicate large land-based mitigation potential, considerable challenges to its realisation, but also a clear nexus at which humankind finds itself, whereby current land management, driven by population growth and consumption patterns, is undermining the very capacity of land, a finite resource, to support wider critical functions and services on which humankind depends. Mitigation within AFOLU is occasionally and wrongly perceived as an opportunity for in-action within other sectors. AFOLU simply cannot compensate for mitigation shortfalls in other sectors. As the outcomes of many critical challenges (UN Environment 2019), including biodiversity loss (Díaz et al. 2019) and soil degradation (FAO and ITPS 2015), are inextricably linked with how we manage land, the evaluation and assessment of AFOLU is crucial. This chapter aims to address three core topics;

1. What is the latest estimated (economic) mitigation potential of AFOLU measures according to both sectoral studies and integrated assessment models, and how much of this may be realistic within each global region?
2. How do we realise the mitigation potential, while minimising trade-offs and risks and maximising co-benefits that can enhance food and fibre security, conserve biodiversity and address other land challenges?
3. How effective have policies been so far and what additional policies or incentives might enable realisation of mitigation potential and at what costs?

This chapter first outlines the latest trends in AFOLU fluxes and the methodology supporting their estimation (Section 7.2). Direct and indirect drivers behind emission trends are discussed in Section 7.3. Mitigation measures, their costs, co-benefits, trade-offs, estimated regional potential and contribution within integrated global mitigation scenarios, is presented in Sections 7.4 and 7.5 respectively. Assessment of associated policy responses and links with SDGs are explored in Section 7.6. The chapter concludes with gaps in knowledge (Section 7.7) and frequently asked questions.

7.2 Historical and current trends in GHG emission and removals; their uncertainties and implications for assessing collective climate progress

The biosphere on land and in wetlands is a source and sink of CO_2 and CH_4, and a source of N_2O due to both natural and anthropogenic processes that happen simultaneously and are therefore difficult to disentangle (IPCC 2010; Angelo and Du Plesis 2017; IPCC 2019a). AFOLU is the only GHG sector to currently include anthropogenic sinks. A range of methodological approaches and data have been applied to estimating AFOLU emissions and removals, each developed for their own purposes, with estimates varying accordingly. Since the SRCCL (Jia et al. 2019), emissions estimates have been updated (Sections 7.2.2 and 7.2.3), while the assessment of biophysical processes and short-lived climate forcers (Section 7.2.4) is largely unchanged. Further progress has been made on the implications of differences in AFOLU emissions estimates for assessing collective climate progress (Section 7.2.2.2, Cross-Chapter Box 6 in this Chapter).

7.2.1 Total net GHG flux from AFOLU

National Greenhouse Gas Inventory (NGHGI) reporting following the IPCC 1996 guidelines (IPCC 1996), separates the total anthropogenic AFOLU flux into: (i) net anthropogenic flux from Land Use, Land-Use Change, and Forestry (LULUCF) due to both change in land cover and land management; and (ii) the net flux from Agriculture. While fluxes of CO_2 (Section 7.2.2) are predominantly from LULUCF and fluxes of CH_4 and N_2O (Section 7.2.3) are predominantly from agriculture, fluxes of all three gases are associated with both sub-sectors. However, not all methods separate them consistently according to these sub-sectors, thus here we use the term AFOLU, separate by gas and implicitly include CO_2 emissions that stem from the agriculture part of AFOLU, though these account for a relatively small portion.

Table 7.1 Net anthropogenic emissions (annual averages for 2010–2019[a]) from Agriculture, Forestry and Other Land Use (AFOLU). For context, the net flux due to the natural response of land to climate and environmental change is also shown for CO_2 in column E. Positive values represent emissions, negative values represent removals.

Anthropogenic						Natural Response	Natural + Anthropogenic
Gas	Units	AFOLU Net anthropogenic emissions [h]	Non-AFOLU anthropogenic GHG emissions [d, f]	Total net anthropogenic emissions (AFOLU + non-AFOLU) by gas	AFOLU as a % of total net anthropogenic emissions by gas	Natural land sinks including natural response of land to anthropogenic environmental change and climate variability [e]	Net-land atmosphere CO_2 flux (i.e. anthropogenic AFOLU + natural fluxes across entire land surface
		A	B	C = A+B	D = (A/C) *100	E	F=A+E
CO_2							
	$GtCO_2$-eq yr^{-1}	5.9 ± 4.1 [b, f] (bookkeeping models only). 0 to 0.8 (NGHGI/ FAOSTAT data)	36.2 ± 2.9	42.0 ± 29.0	14%	**-12.5 ± 3.2**	**-6.6 ± 4.6**
CH_4	$MtCH_4$ yr^{-1}	157.0 ± 47.1 [c]	207.5 ± 62.2	364.4 ± 109.3		- [i]	
	$GtCO_2$-eq yr^{-1}	4.2 ± 1.3 [g]	5.9 ± 1.8	10.2 ± 3.0	41%		
N_2O	MtN_2O yr^{-1}	6.6 ± 4.0 [c]	2.8 ± 1.7	9.4 ± 5.6			
	$GtCO_2$-eq yr^{-1}	1.8 ± 1.1 [g]	0.8 ± 0.5	2.6 ± 1.5	69%		
Total [j]	$GtCO_2$-eq yr^{-1}	11.9 ± 4.4 (CO_2 component considers bookkeeping models only)	44 ± 3.4	55.9 ± 6.1	21%		

[a] Estimates are given until 2019 as this is the latest date when data are available for all gases, consistent with Chapter 2, this report. Positive fluxes are emission from land to the atmosphere. Negative fluxes are removals.

[b] Net anthropogenic flux of CO_2 are due to land-use change such as deforestation and afforestation and land management, including wood harvest and regrowth, peatland drainage and fires, cropland and grassland management. Average of three bookkeeping models (Hansis et al. 2015; Houghton and Nassikas 2017; Gasser et al. 2020), complemented by data on peatland drainage and fires from FAOSTAT (Prosperi et al. 2020) and

GFED4s (Van Der Werf et al. 2017). This number is used for consistency with WGI and Chapter 2, this report. Comparisons with other estimates are discussed in 7.2.2. Based on NGHGIs and FAOSTAT, the range is 0 to 0.8 Gt CO_2 yr^{-1}.

[c] CH_4 and N_2O emission estimates and assessed uncertainty of 30 and 60% respectively, are based on EDGAR data (Crippa et al. 2021) in accordance with Chapter 2, this report (Sections 2.2.1.3 and 2.2.1.4). Both FAOSTAT (FAO 2021a; Tubiello 2019; USEPA 2019) and the USA EPA (USEPA 2019) also provide data on agricultural non-CO_2 emissions, however mean global CH_4 and N_2O values considering the three databases are within the uncertainty bounds of EDGAR. EDGAR only considers agricultural and not overall AFOLU non-CO_2 emissions. Agriculture is estimated to account for approximately 89 and 96% of total AFOLU CH_4 and N_2O emissions respectively. See Section 7.2.3 for further discussion.

[d] Total non-AFOLU emissions are the sum of total CO_2-eq emissions values for energy, industrial sources, waste and other emissions with data from the Global Carbon Project for CO_2, including international aviation and shipping, and from the PRIMAP database for CH_4 and N_2O averaged over 2007-2014, as that was the period for which data were available.

[e] The modelled CO_2 estimates include natural processes in vegetation and soils and how they respond to both natural climate variability and to human-induced environmental changes i.e. the response of vegetation and soils to environmental changes such as increasing atmospheric CO_2 concentration, nitrogen deposition, and climate change (indirect anthropogenic effects) on both managed and unmanaged lands. The estimate shown represents the average from 17 Dynamic Global Vegetation Models with 1SD uncertainty (Friedlingstein et al. 2020)

[f] The NGHGIs take a different approach to calculating "anthropogenic" CO_2 fluxes than the models (Section 7.2.2). In particular the sinks due to environmental change (indirect anthropogenic fluxes) on managed lands are generally treated as anthropogenic in NGHGIs and non-anthropogenic in models such as bookkeeping and IAMs. A reconciliation of the results between IAMs and NGHGIs is presented in Cross-Chapter Box 6 in this Chapter. If applied to this table, it would transfer approximately -5.5 $GtCO^2$ y^{-1}(a sink) from Column E (which would become --7.2 $GtCO_2$ yr^{-1}) to Column A (which would then be 0.4 $GtCO_2$ yr^{-1}).

[g] All values expressed in units of CO_2-eq are based on IPCC AR6 100-year Global Warming Potential (GWP_{100}) values with climate-carbon feedbacks (CH_4 = 27, N_2O = 273) (Chapter 2, Supplementary Material SM2.3 and IPCC WGI AR6 Section 7.6).

[h] For assessment of cross-sector fluxes related to the food sector, see Chapter 12, this report.

[i] While it is acknowledged that soils are a natural CH_4 sink (Jackson et al. 2020) with soil microbial removals estimated to be 30 ± 19 $MtCH_4$ yr^{-1} for the period 2008-2017 (according to bottom-up estimates), natural CH_4 sources are considerably greater (371 (245-488) $MtCH_4$ yr^{-1}) resulting in natural processes being a net CH_4 source (IPCC WGI AR6 Section 5.2.2). The soil CH_4 sink is therefore omitted from Column E.

[j] Total GHG emissions concerning non-AFOLU sectors and all sectors combined (Columns B and C) include fluorinated gases in addition to CO_2, CH_4 and N_2O. Therefore, total values do not equal the sum of estimates for CO_2, CH_4 and N_2O.

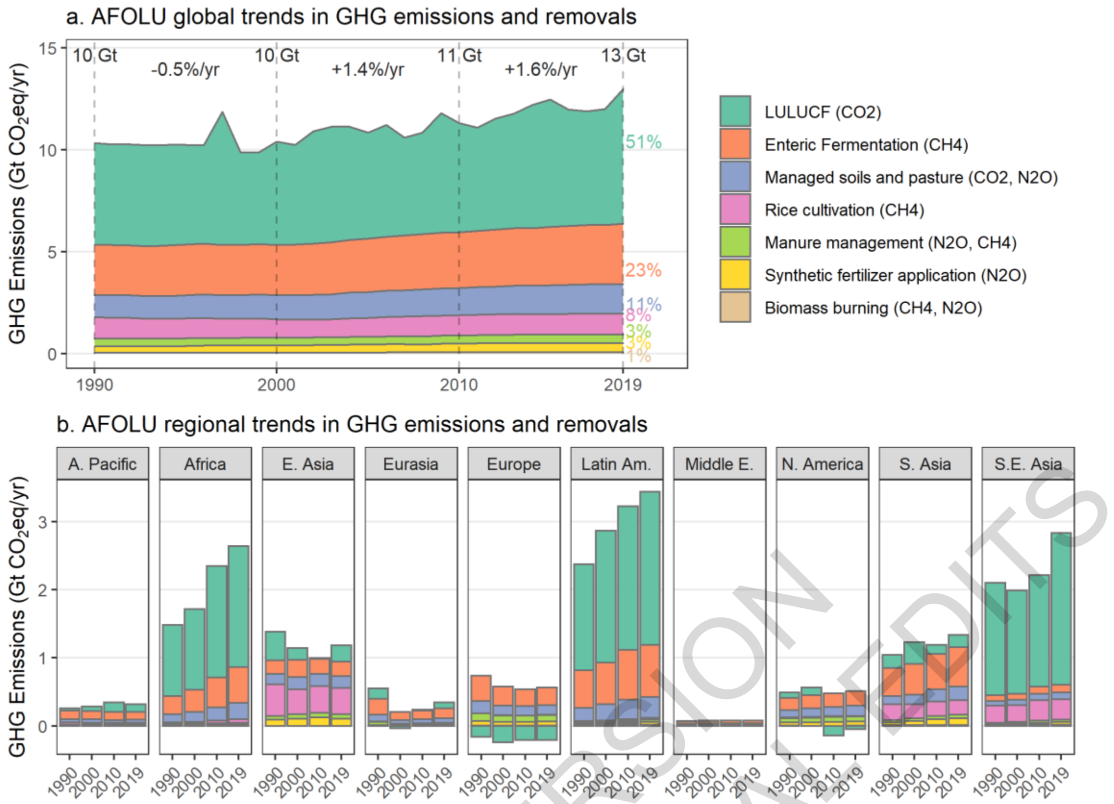

Figure 7.3 Subdivision of the total AFOLU emissions from Table 7.1 by activity and gas for the period 1990 to 2019. Positive values are emissions from land to atmosphere, negative values are removals. Panel A shows emissions divided into major activity and gases. Note that 'biomass burning' is only the burning of agriculture residues in the fields. The indicated growth rates between 1990-2000, 2000-2010, 2010-2019 are annualised across each time period. Panel B illustrates regional emissions in the years 1990, 2000, 2010, 2019 AFOLU CO_2 (green shading) represents all AFOLU CO_2 emissions. It is the mean from three bookkeeping models (Hansis et al. 2015; Houghton and Nassikas 2017; Gasser et al. 2020) as presented in the Global Carbon Budget (Friedlingstein et al. 2020) and is <u>not directly comparable to LULUCF in NGHGIs (Section 7.2.2).</u> Data onCH_4 and N_2O emissions are from the EDGAR database (Crippa et al. 2021). See Sections 7.2.2 and 7.2.3 for comparison of different datasets. All values expressed are asCO_2-eq with GWP_{100} values: CH_4 = 27, N_2O = 273.

Total global net anthropogenic GHG emissions from AFOLU were 11.9 ± 4.4 GtCO2-eq yr^{-1} on average over the period 2010-2019, around 21% of total global net anthropogenic GHG emissions (Table 7.1, Figure 7.3, using the sum of bookkeeping models for the CO_2 component). When using FAOSTAT/NGHGIs CO_2 flux data, then the contribution of AFOLU to total emissions amounts to 13% of global emissions.

This AFOLU flux is the net of anthropogenic emissions of CO_2, CH_4 and N_2O, and anthropogenic removals of CO_2. The contribution of AFOLU to total emissions varies regionally with highest in Latin America and Caribbean with 58% an lowest in Europe and North America with each 7% (Chapter 2, Section 2.2.3). There is a discrepancy in the reported CO_2 AFOLU emissions magnitude because alternative methodlogical approaches that incorporate different assumptions are used (see 7.2.2.2). While there is *low agreement* in the trend of global AFOLU CO_2 emissions over the past few decades (7.2.2), they have remained relatively constant (*medium confidence*) (Chapter 2). Average non-CO_2 emission (aggregated using GWP_{100} IPCC AR6 values) from agriculture have risen from 5.2 ± 1.4 $GtCO_2$-eq yr^{-1} for the period 1990 to 1999, to 6.0 ± 1.7 $GtCO_2$-eq yr^{-1} for the period 2010 to 2019 (Crippa et al. 2021), Section 7.2.3).

To present a fuller understanding of land-atmosphere interactions, Table 7.1 includes an estimate of the natural sink of land to atmospheric CO_2 (IPCC WGI Chapter 5 and (Jia et al. 2019). Land fluxes respond naturally to human-induced environmental change (e.g. climate change, and the fertilising effects of increased atmospheric CO_2 concentration and nitrogen deposition), known as “indirect anthropogenic effects”, and also to “natural effects” such as climate variability (IPCC 2010) (Table 7.1, Section 7.2.2). This showed a removal of -12.5 ± 3.2 $GtCO_2$ yr^{-1} (*medium confidence*) from the atmosphere during 2010-2019 according to global DGVM models (Friedlingstein et al. 2020) 31% of total anthropogenic net emissions of CO_2 from all sectors. It is likely that the NGHIs and FAOSTAT implicitly cover some part of this sink and thus provide a net CO_2 AFOLU balance with some 5 $GtCO_2$ lower net emissions than according to bookkeeping models, with the overall net CO_2 value close to being neutral. Model results and atmospheric observations concur that, when combining both anthropogenic (AFOLU) and natural processes on the entire land surface (the total “land-atmosphere flux”), the land was a global net sink for CO_2 of -6.6 ± 4.6 $GtCO_2$ yr^{-1} with a range for 2010 to 2019 from -4.4 to -8.4 $GtCO_2$ yr^{-1}. (Van Der Laan-Luijkx et al. 2017; Rödenbeck et al. 2003, 2018; Chevallier et al. 2005; Feng et al. 2016; Niwa et al. 2017; Patra et al. 2018). The natural land sink is *highly likely* to be affected by both future AFOLU activity and climate change (IPCC WGI Box 5.1 and IPCC WGI SPM Figure 7), whereby under more severe climate change, the amount of carbon stored on land would still increase although the relative share of the emissions that land takes up, declines.

7.2.2 Flux of CO_2 from AFOLU, and the non-anthropogenic land sink

7.2.2.1 Global net AFOLU CO_2 flux

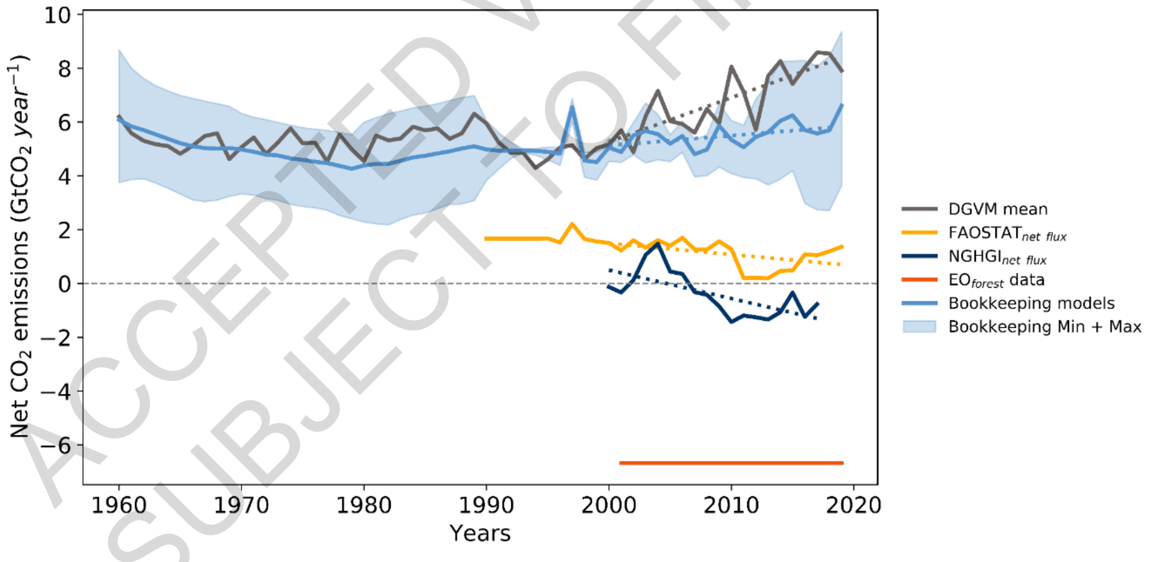

Figure 7.4 Global net CO_2 flux due to AFOLU estimated using different methods for the period 1960 to 2019 ($GtCO_2$ yr^{-1}). Positive numbers represent emissions. (Grey line) The mean from 17 DGVMs all using the same driving data under TrendyV9 used within the Global Carbon Budget 2020 and including different degrees of management (Bastos et al. 2020; Friedlingstein et al. 2020). (Orange line) Data downloaded 6th June 2021 from FAOSTAT (FAO 2021b; http://www.fao.org/faostat/) comprising: net emissions from (i) forest land converted to other land, (ii) net emissions from organic soils in cropland, grassland and from biomass burning (including peat fires and peat draining (Prosperi et al. 2020) and (iii) net emissions from forest land remaining forest land, which includes managed forest lands (Tubiello et al. 2020). (Dark blue line) Net flux estimate from National Greenhouse Gas Inventories (NGHGI) based on

country reports to the UNFCCC for LULUCF (Grassi et al. 2021) which include land-use change, and flux in managed lands. (Red (EO) line) The 2001 – 2019 average net CO_2 flux from non-intact forest-related emissions and removals based on ground and Earth Observation data (EO) (Harris et al. 2021). Data to mask non-intact forest were used in the tropics (Turubanova et al. 2018) and extra-tropics (Potapov et al. 2017).

Light blue line: the mean estimate and minimum and maximum (blue shading) from three bookkeeping models (Hansis et al. 2015; Houghton and Nassikas 2017; Gasser et al. 2020). These include land cover change (e.g. deforestation, afforestation), forest management including wood harvest and land degradation, shifting cultivation, regrowth of forests following wood harvest or abandonment of agriculture, grassland management, agricultural management. Emissions from peat burning and draining are added from external data sets (see text). Both the DGVM and Bookkeeping global data is available at: https://www.icos-cp.eu/science-and-impact/global-carbon-budget/2020 (Accessed on 04/010/2021). Data consistent with IPCC WGI Chapter 5. Dotted lines denote the linear regression from 2000 to 2019. Trends are statistically significant ($P < 0.05$) with exception for the NGHGI trend ($P < 0.01$).

Comparison of estimates of the global net AFOLU flux of CO_2 from diverse approaches (Figure 7.4) show differences on the order of several $GtCO_2$ yr^{-1}. When considering the reasons for the differences, and an approach to reconcile them (Section 7.2.2.3; Grassi et al. 2021), there is *medium confidence* in the magnitude of the net AFOLU CO_2 flux. There is a discrepancy in the reported CO_2 AFOLU emissions magnitude because alternative methodological approaches that incorporate different assumptions are used (see 7.2.2.2). While the mean of the bookkeeping and DGVM model's show a small increase in global CO_2 net emissions since year 2000, individual models suggest opposite trends (Friedlingstein et al. 2020). The latest FAOSTAT and NGHGI estimates show a small reduction in net emission. Overall, the trends are unclear.

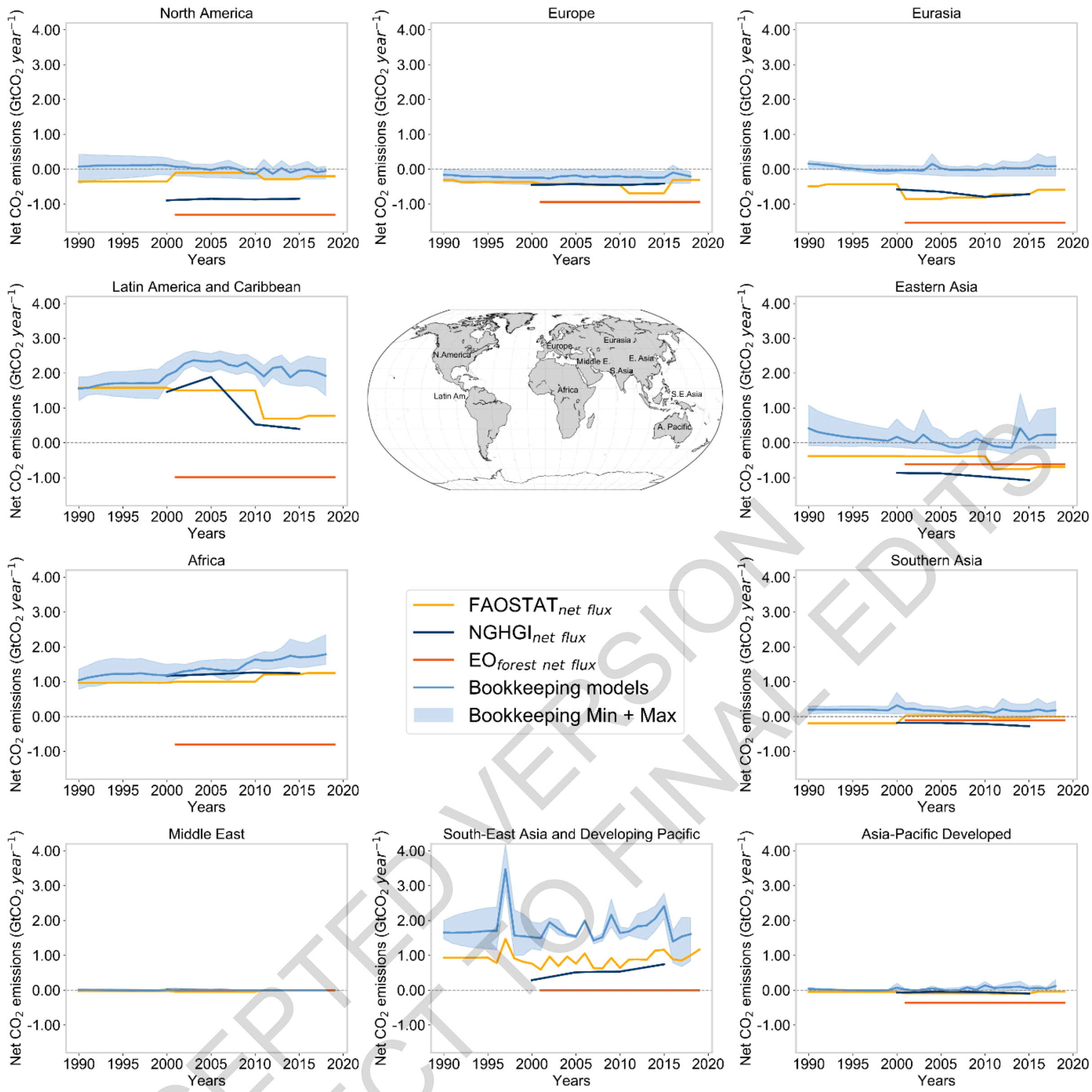

Figure 7.5 Regional net flux of CO_2 due to AFOLU estimated using different methods for the period 1990-2019 ($GtCO_2$ yr^{-1}). Positive numbers represent emissions. The upper-central panel depicts the world map shaded according to the IPCC AR6 regions corresponding to the individual graphs. For each regional panel; (Orange line) Total net flux data from FAOSTAT (Tubiello et al. 2020), (Dark blue line) Net emissions estimates from National Greenhouse Gas Inventories based on country reports to the UNFCCC for LULUCF (Grassi et al. 2021), (Light blue line) The mean estimate and minimum and maximum (blue shading) from three bookkeeping models. (Hansis et al. 2015; Houghton and Nassikas 2017; Gasser et al. 2020). Regional estimates from bookkeeping models are available at: https://zenodo.org/record/5548333#.YVwJB2LMJPY (Minx et al. 2021). See the legend in Figure 7.4 for a detailed explanation of flux components for each dataset.

Regionally (Figure 7.5), there is *high confidence* of net emissions linked to deforestation in Latin America, Africa and South-East Asia from 1990 to 2019. There is *medium confidence* in trends indicating a decrease in net emissions in Latin America since 2005 linked to reduced gross deforestation emissions, and a small increase in net emissions related to increased gross deforestation emissions in

Africa since 2000 (Figure 7.5). There is *high confidence* regarding the net AFOLU CO_2 sink in Europe due to forest regrowth and known other sinks in managed forests, and *medium confidence* of a net sink in North America and Eurasia since 2010.

7.2.2.2 Why do various methods deliver difference in results?

The processes responsible for fluxes from land have been divided into three categories (IPCC 2006, 2010): (1) the *direct human-induced effects* due to changing land cover and land management; (2) the *indirect human-induced effects* due to anthropogenic environmental change, such as climate change, CO_2 fertilisation, nitrogen deposition, etc.; and (3) *natural effects,* including climate variability and a background natural disturbance regime (e.g. wildfires, windthrows, diseases or insect outbreaks).

Global models estimate the anthropogenic land CO_2 flux considering only the impact of direct effects, and only those areas that were subject to intense and direct management such as clear-cut harvest. It is important to note, that DGVMs also estimate the non-anthropogenic land CO_2 flux (Land Sink) that results from indirect and natural effects (Table 7.1). In contrast, estimates of the anthropogenic land CO_2 flux in NGHGIs (LULUCF) include the impact of direct effects and, in most cases, of indirect effects on a much greater area considered "managed" than global models (Grassi et al. 2021).

The approach used by countries follows the IPCC methodological guidance for NGHGIs (IPCC 2006, 2019a). Since separating direct, indirect and natural effects on the land CO_2 sink is impossible with direct observation such as national forest inventories (IPCC 2010), upon which most NGHGIs are based, the IPCC adopted the 'managed land' concept as a pragmatic proxy to facilitate NGHGI reporting. Anthropogenic land GHG fluxes (direct and indirect effects) are defined as all those occurring on managed land, that is, where human interventions and practices have been applied to perform production, ecological or social functions (IPCC 2006, 2019a). GHG fluxes from unmanaged land are not reported in NGHGIs because they are assumed to be non-anthropogenic. Countries report NGHGI data with a range of methodologies, resolution and completeness, dependent on capacity and available data, consistent with IPCC guidelines (IPCC 2006, 2019a) and subject to an international review or assessment processes.

The FAOSTAT approach is conceptually similar to NGHGIs. FAOSTAT data on forests are based on country reports to FAO-FRA 2020 (FAO 2020a), and include changes in biomass carbon stock in "forest land" and "net forest conversions" in five-year intervals. "Forest land" may include unmanaged natural forest, leading to possible overall overestimation of anthropogenic fluxes for both sources and sinks, though emissions from deforestation are likely underestimated (Tubiello et al. 2020). FAOSTAT also estimate emissions from forest fires and other land uses (organic soils), following IPCC methods (Prosperi et al. 2020). The FAO-FRA 2020 (FAO 2020b) update leads to estimates of larger sinks in Russia since 1991, and in China and the USA from 2011, and larger deforestation emissions in Brazil and smaller in Indonesia than FRA 2015 (FAO 2015;Tubiello et al. 2020).

The bookkeeping models by Houghton and Nassikas (2017), Hansis et al. (2015), and Gasser et al. (2020) and the DGVMs used in the Global Carbon Budget (Friedlingstein et al. 2020) use either the LUH2 data set (Hurtt et al. 2020) HYDE (Goldewijk et al. 2017) FRA 2015 (FAO 2015) or a combination. The LUH2 dataset includes a new wood harvest reconstruction, new representation of shifting cultivation, crop rotations, and management information including irrigation and fertilizer application. The area of forest subject to harvest in LUH2 is much less than the area of forest considered "managed" in the NGHGIs (Grassi et al. 2018). The model datasets do not yet include the FAO FRA 2020 update (FAO 2020a). The DGVMs consider CO_2 fertilization effects on forest growth that are sometimes confirmed from the groundbased forest inventory networks (Nabuurs et al. 2013) and sometimes not at all (van der Sleen et al. 2015).

Further, the DGVMs and bookkeeping models do not include a wide range of practices which are implicitly covered by the inventories; for example: forest dynamics (Pugh et al. 2019; Le Noë et al. 2020) forest management including wood harvest (Nabuurs, et al. 2013; Arneth et al. 2017) agricultural and grassland practices (Pugh et al. 2015; Sanderman et al. 2017; Pongratz et al. 2018); or e.g. fire management (Andela et al. 2017; Arora and Melton 2018).

Increasingly higher emissions estimates are expected from DGVMs compared to bookkeeping models, because DGVMs include a loss of additional sink capacity of 3.3 ± 1.1 $GtCO_2$ yr^{-1} on average over 2009-2018, which is increasing with larger climate and CO_2 impacts (Friedlingstein et al. 2020). This arises because the DGVM methodological setup requires a reference simulation including climate and environmental changes but without any land use change such as deforestation, so DGVMs implicitly include the sink capacity forests would have developed in response to environmental changes on areas that in reality have been cleared (Gitz and Ciais 2003; Pongratz et al. 2014)(IPCC WGI Chapter 5).

Carbon emissions from peat burning have been estimated based on the Global Fire Emission Database (GFED4s; Van Der Werf et al. 2017). These were included in the bookkeeping model estimates and added 2.0 Gt Carbon over 1960-2019 (e.g. causing the peak in South-East Asia in 1998, Figure 7.5). Within the Global Carbon Budget (Friedlingstein et al. 2020), peat drainage from agriculture accounted for an additional 8.6 Gt Carbon from 1960-2019 according to FAOSTAT (Conchedda and Tubiello, 2020) used by two of the bookkeeping models, (Hansis et al. 2015; Gasser et al. 2020).

Remote-sensing products provide valuable spatial and temporal land-use and biomass data globally (including in remote areas), at potentially high spatial and temporal resolutions, that can be used to calculate CO_2 fluxes, but have mostly been applied only to forests at the global or even regional scale. While such data can strongly support monitoring reporting and verification, estimates of forest carbon fluxes directly from Earth Observation (EO) data vary considerably in both their magnitude and sign (i.e. whether forests are a net source or sink of carbon). For the period 2005 – 2017, net tropical forest carbon fluxes were estimated as -0.4 $GtCO_2$ yr^{-1} (Fan et al. 2019); 0.58 $GtCO_2$ yr^{-1} (Grace et al. 2014); 1.6 $GtCO_2 yr^{-1}$ (Baccini et al. 2017) and 2.87 $GtCO_2$ yr^{-1} (Achard et al. 2014). Differences can in part be explained by spatial resolution of the data sets, the definition of "forest" and the inclusion of processes and methods used to determine degradation and growth in intact and secondary forests, or the changes in algorithm over time (Palahí et al. 2021). A recent global study integrated ground observations and remote sensing data to map forest-related GHG emissions and removals at a high spatial resolution (30m spatial scale), although it only provides an average estimate of annual carbon loss over 2001–2019 (Harris et al. 2021). The estimated net global forest carbon sink globally was -7.66 $GtCO_2$ yr^{-1}, being -1.7 $GtCO_2 yr^{-1}$ in the tropics only.

Remote sensing products can help to attribute changes to anthropogenic activity or natural inter-annual climate variability (Fan et al. 2019; Wigneron et al. 2020). Products with higher spatial resolution make it easier to determine forest and carbon dynamics in relatively small-sized managed forests (e.g. Wang et al. 2020; Heinrich et al. 2021; Reiche et al. 2021). For example secondary forest regrowth in the Brazilian Amazon offset 9 to 14% of gross emissions due to deforestation [1] (Silva Junior et al. 2021; Aragão et al. 2018). Yet disturbances such as fire and repeated deforestation cycles due to shifting cultivation over the period 1985 to 2017, were found to reduce the regrowth rates of secondary forests by 8 to 55% depending on the climate region of regrowth (Heinrich et al. 2021).

7.2.2.3 Implications of differences in AFOLU CO_2 fluxes between global models and National Greenhouse Gas Inventories (NGHGIs), and reconciliation

There is about 5.5 $GtCO_2\ yr^{-1}$ difference in the anthropogenic AFOLU estimates between NGHGIs and global models (this number relates to an IAMs comparison for the period 2005-2015 - see Cross-Chapter Box 6 in this Chapter; for comparison with other models see Figure 7.4). Reconciling the differences i.e. making estimates comparable, can build confidence in land-related CO_2 estimates, for example for the purpose of assessing collective progress in the context of the Global Stocktake (Cross-Chapter Box 6 in this Chapter). The difference largely results from greater estimated CO_2 in NGHGIs, mostly occurring in forests (Grassi et al. 2021). This difference is potentially a consequence of: (i) simplified and/or incomplete representation of management in global models (Popp et al. 2017; Pongratz et al. 2018), e.g. concerning impacts of forest management in biomass expansion and thickening (Nabuurs et al. 2013; Grassi et al. 2017) (ii) inaccurate and/or incomplete estimation of LULUCF fluxes in NGHGIs (Grassi et al. 2017), especially in developing countries, primarily in non-forest land uses and in soils, and (iii) conceptual differences in how global models and NGHGIs define 'anthropogenic' CO_2 flux from land (Grassi et al. 2018). The impacts of (i) and (ii) are difficult to quantify and result in uncertainties that will decrease slowly over time through improvements of both models and NGHGIs. By contrast, the inconsistencies in (iii) and its resulting biases were assessed as explained below.

Since changing the NGHGIs' approach is impractical, an interim method to translate and adjust the output of global models was outlined for reconciling a bookkeeping model and NGHGIs (Grassi et al. 2018). More recently, an improved version of this approach has been applied to the future mitigation pathways estimated by IAMs (Grassi et al. 2021), with the implications for the Global Stocktake discussed in Cross-Chapter Box 6 in this Chapter. This method implies a post-processing of current global models' results that addresses two components of the conceptual differences in the "anthropogenic" CO_2 flux; (i) how the impact of human-induced environmental changes (indirect effects) are considered, and (ii) the extent of forest area considered 'managed'. Essentially, this approach adds DGVM estimates of CO_2 fluxes due to indirect effects from countries' managed forest area (using non-intact forest area maps as a proxy) to the original global models' anthropogenic land CO_2 fluxes (Figure 7.6).

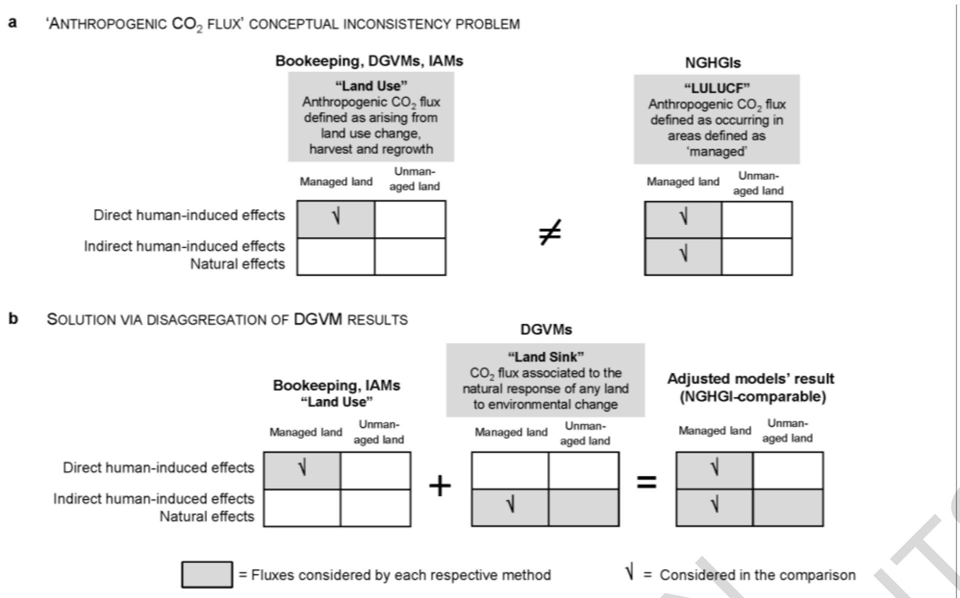

Figure 7.6 Main conceptual differences between global models (bookkeeping models, IAMs and DGVMs) and NGHGIs definitions of what is considered the 'anthropogenic' land CO_2 flux, and proposed solution (from Grassi et al. 2021). (Panel a) Differences in defining the anthropogenic land CO_2 flux by global models ('Land Use') and NGHGIs ('LULUCF'), including the attribution of processes responsible for land fluxes (IPCC 2006; 2010) in managed and unmanaged lands. The anthropogenic land CO_2 flux by global models typically includes only the CO_2 flux due to 'direct effects' (land-use change, harvest, regrowth). By contrast, most NGHGIs consider anthropogenic all fluxes occurring in areas defined as 'managed', including also the sink due to 'indirect effects' (climate change, atmospheric CO_2 increase, N deposition etc.) and due to 'natural effects' (climate variability, background natural disturbances). (Panel b) Proposed solution to the inconsistency, via disaggregation of the 'Land Sink' flux from DGVMs into CO_2 fluxes occurring in managed and in unmanaged lands. The sum of 'Land Use' flux (direct effects from bookkeeping models or IAMs) and the 'Land Sink' (indirect effects from DGVMs) in managed lands produces an adjusted global model CO_2 flux which is conceptually more comparable with LULUCF fluxes from NGHGIs. Note that the figure may in some cases be an oversimplification, e.g. not all NGHGIs include all recent indirect effects.

START CROSS-CHAPTER BOX 6 HERE

Cross-Chapter Box 6 Implications of reconciled anthropogenic land CO_2 fluxes for assessing collective climate progress in the global stocktake

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The Global Stocktake aims to assess countries' collective progress towards the long-term goals of the Paris Agreement in the light of the best available science. Historic progress is assessed based on NGHGIs, while expectations of future progress are based on country climate targets (e.g., NDCs for 2025 or 2030 and long-term strategies for 2050). Scenarios consistent with limiting warming well-below 2°C and 1.5°C developed by IAMs (Chapter 3) are expected to play a key role as benchmarks against which countries' aggregated future mitigation pledges will be assessed. This, however, implies that estimates by IAMs and country data used to measure progress are comparable.

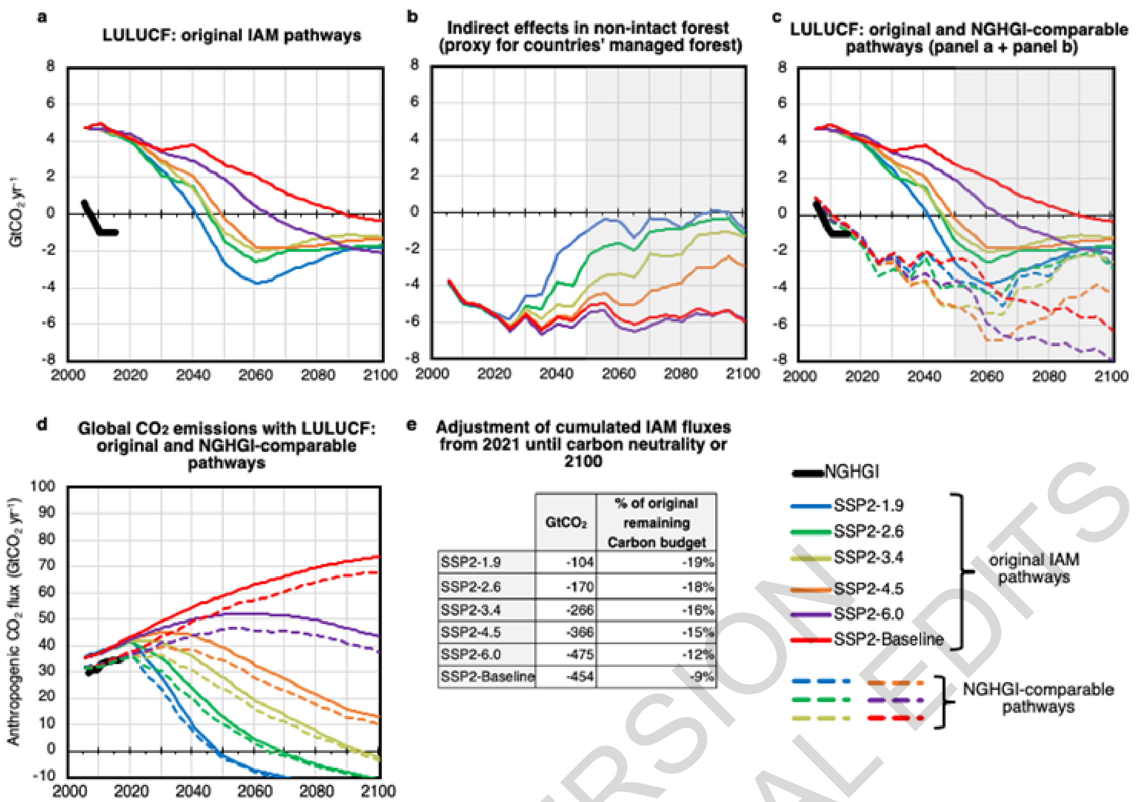
In fact, there is ~5.5 $GtCO_2$ yr^{-1} difference during 2005-2015 between global anthropogenic land CO_2 net flux estimates of IAMs and aggregated NGHGIs, due to different conceptual approaches to what is "anthopogenic". This approach and its implications when comparing climate targets with global mitigation pathways are illustrated in this Box Figure 1a-e.

By adjusting the original IAM output (Cross-Chapter Box 6, Figure 1a) with the indirect effects from countries' managed forest (Cross-Chapter Box 6, Figure 1b, estimated by DGVMs, see also Figure 7.6), NGHGI-comparable pathways can be derived (Cross-Chapter Box 6, Figure 1c). The resulting apparent increase in anthropogenic sink reflects simply a reallocation of a CO_2 flux previously labelled as natural, and thus does not reflect a mitigation action. These changes do not affect non-LULUCF emissions. However, since the atmosphere concentration is a combination of CO_2 emissions from LULUCF and from fossil fuels, the proposed land-related adjustments also influence the NGHGI-comparable economy-wide (all sector) CO_2 pathways (Cross-Chapter Box 6 Figure 1d).

This approach does not imply a change in the original decarbonisation pathways, nor does it suggest that indirect effects should be considered in the mitigation efforts. It simply ensures that a like-with-like comparison is made: if countries' climate targets use the NGHGI definition of anthropogenic emissions, this same definition can be applied to derive NGHGI-comparable future CO_2 pathways. This would have an impact on the NGHGI-comparable remaining carbon or GHG budget (i.e. the allowable emissions until net zero CO_2 or GHG emissions consistent with a certain climate target). For example, for SSP2-1.9 and SSP2-2.6 (representing pathways in line with 1.5°C and well-below 2°C limits under SSP2 assumptions), carbon budget is lower by -170 carbon $GtCO_2$-eq than the original remaining carbon budget according to the models' approach (Cross-Chapter Box 6, Figure 1e). Similarly, the remaining carbon (or GHG) budgets in Chapter 3 (this report), as well as the net zero carbon (or GHG) targets, could only be used in combination with the definition of anthropogenic emissions as used by the IAMs (Cross-Chapter Box 3 in Chapter 3). In the absence of these adjustments, collective progress would appear better than it is.

The UNEP's annual assessment of the global 2030 'emission gap' between aggregated country NDCs and specific target mitigation pathways (UNEP 2020), is only affected to a limited degree. This is because some estimates of global emissions under the NDCs already use the same land-use definitions as the IAM mitigation pathways (Rogelj et al. 2017), and because historical data of global NDC estimates is typically harmonised to the historical data of global mitigation pathway projections (Rogelj et al. 2011). This latter procedure, however, is agnostic to the reasons for the observed mismatch, and often uses a constant offset. The adjustment described here allows this mismatch to be resolved by drawing on a scientific understanding of the underlying reasons, and thus provides a more informed and accurate basis for estimating the emission gap.

The approach to deriving a NGHGI-comparable emission pathways presented here can be further refined with improved estimates of the future forest sink. Its use would enable a more accurate assessment of the collective progress achieved and of mitigation pledges under the Paris Agreement.



Cross-Chapter Box 6, Figure 1. Impact on global mitigation pathways of adjusting the modelled anthropogenic land CO_2 fluxes to be comparable with National Greenhouse Gas Inventories (NGHGIs) (from Grassi et al. 2021). Panel a: The mismatch between global historical LULUCF CO_2 net flux from NGHGIs (black), and the original (un-adjusted) modelled flux historically and under future mitigation pathways for SSP2 scenarios from Integrated Assessment Models (IAMs, Chapter 3). Panel b: fluxes due to indirect effects of environmental change on areas equivalent to countries' managed forest (i.e. those fluxes generally considered 'anthropogenic' by countries and 'natural' by global models). Panel c: original modelled (solid line) LULUCF mitigation pathways adjusted to be NGHGI-comparable (dashed line) i.e. by adding the indirect effects in panel b. The indirect effects in panel b decline over time with increasing mitigation ambition, mainly because of the weaker CO_2 fertilisation effect. In Panel c, the dependency of the adjusted LULUCF pathways on the target becomes less evident after 2030, because the indirect effects in countries' managed forest (which are progressively more uncertain with time, as highlighted by the grey areas) compensate the effects of the original pathways. Panel d: NGHGI-comparable pathways for global CO_2 emissions from all sectors including LULUCF (obtained by combining global CO_2 pathways without LULUCF - where no adjustment is needed - and the NGHGI-comparable CO_2 pathways for LULUCF (Gütschow et al. 2019; Grassi et al. 2017). Panel e: Cumulative impact of the adjustments from 2021 until net zero CO_2 emissions or 2100 (whatever comes first) on the remaining carbon budget.

END CROSS-CHAPTER BOX 6 HERE

7.2.3 CH_4 and N_2O flux from AFOLU

Trends in atmospheric CH_4 and N_2O concentrations and the associated sources, including land and land use are discussed in Sections 5.2.2 and 5.2.3 of the IPCC WGI sixth assessment report. Regarding AFOLU, the SRCCL and AR5 (Jia et al. 2019; Smith et al. 2014) identified three global non-CO_2 emissions data sources; EDGAR (Crippa et al. 2021), FAOSTAT (FAO 2021a; Tubiello, 2019) and the USA EPA (USEPA 2019). Methodological differences have been previously discussed (Jia et al. 2019).

In accordance with Chapter 2, this report, EDGAR data are used in Table 7.1 and Figure 7.3. It is important to note that in terms of AFOLU sectoral CH_4 and N_2O emissions, only FAOSTAT provides data on AFOLU emissions, while EDGAR and USEPA data consider just the agricultural component. However, the mean of values across the three databases for both CH_4 and N_2O, fall within the assessed uncertainty bounds (30 and 60% for CH_4 and N_2O respectively, Section 2.2.1, this report) of EDGAR data. NGHGIs annually submitted to the UNFCCC (Section 7.2.2.3) provide national AFOLU CH_4 and N_2O data, as included in the SRCCL (Jia et al. 2019). Aggregation of NGHGIs to indicate global emissions must be considered with caution, as not all countries compile inventories, nor submit annually. Additionally, NGHGIs may incorporate a range of methodologies for CH_4 and N_2O accounting (e.g. Thakuri et al. 2020; Ndung'U et al. 2019; Van der Weerden et al. 2016), making comparison difficult. The analysis of complete AFOLU emissions presented here, is based on FAOSTAT data. For agricultural specific discussion, analysis considers EDGAR, FAOSTAT and USEPA data.

7.2.3.1 Global AFOLU CH_4 and N_2O emissions

Using FAOSTAT data, the SRCCL estimated average CH_4 emissions from AFOLU to be 161.2 ± 43 Mt CH_4 yr^{-1} for the period 2007-2016, representing 44% of total anthropogenic CH_4 emissions, with agriculture accounting for 88% of the AFOLU component (Jia et al. 2019). The latest data (FAO 2021a, 2020b) highlight a trend of growing AFOLU CH_4 emissions, with a 10% increase evident between 1990 and 2019, despite year-to-year variation. Forestry and other land use (FOLU) CH_4 emission sources include biomass burning on forest land and combustion of organic soils (peatland fires) (FAO 2020c). The agricultural share of AFOLU CH_4 emissions remains relatively unchanged, with the latest data indicating agriculture to have accounted for 89% of emissions on average between 1990 and 2019. The SRCCL reported with *medium evidence* and *high agreement* that ruminants and rice production were the most important contributors to overall growth trends in atmospheric CH_4 (Jia et al. 2019). The latest data confirm this in terms of agricultural emissions, with agreement between databases that agricultural CH_4 emissions continue to increase and that enteric fermentation and rice cultivation remain the main sources (Figure 7.7). The proportionally higher emissions from rice cultivation indicated by EDGAR data compared to the other databases, may result from the use of a Tier 2 methodology for this source within EDGAR (Janssens-Maenhout et al. 2019).

The SRCCL also noted a trend of increasing atmospheric N_2O concentration, with *robust evidence* and *high agreement* that agriculture accounted for approximately two-thirds of overall global anthropogenic N_2O emissions. Average AFOLU N_2O emissions were reported to be 8.7 ± 2.5 Mt N_2O yr^{-1} for the period 2007-2016, accounting for 81% of total anthropogenic N_2O emissions, with agriculture accounting for 95% of AFOLU N_2O emissions (Jia et al. 2019). A recent comprehensive review confirms agriculture as the principal driver of the growing atmospheric N_2O concentration (Tian et al. 2020). The latest FAOSTAT data (FAO 2020b, 2021a) document a 25% increase in AFOLU N_2O emissions between 1990 and 2019, with the average share from agriculture remaining approximately the same (96%). Agricultural soils were identified in the SRCCL and in recent literature as a dominant emission source, notably due to nitrogen fertiliser and manure applications to croplands, and manure production and deposition on pastures (Jia et al. 2019; Tian et al. 2020). There is agreement within latest data that agricultural soils remain the dominant source (Figure 7.7).

Aggregation of CH_4 and N_2O to CO_2 equivalence (using GWP_{100} IPCC AR6 values), suggests that AFOLU emissions increased by 15% between 1990 and 2019, though emissions showed trend variability year to year. Agriculture accounted for 91% of AFOLU emissions on average over the period (FAO 2020b, 2021a). EDGAR (Crippa et al. 2021), FAOSTAT (FAO 2021a) and USEPA (USEPA 2019) data suggest aggregated agricultural emissions (CO_2-eq) to have increased since 1990, by 19

(1990-2019), 15 (1990-2019) and 21 (1990-2015) % respectively, with all databases identifying enteric fermentation and agricultural soils as the dominant agricultural emissions sources.

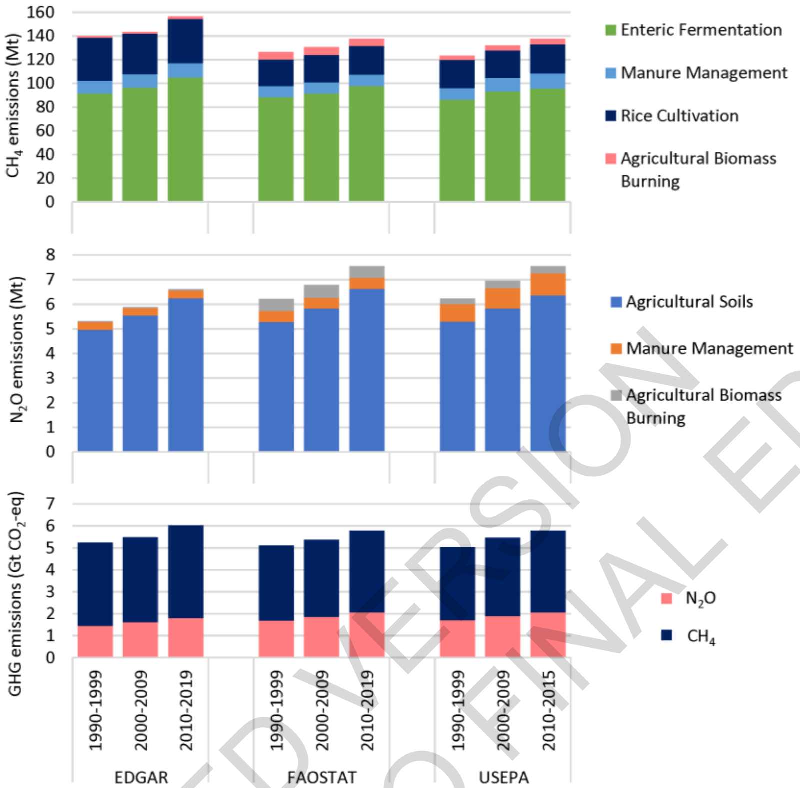


Figure 7.7 Estimated global mean agricultural CH_4 (Top), N_2O (Middle) and aggregated CH_4 and N_2O (using CO_2-eq according to GWP_{100} AR6 values) (Bottom) emissions for three decades according to EDGARv6.0 (Crippa et al. 2021), FAOSTAT (FAO 2021a) and USEPA (USEPA 2019) databases. Latest versions of databases indicate historic emissions to 2019, 2019 and 2015 respectively, with average values for the post-2010 period calculated accordingly. For CH_4, emissions classified as 'Other Ag.' within USEPA data, are re-classified as 'Agricultural Biomass Burning'. Despite CH_4 emissions from agricultural soils also being included, this category was deemed to principally concern biomass burning on agricultural land and classified accordingly. For N_2O, emissions classified within EDGAR as direct and indirect emissions from managed soils, and indirect emissions from manure management are combined under 'Agricultural Soils'. Emissions classified by FOASTAT as from manure deposition and application to soils, crop residues, drainage of organic soils and synthetic fertilisers are combined under 'Agricultural Soils', while emissions reported as 'Other Ag.' under USEPA data are re-classified as 'Agricultural Biomass Burning'.

7.2.3.2 Regional AFOLU CH_4 and N_2O emissions

FAOSTAT data (FAO 2020b, 2021a) indicate Africa (+ 44%), followed by Southern Asia (+ 29%) to have the largest growth in AFOLU CH_4 emissions between 1990 and 2019 (Figure 7.8). Eurasia was characterised by notable emission reductions (--58%), principally as a result of a sharp decline (--63%)

between 1990 and 1999. The average agricultural share of AFOLU emissions between 1990 and 2019 ranged from 66% in Africa to almost 100% in the Middle East.

In agreement with AR5 (Smith et al. 2014), the SRCCL identified Asia as having the largest share (37%) of emissions from enteric fermentation and manure management since 2000, but Africa to have the fastest growth rate. Asia was identified as responsible for 89% of rice cultivation emissions, which were reported as increasing (Jia et al. 2019). Considering classification by ten IPCC regions, data suggest enteric fermentation to have dominated emissions in all regions since 1990, except in South-east Asia and Developing Pacific, where rice cultivation forms the principal source (FAO 2021; USEPA 2019). The different databases broadly indicate the same regional CH_4 emission trends, though the indicated absolute change differs due to methodological differences (Section 7.2.3.1). All databases indicate considerable emissions growth in Africa since 1990 and that this region recorded the greatest regional increases in emissions from both enteric fermentation and rice cultivation since 2010. Additionally, FAOSTAT data suggest that emissions from agricultural biomass burning account for a notably high proportion of agricultural CH_4 emissions in Africa (Figure 7.8).

The latest data suggest growth in AFOLU N_2O emissions in most regions between 1990 and 2019, with Southern Asia demonstrating highest growth (+ 74%) and Eurasia, greatest reductions (- 51%), the latter mainly a result of a 61% reduction between 1990 and 2000 (FAO 2020b, 2021a). Agriculture was the dominant emission source in all regions, its proportional average share between 1990 and 2019 ranging from 87% in Africa, to almost 100% in the Middle East (Figure 7.8).

The SRCCL provided limited discussion on regional variation in agricultural N_2O emissions but reported with *medium confidence* that certain regions (North America, Europe, East & South Asia) were notable sources of grazing land N_2O emissions (Jia et al. 2019). AR5 identified Asia as the largest source and as having the highest growth rate of N_2O emissions from synthetic fertilisers between 2000 and 2010 (Smith et al. 2014). Latest data indicate agricultural N_2O emission increases in most regions, though variation between databases prevents definitive conclusions on trends, with Africa, Southern Asia, and Eastern Asia suggested to have had greatest growth since 1990 according to EDGAR (Crippa et al. 2021), FAOSTAT (FAO 2021a) and USEPA (USEPA 2019) data respectively. However, all databases indicate that emissions declined in Eurasia and Europe from 1990 levels, in accordance with specific environmental regulations put in place since the late 1980s (Tubiello 2019; European Environment Agency 2020; Tian et al. 2020), but generally suggest increases in both regions since 2010.

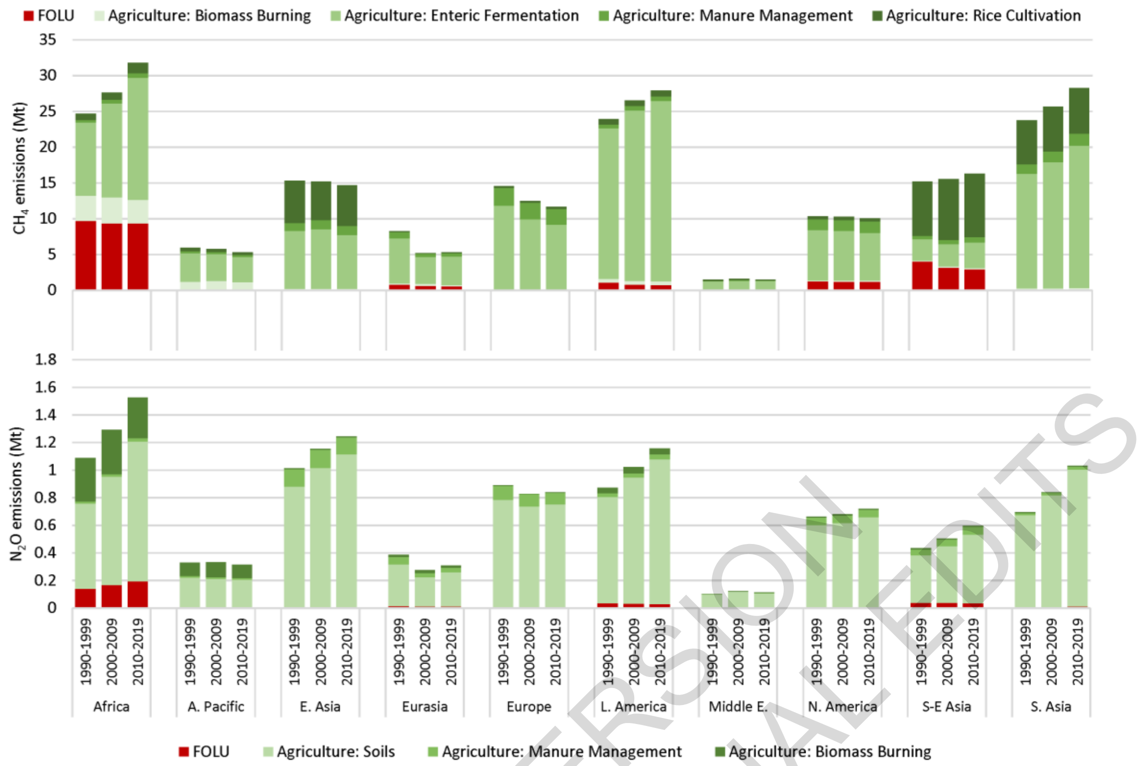


Figure 7.8 Estimated average AFOLU CH_4 (Top) and N_2O (Bottom) emissions for three decades according to FAOSTAT data by ten global regions, with disaggregation of agricultural emissions (FAO 2020b; 2021a). Note for N_2O, emissions from manure deposition and application to soils, crop residues and synthetic fertilisers are combined under 'Agricultural Soils'.

7.2.4 Biophysical effects and short-lived climate forcers

Despite new literature, general conclusions from the SRCCL and WGI-AR6 on biophysical effects and short-lived climate forcers remain the same. Changes in land conditions from land cover change or land management jointly affect water, energy, and aerosol fluxes (biophysical fluxes) as well as GHG fluxes (biogeochemical fluxes) exchanged between the land and atmosphere (*high agreement, robust evidence*) (Erb et al. 2017; Alkama and Cescatti 2016; Naudts et al. 2016; O'Halloran et al. 2012; Anderson et al. 2011). There is *high confidence* that changes in land condition do not just have local impacts but also have non-local impacts in adjacent and more distant areas (Mahmood et al. 2014; Pielke et al. 2011) which may contribute to surpassing climate tipping points (Brando et al. 2014; Nepstad et al. 2008). Non-local impacts may occur through: GHG fluxes and subsequent changes in radiative transfer, changes in atmospheric chemistry, thermal, moisture and surface pressure gradients creating horizontal transport (advection) (De Vrese et al. 2016; Davin and de Noblet-Ducoudre 2010) and vertical transport (convection and subsidence) (Devaraju et al. 2018). Although regional and global biophysical impacts emerge from model simulations (Devaraju et al. 2018; De Vrese et al. 2016; Davin and de Noblet-Ducoudre 2010), especially if the land condition has changed over large areas, there is *very low agreement* on the location, extent and characteristics of the non-local effects across models.

Recent methodological advances, empirically confirmed changes in temperature and precipitation owing to distant changes in forest cover (Meier et al. 2021; Cohn et al. 2019).

Following changes in land conditions, CO_2, CH_4 and N_2O fluxes are quickly mixed into the atmosphere and dispersed, resulting in the biogeochemical effects being dominated by the biophysical effects at local scales (*high confidence*) (Alkama and Cescatti 2016; Li et al. 2015). Afforestation/reforestation (Strandberg and Kjellström 2019; Lejeune et al. 2018), urbanisation (Li and Bou-Zeid 2013) and irrigation (Thiery et al. 2017; Mueller et al. 2016) modulate the likelihood, intensity, and duration of many extreme events including heatwaves (*high confidence*) and heavy precipitation events (*medium confidence*) (Haberlie et al. 2015). There is *high confidence and high agreement* that afforestation in the tropics (Perugini et al. 2017), irrigation (Mueller et al. 2016; Alter et al. 2015) and urban greening result in local cooling, *high agreement and medium confidence* on the impact of tree growth form (deciduous vs. evergreen) (Schwaab et al. 2020; Luyssaert et al. 2018; Naudts et al. 2016), and *low agreement* on the impact of wood harvest, fertilisation, tillage, crop harvest, residue management, grazing, mowing, and fire management on the local climate.

Studies of biophysical effects have increased since AR5 reaching *high agreement* for the effects of changes in land condition on surface albedo (Leonardi et al. 2015). *Low confidence* remains in proposing specific changes in land conditions to achieve desired impacts on local, regional and global climates due to: a poor relationship between changes in surface albedo and changes in surface temperature (Davin and de Noblet-Ducoudre 2010), compensation and feedbacks among biophysical processes (Kalliokoski et al. 2020; Bonan 2016), climate and seasonal dependency of the biophysical effects (Bonan 2016), omittance of short-lived chemical forcers (Kalliokoski et al. 2020; Unger 2014), and study domains often being too small to document possible conflicts between local and non-local effects (Hirsch et al. 2018; Swann et al. 2012).

7.3 Drivers

Since AR5 several global assessments (IPBES 2018; NYDF Assessment Report. 2019; UN Environment 2019; IPCC 2019) and studies (e.g. Tubiello 2019; Tian et al. 2020) have reported on drivers (natural and anthropogenic factors that affect emissions and sinks of the land use sector) behind AFOLU emissions trends, and associated projections for the coming decades. The following analysis aligns with the drivers typology used by (IPBES (2019) and the Global Environmental Outlook (UN Environment 2019). Drivers are divided into direct drivers resulting from human decisions and actions concerning land use and land-use change, and indirect drivers that operate by altering the level or rate of change of one or more direct drivers. Although drivers of emissions in Agriculture and FOLU are presented separately, they are interlinked, operating in many complex ways at different temporal and spatial scales, with outcomes depending on their interactions. For example, deforestation in tropical forests is a significant component of sectorial emissions. A review of deforestation drivers' studies published between 1996 and 2013, indicated a wide range of factors associated with deforestation rates across many analyses and studies, covering different regions (Figure 7.9; Busch and Ferretti-Gallon 2017). Higher agricultural prices were identified as a key driver of deforestation, while law enforcement, area protection, and ecosystem services payments were found to be important drivers of reduced deforestation, while timber activity did not show a consistent impact

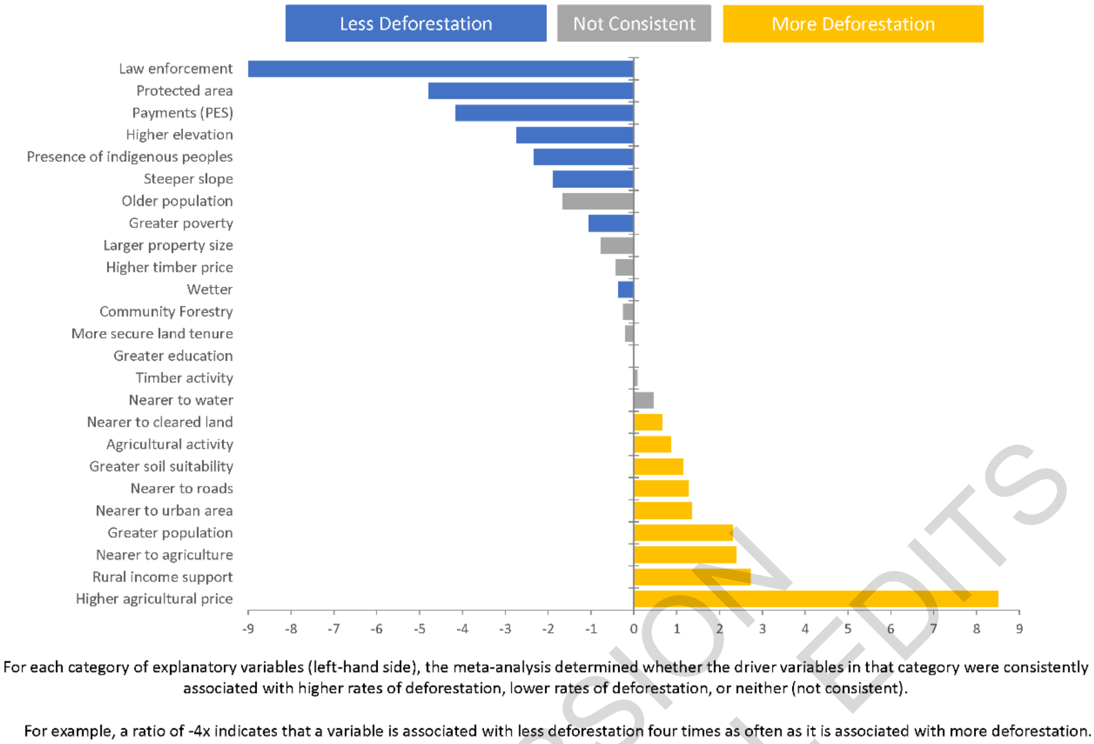


Figure 7.9 Association of driver variables with more or less deforestation
Source: Busch and Ferretti-Gallon (2017)

7.3.1 Anthropogenic direct drivers – Deforestation, conversion of other ecosystems, and land degradation

The global forest area in 2020 is estimated at 4.1 billion ha, representing 31% of the total land area (FAO 2020a). Most forests are situated in the tropics (45%), followed by boreal (27%), temperate (16%) and subtropical (11%) domains. Considering regional distribution of global forest area, Europe and the Russian Federation accounts for 25%, followed by South America (21%), North and Central America (19 %), Africa (16%), Asia (15%) and Oceania (5%). However, a significant share (54%) of the world's forest area concerns five countries – the Russian Federation, Brazil, Canada, the USA and China (FAO 2020a). Forest loss rates differ among regions though the global trend is towards a net forest loss (UN Environment 2019). The global forest area declined by about 178 Mha in the 30 years from 1990 to 2020 (FAO 2020a). The rate of net forest loss has decreased since 1990, a result of reduced deforestation in some countries and forest gains in others. The annual net loss of forest area declined from 7.8 Mha in 1990–2000, to 5.2 Mha in 2000–2010, to 4.7 Mha in 2010–2020, while the total growing stock in global forests increased (FAO 2020a). The rate of decline in net forest loss during the last decade was due mainly to an increase in the rate of forest gain (i.e. afforestation and the natural expansion of forests).

Globally, the area of the more open, other wooded land is also of significant importance, with almost 1 billion hectares (FAO 2020a). The area of other wooded land decreased by 30.6 Mha between 1990 and 2020 with larger declines between 1990–2000 (FAO 2020a). There are still significant challenges in monitoring the area of other wooded land, largely associated with difficulties in measuring tree-canopy cover in the range of 5–10%.The global area of mangroves, one of the most productive terrestrial ecosystems (Neogi 2020a), has also experienced a significant decline (Thomas et al. 2017; Neogi 2020b), with a decrease of 1.0 Mha between 1990 and 2020 (FAO 2020a) due to agriculture and aquaculture (Bhattarai 2011; Ajonina et al. 2014; Webb et al. 2014; Giri et al. 2015; Fauzi et al. 2019; Thomas et al. 2017). Some relevant direct drivers affecting emissions and removal in forests and other ecosystems are discussed in proceeding sections.

7.3.1.1. Conversion of natural ecosystems to agriculture

Previous IPCC reports identify land use change as an important driver of emissions and agriculture as a key driver of land use change, causing both deforestation and wetland drainage (Smith et al. 2019d). AR5 reported a trend of declining global agricultural land area since 2000 (Smith et al. 2014). The latest data (FAO 2021b) indicate a 2% reduction in the global agricultural area between 2000 and 2019 (Figure 7.10). This area includes (though is not limited to) land under permanent and temporary crops or pasture, temporary fallow and natural meadows and pasture utilized for grazing or agricultural purposes (FAO 2021b), although the extent of land used for grazing may not be fully captured (Fetzel et al. 2017). Data indicate changes in how agricultural land is used. Between 2000 and 2019, the area classified as permanent meadow and pasture decreased (- 6%) while cropland area (under arable production and temporary crops) increased (+ 2%). A key driver of this change has been a general trend of intensification, including in livestock production (Barger et al. 2018; OECD/FAO 2019; UN Environment 2019), whereby less grazing land is supporting increasing livestock numbers in conjunction with greater use of crops as livestock feed (Barger et al. 2018). The share of feed crops, such as maize and soybean, of global crop production is projected to grow as the demand for animal feed increases with further intensification of livestock production (OECD/FAO 2019). Despite increased demand for food, feed, fuel and fibre from a growing human population (FAO 2019b), global agricultural land area is projected to remain relatively stable during the next decade, with increases in production expected to result from agricultural intensification (OECD/FAO 2019).

Despite a decline in global agricultural area, the latest data document some regional expansion between 2000 and 2019, specifically in Africa (+ 3%) and Asia and the Developing Pacific (+ 1%). Agricultural area declined in all other regions, notably in developed countries (- 9%), due to multiple factors including among others, urbanisation (see Section 7.3.1.2).

7.3.1.2. Infrastructure development and urbanisation

Although built-up areas (defined as cities, towns, villages and human infrastructure) occupy a relatively small fraction of land (around 1% of global land), since 1975 urban clusters (i.e. urban centres as well as surrounding suburbs) have expanded approximately 2.5 times (UN Environment 2019; Chapter 8, this report). Regional differences are striking. Between 1975 and 2015, built-up areas doubled in size in Europe while urban population remained relatively constant. In Africa built-up areas grew approximately fourfold, while urban population tripled (UN Environment 2019). Trends indicate that rural-to-urban migration will continue and accelerate in developing countries increasing environmental pressure in spite of measures to mitigate some of the impacts (e.g. by preserving or enhancing natural systems within cities for example lakes or natural and urban green infrastructures (UN Environment 2019). If current population densities within cities remain stable, the extent of built-up areas in developed countries is expected to increase by 30% and triple in developing countries between 2000 and 2050 (Barger et al. 2018).

Urban expansion leads to landscape fragmentation and urban sprawl with effects on forest resources and land use (Ünal et al. 2019) while interacting with other drives. For example, in the Brazilian Amazon, the most rapid urban growth occurs within cities that are located near rural areas that produce commodities (minerals or crops) and are connected to export corridors (Richards and VanWey 2015). Urbanisation, coastal development and industrialisation also play crucial roles in the significant loss of mangrove forests (Richards and Friess 2016; Hirales-Cota 2010; Rivera-Monroy et al. 2017). Among infrastructural developments, roads are one of the most consistent and most considerable factors in deforestation, particularly in tropical frontiers (Pfaff et al. 2007; Rudel et al. 2009; Ferretti-Gallon and Busch 2014). The development of roads may also bring subsequent impacts on further development intensity due to increasing economic activities (see Chapter 8) mostly in the tropics and subtropics, where the expansion of road networks increases access to remote forests that act as refuges for biodiversity (Campbell et al. 2017) (Box 7.1). Logging is one of the main drivers of road construction in tropical forests (Kleinschroth and Healey 2017) which leads to more severe long term impacts that include increased fire incidence, soil erosion, landslides, and sediment accumulation in streams, biological invasions, wildlife poaching, illicit land colonisation, illegal logging and mining, land grabbing and land speculation (Laurance et al. 2009; Alamgir et al. 2017).

[START BOX 7.1 HERE]

Box 7.1 Case study: Reducing the impacts of roads on deforestation

Summary

Rapidly expanding roads, particularly in tropical regions, are linked to forest loss, degradation, and fragmentation because the land becomes more generally accessible. Increase of land values of areas adjacent to roads also drives speculation and deforestation related to land tenure (Fearnside 2015). If poorly planned, infrastructure can facilitate fires, illegal mining, and wildlife poaching with consequences for GHG emissions and biodiversity conservation. However, some initiatives are providing new approaches for better planning and then limit environmental and societal impacts**.**

Background

Although the number and extent of protected areas has increased markedly in recent decades (Watson et al. 2014), many other indicators reveal that nature is in broad retreat. For example, the total area of intact wilderness is declining rapidly worldwide (Watson et al. 2016), 70% of the world's forests are now less than 1 km from a forest edge (Haddad et al. 2015), the extent of tropical forest fragmentation is accelerating exponentially (Taubert et al. 2018). One of the most direct and immediate driver of deforestation and biodiversity decline is the dramatic expansion of roads and other transportation infrastructure (Laurance et al. 2014a; Laurance and Arrea 2017; Alamgir et al. 2017).

Case description

From 2010 to 2050, the total length of paved roads is projected to increase by 25 million km (Dulac 2013) including large infrastructure-expansion schemes in Asia (Lechner et al. 2018; Laurance and Arrea 2017) and in South America (Laurance et al. 2001; Killeen 2007)—as well as widespread illegal or unplanned road building (Barber et al. 2014; Laurance et al. 2009). For example, in the Amazon, 95% of all deforestation occurs within 5.5 km of a road, and for every km of legal road there are nearly three km of illegal roads (Barber et al. 2014).

Interactions and limitations

More than any other proximate factor, the dramatic expansion of roads is determining the pace and patterns of habitat disruption and its impacts on biodiversity (Laurance et al. 2009; Laurance and Arrea 2017). Much road expansion is poorly planned. Environmental Impact Assessments (EIAs) for roads and other infrastructure are typically too short-term and superficial to detect rare species or assess long-term or indirect impacts of projects (Flyvbjerg 2009; Laurance and Arrea 2017). Another limitation is the consideration of each project in isolation from other existing or planned developments (Laurance et al. 2014b). Hence, EIAs alone are inadequate for planning infrastructure projects and assessing their broader environmental, social, and financial impacts and risks (Laurance et al. 2015a; Alamgir et al. 2018, 2017).

Lessons

The large-scale, proactive land-use planning is an option for managing the development of modern infrastructure. Approaches such as the "Global Roadmap" scheme (Laurance and Balmford 2013; Laurance et al. 2014a) Strategic Environmental Assessments (Fischer 2007) can be used to evaluate the relative costs and benefits of infrastructure projects, and to spatially prioritise land-uses to optimise human benefits while limited new infrastructure in areas of intact or critical habitats. For example, the Global Roadmap strategy has been used in parts of Southeast Asia (Sloan et al. 2018), Indochina (Balmford et al. 2016), and sub-Saharan Africa (Laurance et al. 2015b) to devise land-use zoning that can help optimise the many risks and rewards of planned infrastructure projects.

[END BOX 7.1 HERE]

7.3.1.3. Extractive industry development

The extent and scale of mining is growing due to increased global demand (UN Environment 2019). Due to declining ore grades, more ore needs to be processed to meet demand, with extensive use of open cast mining. A low-carbon future may be more mineral intensive with for example, clean energy technologies requiring greater inputs in comparison to fossil-fuel-based technologies (Hund et al. 2020). Mining presents cumulative environmental impacts, especially in intensively mined regions (UN Environment 2019). The impact of mining on deforestation varies considerably across minerals and countries. Mining causes significant changes to the environment, for example through mining infrastructure establishment, soil erosion, urban expansion to support a growing workforce and development of mineral commodity supply chains (Sonter et al. 2015). The increasing consumption of gold in developing countries, increased prices, and uncertainty in financial markets is identified as driving gold mining and associated deforestation in the Amazon region (Alvarez-Berrios and Mitchell Aide 2015; Dezécache et al. 2017; Asner and Tupayachi 2017; Espejo et al. 2018). The total estimated area of gold mining throughout the region increased by about 40% between 2012 and 2016 (Asner and Tupayachi 2017). In the Brazilian Amazon, mining significantly increased forest loss up to 70 km beyond mining lease boundaries, causing 11,670 km^2 of deforestation between 2005 and 2015, representing 9% of all Amazon forest loss during this time (Sonter et al. 2015).

Mining is also an important driver of deforestation in African and Asian countries. In the Democratic Republic of Congo, where the second-largest area of tropical forest in the world occurs, mining-related deforestation exacerbated by violent conflict (Butsic et al. 2015). In India, mining has contributed to deforestation at a district level, with coal, iron and limestone having had the most adverse impact on forest area loss (Ranjan 2019). Gold mining is also identified as a driver of deforestation in Myanmar (Papworth et al. 2017).

7.3.1.4. Fire regime changes

Wildland fires account for approximately 70% of the global biomass burned annually (Van Der Werf et al. 2017) and constitute a large global source of atmospheric trace gases and aerosols (Gunsch et al. 2018; IPCC WGI AR6). Although fires are part of the natural system, the frequency of fires has increased in many areas, exacerbated by decreases in precipitation, including in many regions with humid and temperate forests that rarely experience large-scale fires naturally. Natural and human-ignited fires affect all major biomes, from peatlands through shrublands to tropical and boreal forests, altering ecosystem structure and functioning (Argañaraz et al. 2015; Engel et al. 2019; Mancini et al. 2018; Remy et al. 2017; Nunes et al. 2016; Aragão et al. 2018; (Rodríguez Vásquez et al. 2021).

However, the degree of incidence and regional trends are quite different and a study over 14 year indicated, on average, the largest fires in Australia, boreal North America and Northern Hemisphere Africa (Andela et al. 2019). More than half of the terrestrial surface of the Earth has fire regimes outside the range of natural variability, with changes in fire frequency and intensity posing major challenges for land restoration and recovery (Barger et al. 2018). In some ecosystems, fire prevention might lead to accumulation of large fuel loads that enable wildfires (Moreira et al. 2020a).

About 98 Mha of forest and savannahs are estimated to have been affected by fire in 2015 (FAO and UNEP 2020). Fire is a prevalent forest disturbance in the tropics where about 4% of the total forest and savannah area in that year was burned and more than two-thirds of the total area affected was in Africa and South America; mostly open savanna types (FAO and UNEP 2020). Fires have many different causes, with land clearing for agriculture the primary driver in tropical regions, for example, clearance for industrial oil-palm and paper-pulp plantations in Indonesia (Chisholm et al. 2016), or for pastures in the Amazon (Barlow et al. 2020). Other socioeconomic factors are also associated with wildfire regimes such as land-use conflict and socio-demographic aspects (Nunes et al. 2016; Mancini et al. 2018). Wildfire regimes are also changing by the influence of climate change, with wildfire seasons becoming longer, wildfire average size increases in many areas and wildfires occurring in areas where they did not occur before (Jolly et al. 2015; Artés et al. 2019). Human influence has likely increased fire weather in some regions of all inhabited continents (IPCC WGI AR6 Technical Summary) and, in the last years, fire seasons of unprecedented magnitude occurred in diverse regions as California (Goss et al. 2020), the Mediterranean basin (Ruffault et al. 2020), Canada (Kirchmeier-Young et al. 2019) with unprecedented fires in British Columbia in 2021, the Arctic and Siberia (McCarty et al. 2020), Brazilian Amazon (Silva et al. 2021b) and Pantanal (Leal Filho et al. 2021), Chile (Bowman et al. 2019) and Australia (Gallagher et al. 2021; Ward et al. 2020). Lightning plays an important role in the ignition of wildfires, with the incidence of lightning igniting wildfires predicted to increase with rises in global average air temperature (Worden et al. 2017).

7.3.1.5. Logging and fuelwood harvest

The area of forest designated for production has been relatively stable since 1990. Considering forest uses, about 30% (1.2 billion ha) of all forests is used primarily for production (wood and non-wood forest products), about 10% (424 Mha) is designated for biodiversity conservation, 398 Mha for the protection of soil and water, and 186 Mha is allocated for social services (recreation, tourism, education research and the conservation of cultural and spiritual sites) (FAO and UNEP 2020). While the rate of increase in the area of forest allocated primarily for biodiversity conservation has slowed in the last ten years, the rate of increase in the area of forest allocated for soil and water protection has grown since 1990, and notably in the last ten years. Global wood harvest (including from forests, other wooded land and trees outside forests) was estimated to be almost 4.0 billion m^3 in 2018 (considering both industrial roundwood and fuelwood) (FAO, 2019). Overall, wood removals are increasing globally as demand for, and the consumption of wood products grows annually by 1% in line with growing populations and incomes with this trend expected to continue in coming decades. When done in a sustainable way, more regrowth will occur and is stimulated by management, resulting in a net sink. However illegal and unsustainable logging (i.e. harvesting of timber in contravention of the laws and regulations of the country of harvest) is a global problem with significant negative economic (e.g. lost revenue), environmental (e.g. deforestation, forest degradation, GHG emissions and biodiversity losses) and social impact (e.g. conflicts over land and resources, disempowerment of local and indigenous communities) (World Bank 2019). Many countries around the world have introduced regulations for the international trade of forest products to reduce illegal logging, with significant and positive impacts (Guan et al. 2018).

Over-extraction of wood for timber and fuelwood) is identified as an important driver of mangrove deforestation and degradation (Fauzi et al. 2019; Bhattarai 2011; Ajonina et al. 2014; Webb et al. 2014; Giri et al. 2015; Thomas et al. 2017; Bhattarai 2011; Ajonina et al. 2014; Webb et al. 2014; Giri et al. 2015; Thomas et al. 2017; Fauzi et al. 2019). Unsustainable selective logging and over-extraction of wood is a substantial form of forest and mangrove degradation in many tropical and developing countries, with emissions associated with the extracted wood, incidental damage to the surrounding forest and from logging infrastructure (Pearson et al. 2014, (Fauzi et al. 2019; Bhattarai 2011; Ajonina et al. 2014; Webb et al. 2014; Giri et al. 2015; Thomas et al. 2017).). Traditional fuelwood and charcoal continue to represent a dominant share of total wood consumption in low-income countries (Barger et al. 2018). Regionally, the percentage of total wood harvested used as fuelwood varies from 90% in Africa, 62 % in Asia, 50% in South America to less than 20 % in Europe, North America and Oceania. Under current projections, efforts to intensify wood production in plantation forests, together with increases in fuel-use efficiency and electrification, are suggested to only partly alleviate the pressure on native forests (Barger et al. 2018). Nevertheless, the area of forest under management plans has increased in all regions since 2000 by 233 Mha (FAO-FRA 2020). In regions representing the majority of industrial wood production, forests certified under sustainable forest management programs accounted for 51% of total managed forest area in 2017, an increase from 11% in 2000 (ICFPA 2021).

7.3.2. Anthropogenic direct drivers – Agriculture

7.3.2.1. Livestock populations and management

Enteric fermentation dominates agricultural CH_4 emissions (Section 7.2.3) with emissions being a function of both ruminant animal numbers and productivity (output per animal). In addition to enteric fermentation, both CH_4 and N_2O emissions from manure management (i.e. manure storage and application) and deposition on pasture, make livestock the main agricultural emissions source (Tubiello 2019). AR5 reported increases in populations of all major livestock categories between the 1970s and 2000s, including ruminants, with increasing numbers directly linked with increasing CH_4 emissions (Smith et al. 2014). The SRCCL identified managed pastures as a disproportionately high N_2O emissions source within grazing lands, with *medium confidence* that increased manure production and deposition was a key driver (Jia et al. 2019). The latest data (FAO 2021c) indicate continued global livestock population growth between 1990 and 2019 (Figure 7.10), including increases of 18% in cattle and buffalo numbers, and 30% in sheep and goat numbers, corresponding with CH_4 emission trends. Data also indicate increased productivity per animal for example, average increases of 16% in beef, 17% in pig meat and 70% in whole (cow) milk per respective animal between 1990 and 2019 (FAO 2021c). Despite these advances leading to reduced emissions per unit of product (calories, meat and milk) (FAO 2016; Tubiello 2019), increased individual animal productivity generally requires increased inputs (e.g. feed) and this generates increased emissions (Beauchemin et al. 2020). Manipulation of livestock diets, or improvements in animal genetics or health may counteract some of this. In addition, the production of inputs to facilitate increased animal productivity, may indirectly drive further absolute GHG emissions along the feed supply chain.

Although there are several potential drivers (McDermott et al. 2010; Alary V. 2015), increased livestock production is principally in response to growth in demand for animal-sourced food, driven by a growing human population (FAO, 2019) and increased consumption resulting from changes in affluence, notably in middle-income countries (Godfray et al. 2018). Available data document increases in total meat and milk consumption by 24 and 22% respectively between 1990 and 2013, as indicated by average annual per capita supply (FAO 2017a). Updated data indicate that trends of increasing consumption continued between 2014 and 2018 (FAO 2021d). Sustained demand for animal-sourced food is expected to drive further livestock sector growth, with global production projected to expand by 14% by 2029, facilitated by maintained product prices and lower feed prices (OECD/FAO 2019).

7.3.2.2. Rice cultivation

In addition to livestock, both AR5 and the SRCCL identified paddy rice cultivation as an important emissions source (Smith et al. 2014), with *medium evidence* and *high agreement* that its expansion is a key driver of growing trends in atmospheric CH_4 concentration (Jia et al. 2019). The latest data indicate the global harvested area of rice to have grown by 11% between 1990 and 2019, with total paddy production increasing by 46%, from 519 Mt to 755 Mt (FAO 2021c). Global rice production is projected to increase by 13% by 2028 compared to 2019 levels (OECD/FAO 2019). However, yield increases are expected to limit cultivated area expansion, while dietary shifts from rice to protein as a result of increasing per capita income, is expected to reduce demand in certain regions, with a slight decline in related emissions projected to 2030 (USEPA 2019).

Between 1990 and 2019, Africa recorded the greatest increase (+160%) in area under rice cultivation, followed by Asia and the Developing Pacific (+6%), with area reductions evident in all other regions (FAO 2021c) broadly corresponding with related regional CH_4 emission (Figures 7.3 and 7.8). Data indicate the greatest growth in consumption (average annual supply per capita) between 1990 and 2013 to have occurred in Eastern Europe and West Central Asia (+ 42%) followed by Africa (+ 25%), with little change (+ 1%) observed in Asia and the Developing Pacific (FAO 2017a). Most of the projected increase in global rice consumption is in Africa and Asia (OECD/FAO 2019).

7.3.2.3. Synthetic fertiliser use

Both AR5 and the SRCCL described considerable increases in global use of synthetic nitrogen fertilisers since the 1970s, which was identified to be a major driver of increasing N_2O emissions (Jia et al. 2019). The latest data document a 41% increase in global nitrogen fertiliser use between 1990 and 2019 (FAO 2021e) corresponding with associated increased N_2O emissions (Figure 7.3). Increased fertiliser use has been driven by pursuit of increased crop yields, with for example, a 61% increase in average global cereal yield per hectare observed during the same period (FAO 2021c), achieved through both increased fertiliser use and varietal improvements. Increased yields are in response to increased demand for food, feed, fuel and fibre crops which in turn has been driven by a growing human population (FAO, 2019), increased demand for animal-sourced food and bioenergy policy (OECD/FAO 2019). Global crop production is projected to increase by almost 15% over the next decade, with low income and emerging regions with greater availability of land and labour resources expected to experience the strongest growth, and account for about 50% of global output growth (OECD/FAO 2019). Increases in global nitrogen fertiliser use are also projected, notably in low income and emerging regions (USEPA 2019).

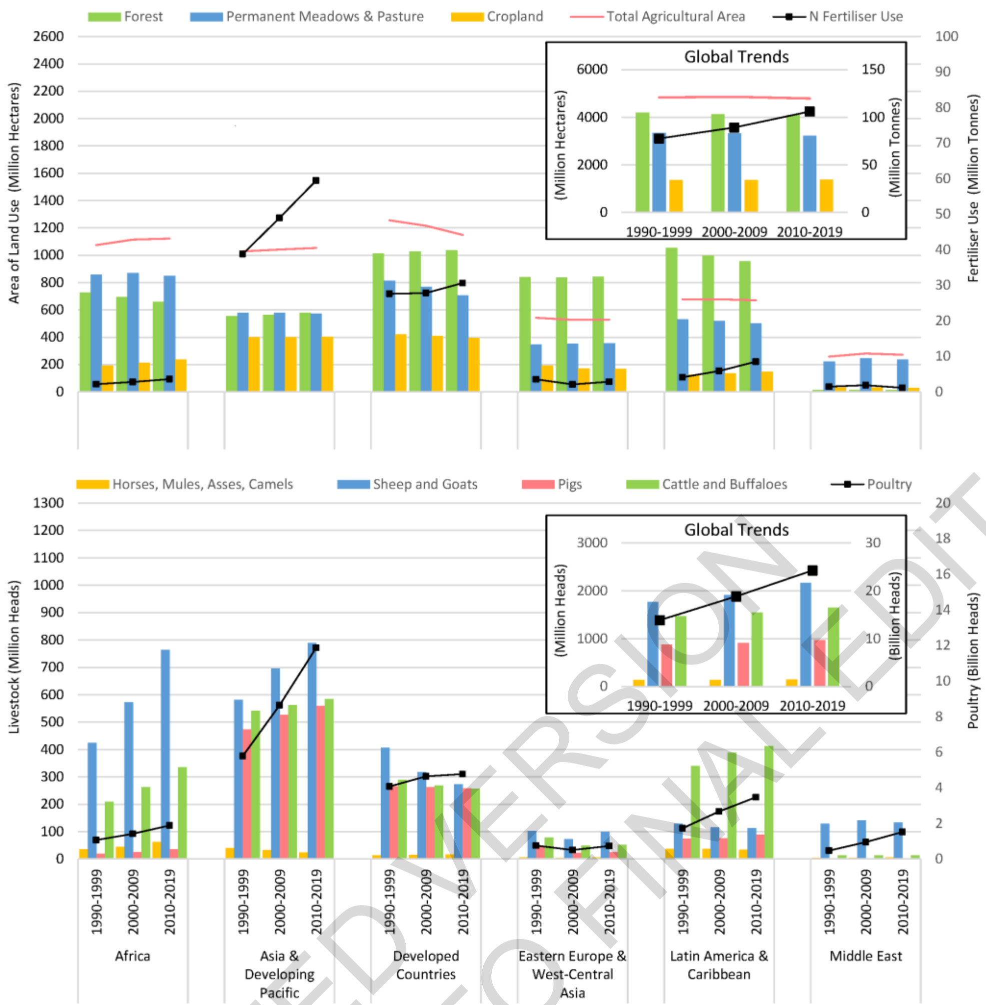


Figure 7.10 Trends in average global and regional land area under specific land uses (FAO 2021b), inorganic nitrogen fertiliser use (FAO 2021e) (Top) and number of livestock (FAO 2021c) (Bottom) for three decades. For land use classification 'cropland' represents the FAOSTAT category 'arable land' which includes land under temporary crops, meadow, pasture and fallow. 'Forest' and 'permanent meadow and pasture' follow FAOSTAT categories.

7.3.3. Indirect drivers

The indirect drivers behind how humans both use and impact natural resources are outlined in Table 7.2, specifically; demographic, economic and cultural, scientific and technological, and institutional and governance drivers. These indirect drivers not only interact with each other at different temporal and spatial scales but are also subject to impacts and feedbacks from the direct drivers (Barger et al. 2018).

Table 7.2 Indirect drivers of anthropogenic land and natural resource use patterns

Demography	***Global and regional trends in population growth:*** There was a 43% increase in global population between 1990 and 2018. The greatest growth was observed in Africa and the

	Middle East (+ 104%) and least growth in Eastern Europe and West-Central Asia (+ 7%) (FAO 2019b). ***Global and regional projections***: Population is projected to increase by 28% between 2018 and 2050 reaching 9.7 billion (FAO 2019). The world's population is expected to become older, more urbanised and live in smaller households (UN Environment 2019). ***Human migration:*** Growing mobility and population are linked to human migration, a powerful driver of changes in land and resource use patterns at decadal timescales, with the dominant flow of people being from rural areas to urban settlements over the past few decades, notably in the developing world (Adger et al. 2015; Barger et al. 2018).
Economic development and cultural factors	Changes in land use and management come from individual and social responses to economic opportunities (e.g. demand for a particular commodity or improved market access), mediated by institutions and policies (e.g. agricultural subsidies and low-interest credit or government-led infrastructure projects) (Barger et al. 2018). ***Projections on consumption***: If the future global population adopts a per capita consumption rate similar to that of the developed world, the global capacity to provide land-based resources will be exceeded (Barger et al. 2018). Economic growth in the developing world is projected to double the global consumption of forest and wood products by 2030, with demand likely to exceed production in many developing and emerging economies in Asia and Africa within the next decade (Barger et al. 2018). ***Global trade***: Market distorting agricultural subsidies and globalisation increases pressure on land systems and functions, with global trade and capital flow influencing land use, notably in developing countries (Yao et al. 2018; Furumo and Aide 2017; Pendrill et al. 2019a; (UN Environment 2019), OECD/FAO 2019). Estimates suggest that between 29 and 39% of emissions from deforestation in the tropics resulted from the international trade of agricultural commodities (Pendrill et al. 2019a).
Science and technology	Technological factors operates in conjunction with economic drivers of land use and management, whether through intensified farming techniques and biotechnology, high-input approaches to rehabilitating degraded land (e.g. Lin et al. 2017; Guo et al. 2020) or through new forms of data collection and monitoring (e.g. Song et al. 2018; Thyagharajan and Vignesh 2019; Arévalo et al. 2020). ***Changes in farming and forestry systems***: Changes can have both positive and negative impacts regarding multiple factors, including GHG emission trends. Fast advancing technologies shape production and consumption, and drive land-use patterns and terrestrial ecosystems at various scales. Innovation is expected to help drive increases in global crop production during the next decade (OECD/FAO 2019). For example, emerging gene editing technologies, may advance crop breeding capabilities, though are subject to biosafety, public acceptance and regulatory approval (Jaganathan et al. 2018; Chen et al. 2019; Schmidt et al. 2020). Technological changes were significant for the expansion of soybean in Brazil by adapting to different soils and photoperiods (Abrahão and Costa 2018). In Asia, technological development changed agriculture with significant improvements in production and adaptation to climate change (Thomson et al. 2019; Giller and Ewert 2019; Anderson et al. 2020; Cassman and Grassini 2020). Developments such as precision agriculture and drip irrigation have facilitated more efficient agrochemical and water use (UN Environment 2019). Research and development are central to forest restoration strategies that have become increasingly important around the world as costs vary depending on methods used, from natural regeneration with native tree species to active restoration using site preparation and planting (Löf et al. 2019). In addition, climate change poses the challenge about tree species selection in the future. Innovations in the forest sector innovations also form the basis of a bioeconomy associated with bioproducts and new processes (Verkerk et al. 2020; Cross-Working Group Box 3 in Chapter 12).

	Emerging mitigation technologies: Chemically synthesised methanogen inhibitors for ruminants are expected to be commercially available in some countries within the next two years and have considerable CH_4 mitigation potential (McGinn et al. 2019; Melgar et al. 2020; Beauchemin et al. 2020; Reisinger et al. 2021) (Section 7.4.3). There is growing literature (in both academic and non-academic sphere) on the biological engineering of protein. Although in its infancy and subject to investment, technological development, regulatory approval and consumer acceptance, it is suggested to have the potential to disrupt current livestock production systems and land use (Stephens et al. 2018; Ben-Arye and Levenberg 2019; Post et al. 2020; RethinkX 2019). The extent to which this is possible and the overall climate benefits are unclear (Lynch and Pierrehumbert 2019; Chriki and Hocquette 2020).
Institutions and governance	Institutional factors often moderate the relevance and impact of changes in economic and demographic variables related to resource exploitation and use. Institutions encompass the rule of law, legal frameworks and other social structures (e.g. civil society networks and movements) determining land management (e.g. formal and informal property rights, regimes and their enforcement); information and knowledge exchange systems; local and traditional knowledge and practice systems (Barger et al. 2018). ***Land rights***: Land tenure often allows communities to exercise traditional governance based on traditional ecological knowledge, devolved and dynamic access rights, judicious use, equitable distribution of benefits (Mantyka-Pringle et al. 2017; Wynberg 2017; Thomas et al. 2017), biodiversity (Contreras-Negrete et al. 2014) and fire and grazing management (Levang et al. 2015; Varghese et al. 2015). ***Agreements and Finance:*** Since AR5, global agreements were reached on climate change, sustainable development goals, and the mobilisation of finance for development and climate action. Several countries adopted policies and commitments to restore degraded land (Barger et al. 2018). The UN Environment Programme (UNEP) and the Food and Agriculture Organization of the UN (FAO), launched the UN Decade on Ecosystem Restoration (https://www.decadeonrestoration.org/). Companies have also made pledges to reduce impacts on forests and on the rights of local communities as well as eliminating deforestation from their supply chains. The finance sector, a crucial driver behind action (Section 7.6, Box 7.12), has also started to make explicit commitments to avoiding environmental damage (Barger et al. 2018) and net zero targets (Forest Trends Ecosystem Marketplace 2021), though investment is sensitive to market outlook.

7.4. Assessment of AFOLU mitigation measures including trade-offs and synergies

AFOLU mitigation or land-based climate change mitigation (used in this chapter interchangeably) are a variety of land management or demand management practices that reduce GHG emissions and/or enhance carbon sequestration within the land system (i.e. in forests, wetlands, grasslands, croplands and pasturelands). If implemented with benefits to human well-being and biodiversity, land-based mitigation measures are often referred to as nature-based solutions and/or natural climate solutions (Glossary). Measures that result in a net removal of GHGs from the atmosphere and storage in either living or dead organic material, or in geological stores, are known as CDR, and in previous IPCC reports were sometimes referred to as greenhouse gas removal (GGR) or negative emissions technologies (NETs) (Rogelj et al. 2018a; Jia et al. 2019). This section evaluates current knowledge and latest scientific literature on AFOLU mitigation measures and potentials, including land-based CDR measures. Section 7.4.1 provides an overview of the approaches for estimating mitigation potential, the co-benefits and risks from land-based mitigation measures, estimated global and regional mitigation potential and associated costs according to literature published over the last decade. Subsequent subsections assess literature on 20 key AFOLU mitigation measures specifically providing:

- A description of activities, co-benefits, risks and implementation opportunities and barriers
- A summary of conclusions in AR5 and IPCC Special Reports (SR15, SROCCC and SRCCL)
- An overview of literature and developments since the AR5 and IPCC Special Reports
- An assessment and conclusion based on current evidence

Measures are categorised as supply-side activities in: (1) forests and other ecosystems (Section 7.4.2), (2) agriculture (Section 7.4.3), (3) bioenergy and other land-based energy technologies (Section 7.4.4); as well as (4) demand-side activities (Section 7.4.5) (Figure 7.11). Several information boxes are dispersed within the section and provide supporting material, including case studies exploring a range of topics from climate-smart forestry in Europe (Box 7.2), agroforestry in Brazil (Box 7.3), climate-smart village approaches (Box 7.4), farm systems approaches (Box 7.5), mitigation within Indian agriculture (Box 7.6), and bioenergy and BECCS mitigation calculations (Box 7.7). Novel measures, including enhanced weathering and novel foods are covered in Chapter 12, this report. In addition, as mitigation within AFOLU concerns land management and use of land resources, AFOLU measures impact other sectors. Accordingly, AFOLU measures are also discussed in other sectoral chapters within this report, notably demand-side solutions (Chapter 5), bioenergy and Bioenergy with Carbon Capture and Storage (BECCS) (Chapter 6), the use of wood products and biomass in buildings (Chapter 9), and CDR measures, food systems and land related impacts, risks and opportunities of mitigation measures (Chapter 12).

7.4.1. Introduction and overview of mitigation potential

7.4.1.1. Estimating mitigation potentials

Mitigation potentials for AFOLU measures are estimated by calculating the scale of emissions reductions or carbon sequestration against a counterfactual scenario without mitigation activities. The types of mitigation potential estimates in recent literature include: (1) technical potential (the biophysical potential or amount possible with current technologies), (2) economic potential (constrained by costs, usually by a given carbon price (Table 7.3), (3) sustainable potential (constrained by environmental safeguards and/or natural resources, e.g. limiting natural forest conversion), and (4) feasible potential (constrained by environmental, socio-cultural, and/or institutional barriers), however, there are no set definitions used in literature. In addition to types of mitigation estimates, there are two

AFOLU mitigation categories often calculated: supply-side measures (land management interventions) and demand-side measures (interventions that require a change in consumer behaviour).

Two main approaches to estimating mitigation potentials include: 1) studies on individual measures and/or sectors – henceforth referred to as sectoral assessments, and 2) integrated assessment models (IAM). Sectoral assessments include studies focusing on one activity (e.g. agroforestry) based on spatial and biophysical data, as well as econometric and optimisation models for a sector, e.g. the forest or agriculture sector, and therefore cover a large suite of practices and activities while representing a broad body of literature. Sectoral assessments however, rarely capture cross-sector interactions or impacts, making it difficult to completely account for land competition, trade-offs, and double counting when aggregating sectoral estimates across different studies and methods (Smith et al. 2014; Jia et al. 2019). On the other hand, IAMs assess the climate impact of multiple and interlinked practices across sectors and therefore, can account for interactions and trade-offs (including land competition, use of other resources and international trade) between them. However, the number of land-based measures used in IAMs are limited compared with the sectoral portfolio (Figure 7.11). The resolution of land-based measures in IAMs are also generally coarser compared to some sectoral estimates, and as such, may be less robust for individual measures (Roe et al. 2021). Given the differences between and strengths and weaknesses of the two approaches, it is helpful to compare the estimates from both. We combine estimates from both approaches to establish an updated range of global land-based mitigation potential.

For the 20 land-based mitigation measures outlined in this section, the mitigation potential estimates are largely derived from sectoral approaches, and where data is available, are compared to IAM estimates. Integrated assessment models and the emissions trajectories, cost-effectiveness and trade-offs of various mitigation pathways are detailed in Section 7.5. It should be noted that the underlying literature for sectoral as well as IAM mitigation estimates consider GWP_{100} IPCC AR5 values (CH_4 = 28, N_2O = 265) as well as GWP_{100} IPCC AR4 values (CH_4 = 25, N_2O = 298) to convert CH_4 and N_2O to CO_2-eq. Where possible, we note the various GWP_{100} values (in IAM estimates, and the wetlands and agriculture sections), however in some instances, the varying GWP_{100} values used across studies prevents description of non-CO_2 gases in native units as well as conversion to AR6 GWP_{100} (CH_4 = 27, N_2O = 273) CO_2-eq values to aggregate sectoral assessment estimates.

7.4.1.2. Co-benefits and risks

Land interventions have interlinked implications for climate mitigation, adaptation, food security, biodiversity, ecosystem services, and other environmental and societal challenges (Section 7.6.5). Therefore, it is important to consider the net effect of mitigation measures for achieving both climate and non-climate goals (Section 7.1).

While it is helpful to assess the general benefits, risks and opportunities possible for land-based mitigation measures (Smith et al. 2019a), their efficacy and scale of benefit or risk largely depends on the type of activity undertaken, deployment strategy (e.g. scale, method), and context (e.g. soil, biome, climate, food system, land ownership) that vary geographically and over time (Smith et al. 2019a,b; Hurlbert et al. 2019; Chapter 12, Section 12.5) *(robust evidence, high agreement).* Impacts of land-based mitigation measures are therefore highly context specific and conclusions from specific studies may not be universally applicable. If implemented at appropriate scales and in a sustainable manner, land-based mitigation practices have the capacity to reduce emissions and sequester billions of tonnes of carbon from the atmosphere over coming decades, while also preserving or enhancing biodiversity, water quality and supply, air quality, soil fertility, food and wood security, livelihoods, resilience to droughts, floods and other natural disasters, and positively contributing to ecosystem health and human wellbeing *(high confidence)* (Toensmeier 2016; Karlsson et al. 2020).

Overall, measures in the AFOLU sector are uniquely positioned to deliver substantial co-benefits.

However, the negative consequences of inappropriate or misguided design and implementation of measures may be considerable, potentially impacting for example, mitigation permanence, longevity, and leakage, biodiversity, wider ecosystem functioning, livelihoods, food security and human well-being (Section 7.6; WGII, Box 2.2. 'Risks of maladaptive mitigation'. Land-based mitigation may also face limitations and trade-offs in achieving sustained emission reductions and/or removals due to other land challenges including climate change impacts. It is widely recognised that land-use planning that is context-specific, considers other sustainable development goals, and is adaptable over time can help achieve land-based mitigation that maximises co-benefits, avoids or limits trade-offs, and delivers on international policy goals including the SDGs, Land Degradation Neutrality, and Convention on Biological Diversity (Section 7.6; Chapter 12).

Potential co-benefits and trade-offs are outlined for each of the 20 land-based mitigation measures in the proceeding sub-sections and summarised in Figure 7.12. Section 7.6.5. discusses general links with ecosystem services, human well-being and adaptation, while Chapter 12 (Section 12.5) provides an in-depth assessment of the land related impacts, risks and opportunities associated with mitigation options across sectors, including positive and negative effects on land resources, water, biodiversity, climate, and food security.

7.4.1.3. Overview of global and regional technical and economic potentials in AFOLU

IPCC AR5 (2014). In the AR5, the economic mitigation potential of supply-side measures in the AFOLU sector was estimated at 7.18–10.60 $GtCO_2$-eq yr^{-1} in 2030 with carbon prices up to USD100 tCO_2-eq^{-1}, about a third of which could be achieved at < USD20 tCO_2-eq^{-1} (*medium evidence; medium agreement*) (Smith et al. 2014). AR5 provided a summary table of individual AFOLU mitigation measures, but did not conduct a detailed assessment for each.

IPCC SRCCL (2019). The SRCCL assessed the full range of technical, economic and sustainability mitigation potentials in AFOLU for the period 2030-2050 and identified reduced deforestation and forest degradation to have greatest potential for reducing supply-side emissions (0.4–5.8 $GtCO_2$-eq yr^{-1}) (*high confidence*) followed by combined agriculture measures, 0.3–3.4 $GtCO_2$-eq yr^{-1} (*medium confidence*) (Jia et al. 2019). For the demand-side estimates, shifting towards healthy, sustainable diets (0.7–8.0 $GtCO_2$-eq yr^{-1}) (*high confidence*) had the highest potential, followed by reduced food loss and waste (0.8–4.5 $GtCO_2$-eq yr^{-1}) (*high confidence*). Measures with greatest potential for CDR were afforestation/reforestation (0.5–10.1 $GtCO_2$-eq yr^{-1}) (*medium confidence*), soil carbon sequestration in croplands and grasslands (0.4–8.6 $GtCO_2$-eq yr^{-1}) (*medium confidence*) and BECCS (0.4–11.3 $GtCO_2$-eq yr^{-1}) (*medium confidence*). The SRCCL did not explore regional potential, associated feasibility nor provide detailed analysis of costs.

IPCC AR6. This assessment concludes the likely range of global land-based mitigation potential is approximately 8 – 14 $GtCO_2$-eq yr^{-1} between 2020-2050 with carbon prices up to USD100 tCO_2-eq^{-1}, about half of the technical potential (*medium evidence; medium agreement*). About 30-50% could be achieved < USD20 tCO_2-eq^{-1} (Table 7.3). The global economic potential estimates in this assessment are slightly higher than the AR5 range. Since AR5, there have been numerous new global assessments of sectoral land-based mitigation potential (Fuss et al. 2018; Griscom et al. 2017, 2020; Roe et al. 2019; Jia et al. 2019; Griscom et al. 2020; Roe et al. 2021) as well as IAM estimates of mitigation potential (Frank et al. 2019; Johnston and Radeloff 2019; Riahi et al. 2017; Baker et al. 2019; Popp et al. 2017; Rogelj et al. 2018a), expanding the scope of AFOLU mitigation measures included and substantially improving the robustness and spatial resolution of mitigation estimates. A recent development is an assessment of country-level technical and economic (USD100 tCO_2-eq^{-1}) mitigation potential for 20 AFOLU measures, including for demand-side and soil organic carbon sequestration in croplands and grasslands, not estimated before (Roe et al. 2021). Estimates on costs, feasibility, sustainability, benefits, and risks have also been developed for some mitigation measures, and they continue to be active areas of research. Developing more refined sustainable potentials at a country-level will be an important next step. Although most mitigation estimates still do not consider the impact of future climate change, there are some emerging studies that do (Doelman et al. 2019; Sonntag et al. 2016). Given the IPCC WG1 finding that the land sink is continuing to increase although its efficiency is decreasing with climate change, it will be critical to better understand how future climate will affect mitigation potentials, particularly from CDR measures.

Across global sectoral studies, the economic mitigation potential (up to USD100 tCO_2-eq^{-1}) of supply-side measures in AFOLU for the period 2020-2050 is 11.4 mean (5.6–19.8 full range) $GtCO_2$-eq yr^{-1}, about 50% of the technical potential of 24.2 (4.9 - 58) $GtCO_2$-eq yr^{-1} (Table 7.3). Adding 2.1 $GtCO_2$-eq yr^{-1} from demand-side measures (accounting only for diverted agricultural production to avoid double counting with land-use change effects), total land-based mitigation potential up to USD100 tCO_2-eq^{-1} is 13.6 (6.7 – 23.4) $GtCO_2$-eq yr^{-1}. This estimate aligns with the most recent regional assessment (Roe et al. 2021), which found the aggregate global mitigation potential of supply and demand-side measures to be 13.8 ± 3.1 $GtCO_2$-eq yr^{-1} up to USD100 tCO_2-eq^{-1} for the period 2020-2050. Across integrated assessment models (IAMs), the economic potential for land-based mitigation (Agriculture, LULUCF and BECCS) for USD100 tCO_2-eq^{-1} is 7.9 mean (4.1–17.3 range) $GtCO_2$-eq yr^{-1} in 2050 (Table 7.3). We add the estimate for BECCS here to provide the full land-based potential, as IAMs optimize land allocation based on costs, which displaces land-based CDR activities for BECCS. Combining both IAM and sectoral approaches, the likely range is therefore 7.9–13.6 (rounded to 8–14) $GtCO_2$-eq yr^{-1} up to USD100 tCO_2-eq^{-1} between 2020-2050. Considering both IAM and sectoral economic potential estimates, land-based mitigation could have the capacity to make the AFOLU sector net negative GHG emissions from 2036 (Figure 7.12), although there are highly variable mitigation strategies for how AFOLU potential can be deployed for achieving climate targets (Illustrative Mitigation Pathways in 7.5.5). Economic potential estimates, which reflect a public willingness to pay, may be more relevant for policy making compared with technical potentials which reflect a theoretical maximum that may not be feasible or sustainable.

Among the mitigation options, the protection, improved management, and restoration of forests and other ecosystems (wetlands, savannas and grasslands) have the largest potential to reduce emissions and/or sequester carbon at 7.3 (3.9–13.1) $GtCO_2$-eq yr^{-1} (up to USD100 tCO_2-eq^{-1}), with measures that 'protect' having the single highest total mitigation and mitigation densities (mitigation per area) in AFOLU (Table 7.3, Figure 7.11). Agriculture provides the second largest share of mitigation, with 4.1 (1.7–6.7) $GtCO_2$-eq yr^{-1} potential (up to USD100 tCO_2-eq^{-1}), from soil carbon management in croplands and grasslands, agroforestry, biochar, rice cultivation, and livestock and nutrient management Table 7.3, Figure 7.11. Demand-side measures including shifting to sustainable healthy diets, reducing food waste, and improving wood products can mitigate 2.2 (1.1 - 3.6) $GtCO_2$-eq yr^{-1} when accounting only for diverted agricultural production from diets and food waste to avoid double counting with measures in forests and other ecosystems (Table 7.3, Figure 7.11). The potential of demand-side measures increases three-fold, to 6.5 (4 – 9.5) $GtCO_2$-eq yr^{-1} when accounting for the entire value chain including land-use effects, but would overlap with other measures and is therefore not additive.

Most mitigation options are available and ready to deploy. Emissions reductions can be unlocked relatively quickly, whereas CDR need upfront investment to generate sequestration over time. The protection of natural ecosystems, carbon sequestration in agriculture, sustainable healthy diets and reduced food waste have especially high co-benefits and cost efficiency. Avoiding the conversion of carbon-rich primary peatlands, coastal wetlands and forests is particularly important as most carbon lost from those ecosystems are irrecoverable through restoration by the 2050 timeline of achieving net zero carbon emissions (Goldstein et al. 2020). Sustainable intensification, shifting diets, reducing food waste could enhance efficiencies and reduce agricultural land needs, and are therefore critical for enabling supply-side measures such as reduced deforestation, restoration, as well as reducing N_2O and CH_4 emissions from agricultural production - as seen in the Illustrative Mitigation Pathway IMP-SP (Section 7.5.6). Although agriculture measures that reduce non-CO_2, particularly of CH_4, are important for near-term emissions reductions, they have less economic potential due to costs. Demand-side measures may be able to deliver non-CO_2 emissions reductions more cost efficiently.

Regionally, economic mitigation potential up to USD100 tCO_2-eq^{-1} is estimated to be greatest in tropical countries in Asia and developing Pacific (34%), Latin America and the Caribbean (24%), and Africa and the Middle East (18%) because of the large potential from reducing deforestation and sequestering carbon in forests and agriculture (Figure 7.11). However, there is also considerable potential in Developed Countries (18%) and more modest potential in Eastern Europe and West-Central Asia (5%). These results are in line with the IAM regional mitigation potentials (Figure 7.11). The protection of forests and other ecosystems is the dominant source of mitigation potential in tropical regions, whereas carbon sequestration in agricultural land and demand-side measures are important in Developed Countries and Asia and developing Pacific. The restoration and management of forests and other ecosystems is more geographically distributed, with all regions having significant potential. Regions with large livestock herds (Developed Countries, Latin America) and rice paddy fields (Asia and developing Pacific) have potential to reduce CH_4. As expected, the highest total potential is associated with countries and regions with large land areas, however when considering mitigation density (total potential per hectare), many smaller countries, particularly those with wetlands have disproportionately high levels of mitigation for their size (Roe et al. 2021). As global commodity markets connect regions, AFOLU measures may create synergies and trade-offs across the world, which could make national demand-side measures for example, important in mitigating supply-side emissions elsewhere (Kallio & Solberg 2018).

Although economic potentials provide more realistic, near-term climate mitigation compared to technical potentials, they still do not account for feasibility barriers and enabling conditions that vary by region and country. For example, according to most models, including IAMs, avoided deforestation is the cheapest land-based mitigation option (Table 7.3, Sections 7.5.3 and 7.5.4), however implementing interventions aimed at reducing deforestation (including REDD+) often have higher transaction and implementation costs than expected due to various barriers and enabling conditions (Luttrell et al. 2018; Section 7.6). The feasibility of implementing AFOLU mitigation measures, including those with multiple co-benefits, depends on varying economic, technological, institutional, socio-cultural, environmental and geophysical barriers (*high confidence*) (Smith et al. 2019a). The section for each individual mitigation measure provides an overview of co-benefits and risks associated with the measure and Section 7.6.6 outlines key enabling factors and barriers for implementation.

Table 7.3 Estimated annual mitigation potential ($GtCO_2$-eq yr^{-1}) in 2020-2050 of AFOLU mitigation options by carbon price. Estimates reflect sectoral studies based on a comprehensive literature review updating data from (Roe et al. 2019) and integrated assessment models using the IPCC AR6 database (Section 7.5). Values represent the mean, and full range of potential. Sectoral mitigation estimates are averaged for the years 2020-2050 to capture a wider range of literature, and the IAM estimates are given for 2050 as many model assumptions delay most land-based mitigation to mid-century. The sectoral potentials are the sum of global estimates for the individual measures listed for each option. IAM potentials are given for mitigation options with available data; e.g., net land-use CO_2 for total forests & other ecosystems, and land sequestration from A/R, but not reduced deforestation (protect). Sectoral estimates predominantly use GWP_{100} IPCC AR5 values (CH_4 = 28, N_2O = 265), although some use GWP_{100} IPCC AR4 values (CH_4 = 25, N_2O = 298); and the IAMs use GWP_{100} IPCC AR6 values (CH_4 =

27, N_2O = 273). The sectoral and IAM estimates reflected here do not account for the substitution effects of avoiding fossil fuel emissions nor emissions from other more energy intensive resources/materials. For example, BECCS estimates only consider the carbon dioxide removal (CDR) via geological storage component and not potential mitigation derived from the displacement of fossil fuel use in the energy sector. Mitigation potential from substitution effects are included in the other sectoral chapters like energy, transport, buildings and industry. The total AFOLU sectoral estimate aggregates potential from agriculture, forests & other ecosystems, and diverted agricultural production from avoided food waste and diet shifts (excluding land-use impacts to avoid double counting). Because of potential overlaps between measures, sectoral values from BECCS and the full value chain potential from demand-side measures are not summed with AFOLU. IAMs account for land competition and resource optimization and can therefore sum across all available categories to derive the total AFOLU potential. Key: ND = no data; Sectoral = as assessed by sectoral literature review; IAM = as assessed by integrated assessment models; EJ = ExaJoule primary energy.

Mitigation option	Estimate type	< USD20 tCO_2-eq^{-1}	< USD50 tCO_2-eq^{-1}	< USD100 tCO_2-eq^{-1}	Technical
Agriculture total	Sectoral	0.9 (0.5 - 1.4)	1.6 (1 – 2.4)	4.1 (1.7 - 6.7)	11.2 (1.6 - 28.5)
	IAM	0.9 (0 - 3.1)	1.3 (0 - 3.2)	1.8 (0.7 - 3.3)	ND
Agriculture - Carbon sequestration (soil carbon management in croplands and grasslands, agroforestry, and biochar)	Sectoral	0.5 (0.4 - 0.6)	1.2 (0.9 - 1.6)	3.4 (1.4 - 5.5)	9.5 (1.1 - 25.3)
	IAM	ND	ND	ND	ND
Agriculture - Reduce CH4 and N2O emissions (improve enteric fermentation, manure management, nutrient management, and rice cultivation)	Sectoral	0.4 (0.1 - 0.8)	0.4 (0.1 - 0.8)	0.6 (0.3 - 1.3)	1.7 (0.5 - 3.2)
	IAM	0.9 (0 - 3.1)	1.3 (0 - 3.2)	1.8 (0.7 - 3.3)	ND
Forests & other ecosystems total	Sectoral	2.9 (2.2 - 3.5)	3.1 (1.4 - 5.1)	7.3 (3.9 - 13.1)	13 (5 - 29.5)
	IAM	2.4 (0 - 10.5)	3.3 (0 - 9.9)	4.2 (0 - 12.1)	ND
Forests & other ecosystems - Protect (reduce deforestation, loss and degradation of peatlands, coastal wetlands, and grasslands)	Sectoral	2.3 (1.7 - 2.9)	2.4 (1.2 - 3.6)	4.0 (2.5 - 7.4)	6.2 (2.8 - 14.4)
	IAM	ND	ND	ND	ND
Forests & other ecosystems - Restore (afforestation, reforestation, peatland restoration, coastal wetland restoration)	Sectoral	0.15	0.7 (0.2 - 1.5)	2.1 (0.8 - 3.8)	5 (1.1 - 12.3)
	IAM (A/R)	0.6 (0.2 - 6.5)	0.6 (0.01 - 8.3)	0.7 (0.07 - 6.8)	ND
Forests & other ecosystems - Manage (improve forest management, fire management)	Sectoral	0.4 (0.3 - 0.4)	ND	1.2 (0.6 - 1.9)	1.8 (1.1 - 2.8)
	IAM	ND	ND	ND	ND
Demand-side measures (shift to sustainable healthy diets, reduce food waste, and enhanced and improved use of wood products) ** for all three only the direct avoided emissions; land use effects are in measures above*	Sectoral	ND	ND	*2.2 (1.1 - 3.6)**	*4.2 (2.2 - 7.1)**
	IAM	ND	ND	ND	ND
	Sectoral	ND	ND	1.6 (0.5 - 3.5)	5.9 (0.5 - 11.3)

BECCS (only the CDR component, i.e the geological storage. Substitution effects are accounted in other sectoral chapters: energy, transport)	IAM	0.08 (0 - 0.7)	0.5 (0 - 6)	1.8 (0.2 - 9.9)	ND
Bioenergy from residues	Sectoral	ND	ND	ND	Up to 57 EJ yr^{-1}
TOTAL AFOLU (agriculture, forests & other ecosystems, diverted ag production from demand-side)	Sectoral	3.8 (2.7 - 4.9)	4.3 (2.3 - 6.7)	13.6 (6.7 - 23.4)	28.4 (8.8 - 65.1)
TOTAL AFOLU (agriculture, forests & other ecosystems, BECCS)	IAM	3.4 (0 - 14.6)	5.3 (0.6 - 19.4)	7.9 (4.1 - 17.3)	ND

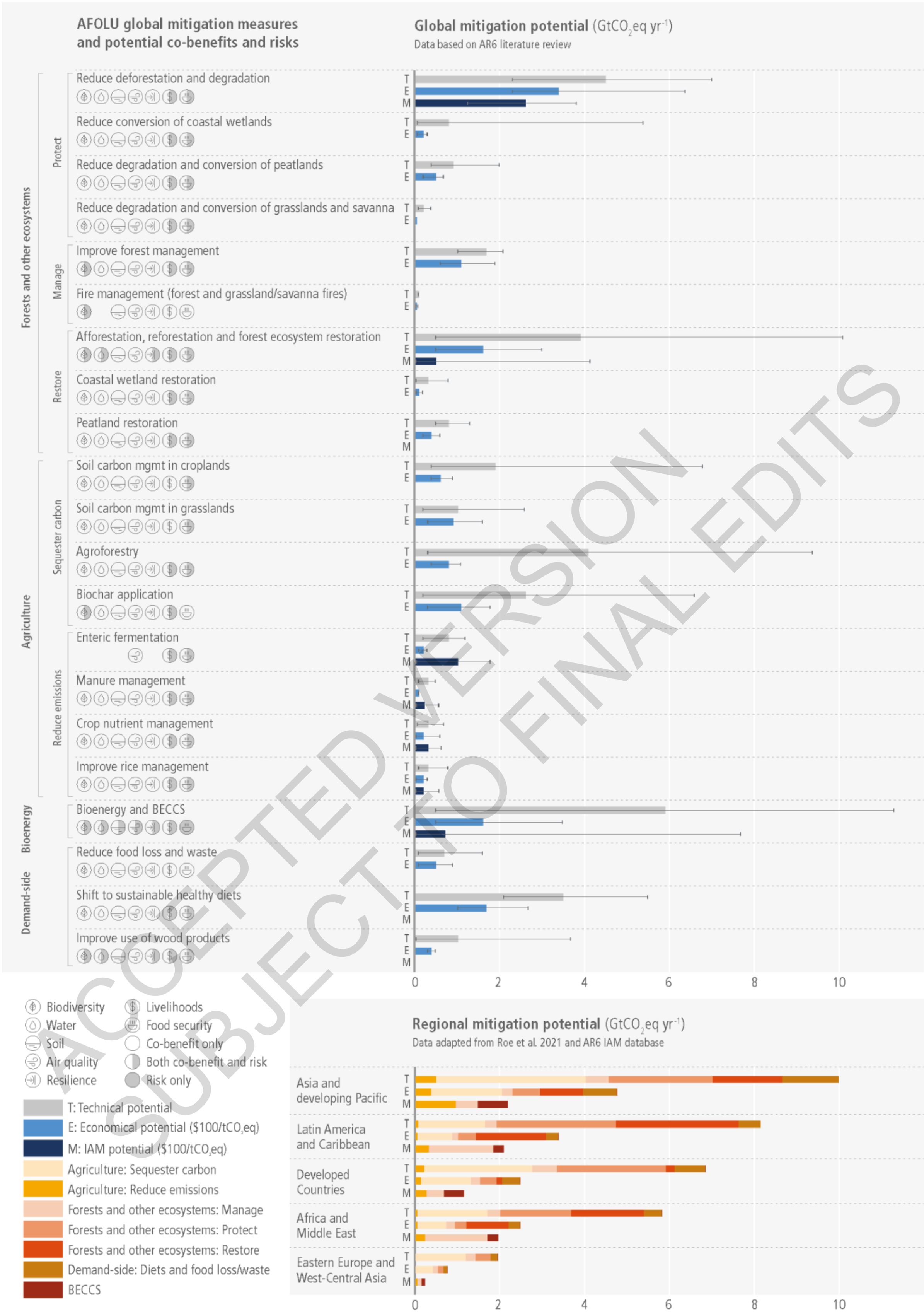


Figure 7.11 Global and regional mitigation potential ($GtCO_2$-eq yr^{-1}) in 2020–2050 for 20 land-based measures. (a) Global estimates represent the mean (bar) and full range (error bars) of the economic

potential (up to USD100 tCO_2-eq^{-1}) based on a comprehensive literature review of sectoral studies (references are outlined in the sub-section for each measure in 7.4.2–7.4.5). Potential co-benefits and trade-offs for each of the 20 measures are summarized in icons. (b) Regional estimates illustrate the mean technical (T) and economic (E) (up to USD100 tCO_2-eq^{-1}) sectoral potential based on data from (Roe et al. 2021). IAM economic potential (M) (USD100 tCO_2-eq^{-1}) data is from the IPCC AR6 database.

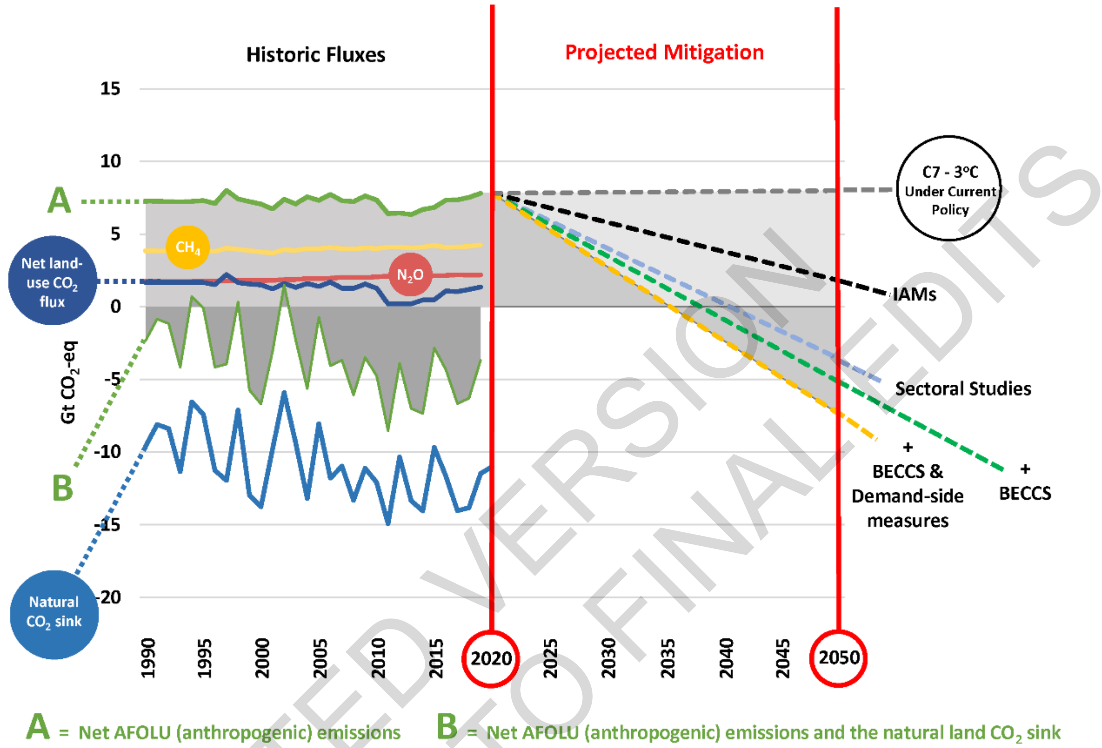


Figure 7.12 Historic land sector GHG flux estimates and illustrative AFOLU mitigation pathways to 2050, based on data presented in Sections 7.2, 7.4 and 7.5. Historic trends consider both (A) anthropogenic (AFOLU) GHG fluxes ($GtCO_2$-eq yr^{-1}) according to FAOSTAT (FAO 2021a; 2021b) and (B) the estimated natural land CO_2 sink according to (Friedlingstein et al. 2020). Note that for the anthropogenic net land CO_2 flux component, several approaches and methods are described within the literature (Section 7.2.2) with a wide range in estimates. For clarity, only one dataset (FAOSTAT) is illustrated here. It is not intended to indicate preference for one particular method over others. Historic flux trends are illustrated to 2019, the latest year for which data is available. Projected economic mitigation potential (at costs of up to USD100 tCO_2-eq^{-1}) includes estimates from IAMs and sectoral studies (Table 7.3). The sectoral estimates are disaggregated into agriculture + forests & other ecosystems, + demand-side measures (only accounting for diverted agricultural production to avoid double counting), and + BECCS (illustrating that there may be additional potential, with the caveat that there is likely overlap with other measures). Projected mitigation assumes adoption of measures to achieve increasing, linear mitigation, reaching average annual potential in 2050, although this does not reflect deployment rates for most measures. For illustrative purposes, a pathway to projected emissions in 2050 according to a scenario of current policy (C7 - Above 3.0°C - Model: GCAM 5.3) is additionally included for reference.

7.4.2. Forests and other ecosystems

7.4.2.1. Reduce deforestation and degradation

Activities, co-benefits, risks and implementation opportunities and barriers. Reducing deforestation and forest degradation conserves existing carbon pools in forest vegetation and soil by avoiding tree cover loss and disturbance. Protecting forests involves controlling the drivers of deforestation (such as commercial and subsistence agriculture, mining, urban expansion) and forest degradation (such as overharvesting including fuelwood collection, poor harvesting practices, overgrazing, pest outbreaks, and extreme wildfires), as well as by establishing well designed, managed and funded protected areas (Barber et al. 2020), improving law enforcement, forest governance and land tenure, supporting community forest management and introducing forest certification (Smith et al. 2019b). Reducing deforestation provides numerous and substantial co-benefits, preserving biodiversity and ecosystem services (e.g. air and water filtration, water cycling, nutrient cycling) more effectively and at lower costs than afforestation/reforestation (Jia et al. 2019). Potential adverse side effects of these conservation measures include reducing the potential for agriculture land expansion, restricting the rights and access of local people to forest resources, or increasing the dependence of local people to insecure external funding. Barriers to implementation include unclear land tenure, weak environmental governance, insufficient funds, and increasing pressures associated to agriculture conversion, resource exploitation and infrastructure development (Sections 7.3 and 7.6).

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. Reducing deforestation and forest degradation represents one of the most effective options for climate change mitigation, with technical potential estimated at 0.4–5.8 $GtCO_2\ yr^{-1}$ by 2050 (*high confidence*) (SRCCL, Chapters 2 and 4, and Table 6.14). The higher technical estimate represents a complete halting of land use conversion in forests and peatland forests (i.e., assuming recent rates of carbon loss are saved each year) and includes vegetation and soil carbon pools. Ranges of economic potentials for forestry ranged in AR5 from 0.01–1.45 $GtCO_2\ yr^{-1}$ for USD20 tCO_2^{-1} to 0.2–13.8 $GtCO_2\ yr^{-1}$ for USD100 tCO_2^{-1} by 2030 with reduced deforestation dominating the forestry mitigation potential LAM and MAF, but very little potential in OECD-1990 and EIT (IPCC AR5).

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). Since the SRCCL, several studies have provided updated and convergent estimates of economic mitigation potentials by region (Busch et al. 2019; Griscom et al. 2020; Austin et al. 2020; Roe et al. 2021). Tropical forests and /savannas in Latin America provide the largest share of mitigation potential (3.9 $GtCO_2\ yr^{-1}$ technical, 2.5 $GtCO_2\ yr^{-1}$ at USD100 tCO_2^{-1}) followed by Southeast Asia (2.2 $GtCO_2\ yr^{-1}$ technical, 1.5 $GtCO_2\ yr^{-1}$ at USD100 tCO_2^{-1}) and Africa (2.2 $GtCO_2\ yr^{-1}$ technical, 1.2 $GtCO_2\ yr^{-1}$ at USD100 tCO_2^{-1}) (Roe et al. 2021). Tropical forests continue to account for the highest rates of deforestation and associated GHG emissions. While deforestation shows signs of decreasing in several countries, in others, it continues at a high rate or is increasing (Turubanova et al. 2018). Between 2010-2020, the rate of net forest loss was 4.7 Mha yr^{-1} with Africa and South America presenting the largest shares (3.9 Mha and 2.6 Mha, respectively) (FAO 2020a).

A major uncertainty in all studies on avoided deforestation potential is their reliance on future reference levels that vary across studies and approaches. If food demand increases in the future, for example, the area of land deforested will likely increase, suggesting more technical potential for avoiding deforestation. Transboundary leakage due to market adjustments could also increase costs or reduce effectiveness of avoiding deforestation (e.g., Ingalls et al. 2018; Gingrich et al. 2019). Regarding forest regrowth, there are uncertainties about the time for the secondary forest carbon saturation (Zhu et al. 2018; Houghton and Nassikas 2017). Permanence of avoided deforestation may also be a concern due to the impacts of climate change and disturbance of other biogeochemical cycles on the world's forests that can result in future potential changes in terrestrial ecosystem productivity, climate-driven vegetation migration, wildfires, forest regrowth and carbon dynamics (Ballantyne et al. 2012; Kim et al. 2017b; Lovejoy and Nobre 2018; Aragão et al. 2018).

Critical assessment and conclusion. Based on studies since AR5, the technical mitigation potential for reducing deforestation and degradation is significant, providing 4.5 (2.3 - 7) $GtCO_2$ yr^{-1} globally by 2050, of which 3.4 (2.3 – 6.4) $GtCO_2$ yr^{-1} is available at below USD100 tCO_2^{-1} (*medium confidence)* (Figure 7.11). Over the last decade, hundreds of subnational initiatives that aim to reduce deforestation related emissions have been implemented across the tropics (Section 7.6). Reduced deforestation is a significant piece of the NDCs in the Paris Agreement (Seddon et al. 2020) and keeping the temperature below 1.5°C (Crusius 2020). Conservation of forests provides multiple co-benefits linked to ecosystem services, biodiversity and sustainable development (Section 7.6.). Still, ensuring good governance, accountability (e.g. enhanced monitoring and verification capacity; Bos 2020), and the rule of law are crucial for implementing forest-based mitigation options. In many countries with the highest deforestation rates, insecure land rights often are significant barriers for forest-based mitigation options (Gren and Zeleke 2016; Essl et al. 2018).

7.4.2.2. Afforestation, reforestation and forest ecosystem restoration

Activities, co-benefits, risks and implementation opportunities and barriers. Afforestation and reforestation (A/R) are activities that convert land to forest, where reforestation is on land that has previously contained forests, while afforestation is on land that historically has not been forested (Box 7.2). Forest restoration refers to a form of reforestation that gives more priority to ecological integrity as well, even though it can still be a managed forest. Depending on the location, scale, and choice and management of tree species, A/R activities have a wide variety of co-benefits and trade-offs. Well-planned, sustainable reforestation and forest restoration can enhance climate resilience and biodiversity, and provide a variety of ecosystem services including water regulation, microclimatic regulation, soil erosion protection, as well as renewable resources, income and livelihoods (Ellison et al. 2017; Locatelli et al. 2015; Verkerk et al. 2020; Stanturf et al. 2015). Afforestation, when well planned, can help address land degradation and desertification by reducing runoff and erosion and lead to cloud formation however, when not well planned, there are localised trade-offs such as reduced water yield or biodiversity (Teuling et al. 2017; Ellison et al. 2017) . The use of non-native species and monocultures may have adverse impacts on ecosystem structure and function, and water availability, particularly in dry regions (Ellison et al. 2017). A/R activities may change the surface albedo and evapotranspiration regimes, producing net cooling in the tropical and subtropical latitudes for local and global climate and net warming at high latitudes (Section 7.4.2). Very large-scale implementation of A/R may negatively affect food security since an increase in global forest area can increase food prices through land competition (Kreidenweis et al. 2016).

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. AR5 did not provide a new specification of A/R potential, but referred to AR4 mostly for forestry measures (Nabuurs et al. 2007). AR5 did view the feasible A/R potential from a diets change scenario that released land for reforestation and bioenergy crops. AR 5 provided top-down estimates of costs and potentials for forestry mitigation options - including reduced deforestation, forest management, afforestation, and agroforestry, estimated to contribute between 1.27 and 4.23 $GtCO_2$ yr^{-1} of economically viable abatement in 2030 at carbon prices up to USD100/t CO_2-eq (Smith et al. 2014).

The SRCCL remained with a reported wide range of mitigation potential for A/R of 0.5–10.1 $GtCO_2$ yr^{-1} by 2050 (*medium confidence*) (SRCCL Chapters 2 and 6; Roe et al. 2019; Fuss et al. 2018; Griscom et al. 2017; Hawken 2017; Kreidenweis et al. 2016). The higher estimate represents a technical potential of reforesting all areas where forests are the native cover type (reforestation), constrained by food security and biodiversity considerations, considering above and below-ground carbon pools and implementation on a rather theoretical maximum of 678 Mha of land (Roe et al. 2019; Griscom et al. 2017). The lower estimates represent the minimum range from an Earth System Model and a sustainable global CDR potential (Fuss et al. 2018). Climate change will affect the mitigation potential of reforestation due to impacts in forest growth and composition, as well as changes in disturbances including fire. However, none of the mitigation estimates included in the SRCCL account for climate impacts.

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). Since SRCCL, additional studies have been published on A/R mitigation potential by Bastin et al. (2019), Lewis et al. (2019), (Doelman et al. 2019), (Favero et al. 2020) and (Austin et al. 2020). These studies are within the range reported in the SRCCL stretching the potentials at the higher range. The rising public interest in nature-based solutions, along with high profile initiatives being launched (UN Decade on Restoration announced in 2019, the Bonn challenge on 150 million ha of restored forest in 2020 and e.g. the trillion-tree campaign launched by the World Economic Forum in 2020), has prompted intense discussions on the scale, effectiveness, and pitfalls of A/R and tree planting for climate mitigation (Anderegg et al. 2020; Bond et al. 2019; Heilmayr et al. 2020; Holl and Brancalion 2020; Luyssaert et al. 2018). The sometimes sole attention on afforestation and reforestation suggesting it may solve the climate problem to large extent in combination with the very high estimates of potentials have led to polarisation in the debate, again resulting in a push back to nature restoration only (Lewis et al. 2019). Our assessment based on most recent literature produced regional economic mitigation potential at USD100 tCO_2^{-1} estimate of 100-400 $MtCO_2$ yr^{-1} in Africa, 210-266 $MtCO_2$ yr^{-1} in Asia and developing Pacific, 291 $MtCO_2$-eq yr^{-1} in Developed countries (87% in North America), 30 $MtCO_2$-eq yr^{-1} in Eastern Europe and West-Central Asia, and 345-898 $MtCO_2$-eq yr^{-1} in Latin America and Caribbean (Roe et al. 2021), which totals to about 1200 $MtCO_2$ yr^{-1}, leaning to the lower range of the potentials in earlier IPCC reports. A recent global assessment of the aggregate costs for afforestation and reforestation suggests that at USD100 tCO_2^{-1}, 1.6 $GtCO_2$ yr^{-1} could be sequestered globally for an annual cost of USD130 billion (Austin et al. 2020). Sectoral studies that are able to deal with local circumstances and limits estimate A/R potentials at 20 $MtCO_2$ yr^{-1} in Russia (Eastern Europe and West-Central Asia) (Romanovskaya et al. 2020) and 64 $MtCO_2$ yr^{-1} in Europe (Nabuurs et al. 2017). (Domke et al. 2020) estimated for the USA an additional 20% sequestration rate from tree planting to achieve full stocking capacity of all understocked productive forestland, in total reaching 187 $MtCO_2$ yr^{-1} sequestration. A new study on costs in the USA estimates 72-91 $MtCO_2$ yr^{-1} could be sequestered between now and 2050 for USD100/t CO_2 (Wade et al. 2019). The tropical and subtropical latitudes are the most effective for forest restoration in terms of carbon sequestration because of the rapid growth and lower albedo of the land surface compared with high latitudes (Lewis et al. 2019).. Costs may be higher if albedo is considered in North America, Russia, and Africa (Favero et al. 2017). In addition, a wide variety of sequestration rates have been collected and published in e.g. IPCC Good Practice Guidance for the AFOLU sector (IPCC 2006).

Critical assessment and conclusion. There is *medium confidence* that the global technical mitigation potential of afforestation and reforestation activities by 2050 is 3.9 (0.5–10.1) $GtCO_2$ yr^{-1}, and the economic mitigation potential (< USD100 tCO_2^{-1}) is 1.6 (0.5 – 3.0) $GtCO_2$ yr^{-1} (requiring about 200 Mha). Per hectare a long (about 100 year) sustained effect of 5-10 $t(CO_2)$ ha^{-1} yr^{-1} is realistic with ranges between 1-20 $t(CO_2)$ ha^{-1} yr^{-1}. Not all sectoral studies rely on economic models that account for leakage (Murray et al. 2004; Sohngen and Brown 2004), suggesting that technical potential may be overestimated.

7.4.2.3. Improved forest management

Activities, co-benefits, risks and implementation opportunities and barriers.

Improved sustainable forest management of already managed forests can lead to higher forest carbon stocks, better quality of produced wood, continuously produce wood while maintaining and enhancing the forest carbon stock, and can also partially prevent and counteract the impacts of disturbances (Kurz et al. 2008; Marlon et al. 2012; Abatzoglou and Williams 2016; Tian et al. 2018; Seidl et al. 2017; Nabuurs et al. 2017; Ekholm 2020). Furthermore it can provide benefits for climate change adaptation, biodiversity conservation, microclimatic regulation, soil erosion protection and water and flood regulation with reduced lateral C fluxes (Ashton et al. 2012; Verkerk et al. 2020; Martínez-Mena et al. 2019). Often, in existing (managed) forests with existing C stocks, large changes per hectare cannot be expected, although many forest owners may respond to carbon price incentives (Favero et al. 2020; Ekholm 2020). The full mitigation effects can be assessed in conjunction with the overall forest and wood use system i.e., carbon stock changes in standing trees, soil, harvested wood products (HWPs) and its bioenergy component with the avoided emissions through substitution. Forest management strategies aimed at increasing the biomass stock may have adverse side effects, such as decreasing the stand-level structural complexity, large emphasis on pure fast growing stands, risks for biodiversity and resilience to natural disasters.

Generally measures can consist of one or combination of longer rotations, less intensive harvests, continuous-cover forestry, mixed stands, more adapted species, selected provenances, high quality wood assortments, etc. Further, there is a trade-off between management in various parts of the forest product value chain, resulting in a wide range of results on the role of managed forests in mitigation (Agostini et al. 2013; Braun et al. 2016; Gustavsson et al. 2017; Erb et al. 2017; Soimakallio et al. 2016; Hurmekoski et al. 2020; Favero et al. 2020). Some studies conclude that reduction in forest carbon stocks due to harvest exceeds for decades the joint sequestration of carbon in harvested wood product stocks and emissions avoided through wood use (Soimakallio et al. 2016; Seppälä et al. 2019), whereas others emphasise country level examples where investments in forest management have led to higher growing stocks while producing more wood (Cowie et al. 2021; Schulze et al. 2020; Ouden et al. 2020).

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. In the SRCCL, forest management activities have the potential to mitigate 0.4–2.1 $GtCO_2$-eq yr^{-1} by 2050 (*medium confidence*) (SRCCL: Griscom et al. 2017; Roe et al. 2019). The higher estimate stems from assumptions of applications on roughly 1.9 billion ha of already managed forest which can be seen as very optimistic. It combines both natural forest management as well as improved plantations, on average with a small net additional effect per hectare, not including substitution effects in the energy sector nor the buildings sector.

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). The area of forest under management plans has increased in all regions since 2000 by 233 Mha (FAO-FRA 2020). The roughly 1 billion ha of secondary and degraded forests would be ideal to invest in and develop a sustainable sector that pays attention to biodiversity, wood provision and climate mitigation at the same time. This all depends on the effort made, the development of expertise, know-how in the field, nurseries with adapted provenances, etc as was also found for Russian climate smart forestry options (Leskinen et al. 2020). Regionally, recently updated economic mitigation potential at USD100 tCO_2^{-1} have 179-186 $MtCO_2$-eq yr^{-1} in Africa, 193-313 $MtCO_2$-eq yr^{-1} in Asia and developing Pacific, 215-220 $MtCO_2$-eq yr^{-1} in Developed countries , 82-152 $MtCO_2$-eq yr^{-1} in Eastern Europe and West-Central Asia, and 62-204 $MtCO_2$-eq yr^{-1} in Latin America and Caribbean (Roe et al. 2021).

Regional studies can take into account the local situation better: Russia Romanovskaya et al. (2020) estimate the potential of forest fires management at 220–420 $MtCO_2$ yr^{-1}, gentle logging technology at 15–59, reduction of wood losses at 61–76 $MtCO_2$ yr^{-1}. In North America, (Austin et al. 2020) estimate that in the next 30 years, forest management could contribute 154 $MtCO_2$ yr^{-1} in the USA and Canada with 81 $MtCO_2$ yr^{-1} available at less than USD100 tCO_2^{-1}. In one production region (British Columbia) a cost-effective portfolio of scenarios was simulated that directed more of the harvested wood to longer-lived wood products, stopped burning of harvest residues and instead produced bioenergy to displace fossil fuel burning, and reduced harvest levels in regions with low disturbance rates. Net GHG emissions were reduced by an average of -9 $MtCO_2$-eq yr^{-1} (Smyth et al. 2020). In Europe, climate smart forestry could mitigate an additional 0.19 $GtCO_2$ yr^{-1} by 2050 (Nabuurs et al. 2017), in line with the regional estimates in (Roe et al. 2021).

In the tropics, estimates of the pantropical climate mitigation potential of natural forest management (a light intensity management in secondary forests), across three tropical regions (Latin America, Africa, Asia), is around 0.66 $GtCO_2$-eq yr^{-1} with Asia responding for the largest share followed by Africa and Latin America (Roe et al. 2021). Selective logging occurs in at least 20% of the world's tropical forests and causes at least half of the emissions from tropical forest degradation (Asner et al. 2005; Blaser and Küchli 2011; Pearson et al. 2017). Reduced-impact logging for climate (RIL-C; promotion of reduced wood waste, narrower haul roads, and lower impact skidding equipment) has the potential to reduce logging emissions by 44% (Ellis et al. 2019), while also providing timber production.

Critical assessment and conclusion. There is *medium confidence* that the global technical mitigation potential for improved forest management by 2050 is 1.7 (1–2.1) $GtCO_2$ yr^{-1}, and the economic mitigation potential (< USD100 tCO_2^{-1}) is 1.1 (0.6–1.9) $GtCO_2$ yr^{-1}. Efforts to change forest management do not only require e.g. a carbon price incentive, but especially require knowledge, institutions, skilled labour, good access etc. These requirements outline that although the potential is of medium size, we estimate a feasible potential towards the lower end. The net effect is also difficult to assess, as management changes impact not only the forest biomass, but also the wood chain and substitution effects. Further, leakage can arise from efforts to change management for carbon sequestration. Efforts e.g. to set aside large areas of forest may be partly counteracted by higher harvesting pressures elsewhere (Kallio and Solberg 2018). studies such as (Austin et al. 2020) implicitly account for leakage and thus suggest higher costs than other studies. We therefore judge the mitigation potential at medium potential with medium agreement.

[START BOX 7.2 HERE]

Box 7.2 Climate Smart Forestry in Europe

Summary

European forests have been regarded as prospering and increasing for the last 5 decades. However, these views also changed recently. Climate change is putting a large pressure on mono species and high stocked areas of Norway spruce in Central Europe (Hlásny et al. 2021; Senf and Seidl 2021) with estimates of mortality reaching 200 million m^3, biodiversity under pressure, the Mediterranean area showing a weak sector and harvesting pressure in the Baltics and north reaching maxima achievable. A European strategy for unlocking the EU's forests and forest sector potential was needed at the time of developing the LULUCF regulation and was based on the concept of "Climate Smart Forestry" (CSF) (Nabuurs et al. 2017; Verkerk et al. 2020).

Background

The idea behind CSF is that it considers the whole value chain from forest to wood products and energy, illustrating that a wide range of measures can be applied to provide positive incentives for more firmly integrating climate objectives into the forest and forest sector framework. CSF is more than just storing carbon in forest ecosystems; it builds upon three main objectives; (i) reducing and/or removing GHG emissions; (ii) adapting and building diverse forests for forest resilience to climate change; and (iii) sustainably increasing forest productivity and incomes. These three CSF objectives can be achieved by tailoring policy measures and actions to regional circumstances in Member States forest sectors.

Case description

The 2015 annual mitigation effect of EU-28 forests via contributions to the forest sink, material substitution and energy substitution is estimated at 569 $MtCO_2$ yr^{-1}, or 13% of total current EU emissions. With the right set of incentives in place at EU and Member States levels, it was found that the EU-28 has the potential to achieve an additional combined mitigation impact through the implementation of CSF of 441 $MtCO_2$ yr^{-1} by 2050. Also, with the Green Deal and its Biodiversity and Forest Strategy more emphasis will be placed on forests, forest management and the provision of renewables. It is the diversity of measures (from strict reserves to more intensively managed systems while adapting the resource) that will determine the success. Only with co-benefits in e.g. nature conservation, soil protection, and provision of renewables, wood for buildings and income, the mitigation and adaptation measures will be successful.

Interactions, limitations and lessons

Climate Smart Forestry is now taking shape across Europe with various research and implementation projects (Climate Smart Forest and Nature Management, 2021). Pilots and projects are being implemented by a variety of forest owners, some with more attention on biodiversity and adaptation, some with more attention on production functions. They establish examples and in longer term the outreach to the 16 million private owners in Europe. However, the right triggers and incentives are often still lacking. E.g. adapting the spruce forest areas in Central Europe to climate change requires knowledge about different species, biodiversity and different management options and eventually use in industry. It requires alternative species to be available from the nurseries, as well improved monitoring to assess the success and steer activities.

[END BOX 7.2 HERE]

7.4.2.4. Fire management (forest and grassland/savanna fires)

Activities, co-benefits, risks and implementation opportunities and barriers. Fire management objectives include safeguarding life, property, and resources through the prevention, detection, control, restriction, and management of fire for diverse purposes in natural ecosystems (SRCCL Chapter 6). Controlled burning is an effective economic method of reducing fire danger and stimulating natural regeneration. Co-benefits of fire management include reduced air pollution compared to much larger, uncontrolled fires, prevention of soil erosion and land degradation, biodiversity conservation in rangelands, and improvement of forage quality (Hurteau et al. 2019; Hurteau and Brooks 2011; Falk 2017). Fire management is still challenging because it is not only fire suppression at times of fire, but especially proper natural resource management in between fire events. Furthermore, it is challenging because of legal and policy issues, equity and rights concerns, governance, capacity, and research needs (Russell-Smith et al. 2017; Goldammer 2016 ; Wiedinmyer and Hurteau 2010). It will increasingly be needed under future enhanced climate change.

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. In the SRCCL, fire management is among the nine options that can deliver medium-to-large benefits across multiple land challenges (climate change mitigation, adaptation, desertification, land degradation, and food security) (*high confidence*). Total emissions from fires have been on the order of 8.1 $GtCO_2$-eq yr^{-1} in terms of gross biomass loss for the period 1997–2016 (SRCCL, Chapter 2 and Cross-Chapter Box 3 in Chapter 2). Reduction in fire CO_2 emissions was calculated to enhance land carbon sink by 0.48 $GtCO_2$-eq yr^{-1} for the 1960–2009 period (Arora and Melton 2018) (SRCCL, Table 6.16).

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL).
Savannas. Savannas constitute one of the most fire-prone vegetation types on Earth and are a significant source of GHG emissions. Savanna fires contributed 62% (4.92 $PgCO_2$-eq yr^{-1}) of gross global mean fire emissions between 1997 and 2016. Regrowth from vegetation postfire sequesters the CO_2 released into the atmosphere, but not the CH_4 and N_2O emissions which contributed an approximate net of 2.1 PgCO2-eq yr−1 (Lipsett-Moore et al. 2018). Therefore, implementing prescribed burning with low intensity fires, principally in the early dry season, to effectively manage the risk of wildfires occurring in the late dry season is associated with reducing emissions (Whitehead et al. 2014). Considering this fire management practice, estimates of global opportunities for emissions reductions were estimate at 69.1 $MtCO_2$-eq yr^{-1} in Africa (29 countries, with 20 least developed African countries accounting for 74% of the mitigation potential), 13.3 $MtCO_2$-eq yr^{-1} in South America (six countries), and 6.9 $MtCO_2$-eq yr^{-1} in Australia and Papua New Guinea (Lipsett-Moore et al. 2018). In Australia, savanna burning emissions abatement methodologies have been available since 2012, and abatement has exceeded 4 $MtCO_2$-eq mainly through the management of low intensity early dry season fire (Lynch et al. 2018). Until August 2021, 78 were registered (Australian Government, Clean Energy Regulator, 2021).

Forests. Fire is also a prevalent forest disturbance (Scott et al. 2014; Falk et al. 2011; Andela et al. 2019). About 98 Mha of forest were affected by fire in 2015, affecting about 4% of the tropical (dry) forests, 2% of the subtropical forests, and 1% of temperate and boreal forests (FAO 2020a). Between 2001-2018, remote sensing data showed that tree-covered areas correspond to about 29% of the total area burned by wildfires, most in Africa. Prescribed fires are also applied routinely in forests worldwide for fuel reduction and ecological reasons (Kalies and Yocom Kent 2016). Fire resilience is increasingly managed in southwestern USA forest landscapes, which have experienced droughts and widespread, high-severity wildfires (Keeley et al. 2019). In these forests, fire exclusion management, coupled with a warming climate, has led to increasingly severe wildfires (Hurteau et al. 2014). However, the impacts of prescribed fires in forests in reducing carbon emissions are still inconclusive. Some positive impacts of prescribed fires are associated with other fuel reduction techniques (Loudermilk et al. 2017; Flanagan et al. 2019; Stephens et al. 2020), leading to maintaining C stocks and reducing C emissions in the future where extreme fire weather events are more frequent (Krofcheck et al. 2018, 2019; Hurteau et al. 2019). (Bowman et al. 2020b,a; Goodwin et al. 2020; Hurteau et al. 2019). Land management approaches will certainly need to consider the new climatic conditions (e.g., the proportion of days in fire seasons with the potential for unmanageable fires more than doubling in some regions in northern and eastern boreal forest) (Wotton et al. 2017).

Critical assessment and conclusion. There is *low confidence* that the global technical mitigation potential for grassland and savanna fire management by 2050 is 0.1 (0.09–0.1) $GtCO_2$ yr^{-1}, and the economic mitigation potential (< USD100 tCO_2^{-1}) is 0.05 (0.03–0.07) $GtCO_2$ yr^{-1}. Savanna fires produce significant emissions globally, but prescribed fires in the early dry season could mitigate emissions in different regions, particularly Africa. Evidence is less clear for fire management of forests, with the contribution of GHG mitigation depending on many factors that affect the carbon balance (e.g., Simmonds et al. 2021). Although prescribed burning is promoted to reduce uncontrolled wildfires in forests, the benefits for the management of carbon stocks are unclear, with different studies reporting varying results especially concerning its long term effectiveness. (Bowman et al. 2020b; Wotton et al. 2017). Under increasing climate change however, an increased attention on fire management will be necessary.

7.4.2.5. Reduce degradation and conversion of grasslands and savannas

Activities, co-benefits, risks and implementation opportunities and barriers. Grasslands cover approximately 40.5 % of the terrestrial area (i.e., 52.5 million km^2) divided as 13.8% woody savanna and savanna; 12.7% open and closed shrub; 8.3 % non-woody grassland; and 5.7% is tundra (White et al. 2000). Sub-Saharan Africa and Asia have the most extensive total area, 14.5 and 8.9 million km^2, respectively. A review by Conant et al. (2017) reported based on data on grassland area (FAO 2013) and grassland soil carbon stocks (Sombroek et al. 1993) a global estimate of about 343 Pg C (in the top 1 m), nearly 50% more than is stored in forests worldwide (FAO 2007). Reducing the conversion of grasslands and savannas to croplands prevents soil carbon losses by oxidation, and to a smaller extent, biomass carbon loss due to vegetation clearing (SRCCL, Chapter 6). Restoration of grasslands through enhanced soil carbon sequestration, including a) management of vegetation, b) animal management, and c) fire management, was also included in the SRCCL and is covered in Section 7.4.3.1. Similar to other measures that reduce conversion, conserving carbon stocks in grasslands and savannas can be achieved by controlling conversion drivers (e.g., commercial and subsistence agriculture, see Section 7.3) and improving policies and management. In addition to mitigation, conserving grasslands provide various socio-economic, biodiversity, water cycle and other environmental benefits (Claassen et al. 2010; Ryals et al. 2015; Bengtsson et al. 2019). Annual operating costs, and opportunity costs of income foregone by undertaking the activities needed for avoiding conversion of grasslands making costs one of the key barriers for implementation (Lipper et al. 2010).

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. The SRCCL reported a mitigation potential for reduced conversion of grasslands and savannas of 0.03–0.12 $GtCO_2$-eq yr^{-1} (SRCCL: Griscom et al. 2017) considering the higher loss of soil organic carbon in croplands (Sanderman et al. 2017). Assuming an average starting soil organic carbon stock of temperate grasslands (Poeplau et al. 2011), and the mean annual global cropland conversion rates (1961–2003) (Krause et al. 2017), the equivalent loss of soil organic carbon over 20 years would be 14 $GtCO_2$-eq, i.e. 0.7 $GtCO_2$ yr^{-1} (SRCCL, Chapter 6). IPCC AR5 and AR4 did not explicitly consider the mitigation potential of avoided conversion of grasslands-savannas but the management of grazing land is accounted for considering plant, animal, and fire management with a mean mitigation potential of 0.11-0.80 tCO_2-eq ha^{-1} yr^{-1} depending on the climate region. This resulted in 0.25 $GtCO_2$-eq yr^{-1} at USD20 tCO_2^{-1} to 1.25 $GtCO_2$-eq yr^{-1} at USD100 tCO_2^{-1} by 2030.

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). Unlike most of the measures covered in Section 7.4, there are currently no global, spatially explicit mitigation potential estimates for reduced grassland conversion to generate technical and economic potentials by region. Literature developments since AR5 and SRCCL are studies that provide mitigation estimates in one or a few countries or regions. Modelling experiments comparing Californian forests and grasslands found that grasslands resulted in a more resilient C sink than forests to future climate change (Dass et al. 2018). However, previous studies indicated that precipitation is a key controller of the carbon storage in these grasslands, with the grassland became a carbon sink in 2005, when the region received relatively high spring precipitation (Ma et al. 2007). In North America, grassland conversion was the source for 77% of all new croplands from 2008-2012 (Lark et al. 2015). Avoided conversion of North American grasslands to croplands presents an economic mitigation potential of 0.024 $GtCO_2$-eq yr^{-1} and technical potential of 0.107 $GtCO_2$-eq yr^{-1} (Fargione et al. 2018). This potential is related mainly to root biomass and soils (81% of emissions from soils). Estimates of GHG emissions from any future deforestation in Australian savannas also point to the potential mitigation of around 0.024 GtCO2-eq yr-1 (Bristow et al. 2016). The expansion of the Soy Moratorium (SoyM) from the Brazilian Amazon to the Cerrado (Brazilian savannas) would prevent the direct conversion of 3.6 Mha of native vegetation to soybeans by 2050 and avoid the emission of 0.02 $GtCO_2$-eq yr^{-1} (Soterroni et al. 2019).

Critical assessment and conclusion. There is *low confidence* that the global technical mitigation potential for reduced grassland and savanna conversion by 2050 is 0.2 (0.1–0.4) $GtCO_2$ yr^{-1}, and the economic mitigation potential (< USD100 tCO_2^{-1}) is 0.04 $GtCO_2$ yr^{-1}. Most of the carbon sequestration potential is in belowground biomass and soil organic matter. However, estimates of potential are still based on few studies and vary according the levels of soil carbon, and ecosystem productivity (e.g. in response to rainfall distribution). Conservation of grasslands presents significant benefits for desertification control, especially in arid areas (SRCCL, Chapter 3). Policies supporting avoided conversion can help protect at-risk grasslands, reduce GHG emissions, and produce positive outcomes for biodiversity and landowners (Ahlering et al. 2016). In comparison to tropical rainforest regions that have been the primary target for mitigation policies associated to natural ecosystems (e.g. REDD+), Conversion grasslands and savannas has received less national and international attention, despite growing evidence of concentrated cropland expansion into these areas with impacts of carbon losses.

7.4.2.6. Reduce degradation and conversion of peatlands

Activities, co-benefits, risks and implementation barriers. Peatlands are carbon-rich wetland ecosystems with organic soil horizons in which soil organic matter concentration exceeds 30% (dry weight) and soil carbon concentrations can exceed 50% (Page and Baird 2016, Boone Kauffman et al. 2017). Reducing the conversion of peatlands avoids emissions of above- and below-ground biomass and soil carbon due to vegetation clearing, fires, and peat decomposition from drainage. Similar to deforestation, peatland carbon stocks can be conserved by controlling the drivers of conversion and degradation (e.g. commercial and subsistence agriculture, mining, urban expansion) and improving governance and management. Reducing conversion is urgent because peatland carbon stocks accumulate slowly and persist over millennia; loss of existing stocks cannot be easily reversed over the decadal timescales needed to meet the Paris Agreement (Goldstein et al. 2020). The main co-benefits of reducing conversion of peatlands include conservation of a unique biodiversity including many critically endangered species, provision of water quality and regulation, and improved public health through decreased fire-caused pollutants (Griscom et al. 2017). Although reducing peatland conversion will reduce land availability for alternative uses including agriculture or other land-based mitigation, drained peatlands constitute a small share of agricultural land globally while contributing significant emissions (Joosten 2009). Mitigation through reduced conversion of peatlands therefore has a high potential of avoided emissions per hectare (Roe et al. 2019).

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. In the SRCCL (Chapters 2 and 6), it was estimated that avoided peat impacts could deliver 0.45–1.22 $GtCO_2$-eq yr^{-1} technical potential by 2030-2050 (*medium confidence*) (Griscom et al. 2017; Hawken 2017; Hooijer et al. 2010). The mitigation potential estimates cover tropical peatlands and include CO_2, N_2O and CH_4 emissions. The mitigation potential is derived from quantification of losses of carbon stocks due to land conversion, shifts in GHG fluxes, alterations in net ecosystem productivity, input factors such as fertilisation needs, and biophysical climate impacts (e.g., shifts in albedo, water cycles, etc). Tropical peatlands account for only ~10% of peatland area and about 20% of peatland carbon stock but about 80% of peatland carbon emissions, primarily from peatland conversion in Indonesia (about 60%) and Malaysia (about 10%) (Page et al. 2011; Leifeld and Menichetti 2018; Hooijer et al. 2010). While the total mitigation potential of peatland conservation is considered moderate, the per hectare mitigation potential is the highest among land-based mitigation measures (Roe et al. 2019).

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). Recent studies continue to report high carbon stocks in peatlands and emphasize the vulnerability of peatland carbon after conversion. The carbon stocks of tropical peatlands are among the highest of any forest, 1,211-4,257 tCO_2-eq ha^{-1} in the Peruvian Amazon (Bhomia et al. 2019) and 1,956-14,757 tCO_2-eq ha^{-1} in

Indonesia (Novita et al. 2021). Ninety percent of tropical peatland carbon stocks are vulnerable to emission during conversion and may not be recoverable through restoration; in contrast, boreal and temperate peatlands hold similar carbon stocks (1,439-5,619 tCO_2-eq ha^{-1}) but only 30% of northern carbon stocks are vulnerable to emission during conversion and irrecoverable through restoration (Goldstein et al. 2020). A recent study shows global mitigation potential of about 0.2 $GtCO_2$-eq yr^{-1} at costs up to USD100 tCO_2^{-1} (Roe et al. 2021). Another study estimated that 72% of mitigation is achieved through avoided soil carbon impacts, with the remainder through avoided impacts to vegetation (Bossio et al. 2020). Recent model projections show that both peatland protection and peatland restoration (Section 7.4.2.7) are needed to achieve a 2ºC mitigation pathway and that peatland protection and restoration policies will have minimal impacts on regional food security (Leifeld et al. 2019, Humpenöder et al. 2020). Global studies have not accounted for extensive peatlands recently reported in the Congo Basin, estimated to cover 145,500 km2 and contain 30.6 Pg C, as much as 29% of total tropical peat carbon stock (Dargie et al. 2017). These Congo peatlands are relatively intact; continued preservation is needed to prevent major emissions (Dargie et al. 2019). In northern peatlands that are underlain by permafrost (roughly 50% of the total peatlands north of 23º latitude, (Hugelius et al. 2020), climate change (i.e. warming) is the major driver of peatland degradation (e.g. through permafrost thaw) (Schuur et al. 2015, Goldstein et al. 2020). However, in non-permafrost boreal and temperate peatlands, reduction of peatland conversion is also a cost-effective mitigation strategy. Peatlands are sensitive to climate change and there is *low confidence* about the future peatland sink globally (SRCCL, Chapter 2). Permafrost thaw may shift northern peatlands from a net carbon sink to net source (Hugelius et al. 2020). Uncertainties in peatland extent and the magnitude of existing carbon stocks, in both northern (Loisel et al. 2014) and tropical (Dargie et al. 2017) latitudes limit understanding of current and future peatland carbon dynamics (Minasny et al. 2019).

Critical assessment and conclusion. Based on studies to date, there is *medium confidence* that peatland conservation has a technical potential of 0.86 (0.43–2.02) $GtCO_2$-eq yr^{-1} of which 0.48 (0.2–0.68) $GtCO_2$-eq yr^{-1} is available at USD100 tCO_2^{-1} (Figure 7.11). High per hectare mitigation potential and high rate of co-benefits particularly in tropical countries, support the effectiveness of this mitigation strategy (Roe et al. 2019). Feasibility of reducing peatland conversion may depend on countries' governance, financial capacity and political will.

7.4.2.7. Peatland restoration

Activities, co-benefits, risks and implementation barriers. Peatland restoration involves restoring degraded and damaged peatlands, for example through rewetting and revegetation, which both increases carbon accumulation in vegetation and soils and avoids ongoing CO_2 emissions. Peatlands only account for about 3% of the terrestrial surface, predominantly occurring in boreal ecosystems (78%), with a smaller proportion in tropical regions (13%), but may store about 600 Gt Carbon or 21% of the global total soil organic Carbon stock of about 3000 Gt (Leifeld and Menichetti 2018; Page et al. 2011). Peatland restoration delivers co-benefits for biodiversity, as well as regulating water flow and preventing downstream flooding, while still allowing for extensive management such as paludiculture (Tan et al. 2021). Rewetting of peatlands also reduces the risk of fire, but may also mobilize salts and contaminants in soils (van Diggelen et al. 2020) and in severely degraded peatlands, restoration of peatland hydrology and vegetation may not be feasible (Andersen et al. 2017). At a local level, restoration of peatlands drained for agriculture could displace food production and damage local food supply, although impacts to regional and global food security would be minimal (Humpenöder et al. 2020). Collaborative and transparent planning processes are needed to reduce conflict between competing land uses (Tanneberger et al. 2020b). Adequate resources for implementing restoration policies are key to engage local communities and maintain livelihoods (Ward et al. 2021; Resosudarmo et al. 2019).

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. Large areas (0.51 Mkm^2) of global peatlands are degraded of which 0.2 Mkm^2 are tropical peatlands (Griscom et al. 2017; Leifeld and Menichetti 2018). According the SRCCL, peatland restoration could deliver technical mitigation potentials of 0.15 - 0.81$GtCO_2$-eq yr^{-1} by 2030-2050 (*low confidence*) (Chapter 2 and 6 of the SRCCL; (Couwenberg et al. 2010; Griscom et al. 2017), though there could be an increase in methane emissions after restoration (Jauhiainen et al. 2008). The mitigation potential estimates cover global peatlands and include CO_2, N_2O and CH_4 emissions. Peatlands are highly sensitive to climate change (*high confidence*), however there are currently no studies that estimate future climate effects on mitigation potential from peatland restoration.

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). The most recent literature and reviews indicate with *high confidence* that restoration would decrease CO_2 emissions and with *medium confidence* that restoration would decrease net GHG emissions from degraded peatlands (Wilson et al. 2016; Ojanen and Minkkinen 2020; van Diggelen et al. 2020). Although rewetting of drained peatlands increases CH_4 emissions, this effect is often outweighed by decreases in CO_2 and N_2O emissions but depends very much on local circumstances (Günther et al. 2020). Restoration and rewetting of almost all drained peatlands is needed by 2050 to meet 1.5-2ºC pathways which is unlikely to happen (Leifeld et al. 2019); immediate rewetting and restoration minimises the warming from cumulative CO_2 emissions (Nugent et al. 2019).

According to recent data, the technical mitigation potential for global peatland restoration is estimated at 0.5-1.3 $GtCO_2$-eq yr^{-1} (Leifeld and Menichetti 2018; Griscom et al. 2020; Bossio et al. 2020; Roe et al. 2021; Figure 7.11), with 80% of the mitigation potential derived from improvements to soil carbon (Bossio et al. 2020). The regional mitigation potentials of all peatlands outlined in Roe et al. (2021) reflect the country-level estimates from (Humpenöder et al. 2020).

Climate mitigation effects of peatland rewetting depend on the climate zone and land use. Recent analysis shows the strongest mitigation gains from rewetting drained temperate and boreal peatlands used for agriculture and drained tropical peatlands (Ojanen and Minkkinen 2020). However, estimates of emission factors from rewetting drained tropical peatlands remain uncertain (Wilson et al. 2016; Murdiyarso et al. 2019). Topsoil removal, in combination with rewetting, may improve restoration success and limit CH_4 emissions during restoration of highly degraded temperate peatlands (Zak et al. 2018). In temperate and boreal regions, co-benefits mentioned above are major motivations for peatland restoration (Chimner et al. 2017; Tanneberger et al. 2020a).

Critical assessment and conclusion. Based on studies to date, there is *medium confidence* that peatland restoration has a technical potential of 0.79 (0.49–1.3) $GtCO_2$-eq yr^{-1} (median) of which 0.4 (0.2–0.6) $GtCO_2$-eq yr^{-1} is available up to USD100 tCO_2^{-1}. The large land area of degraded peatlands suggests that significant emissions reductions could occur through large-scale restoration especially in tropical peatlands. There is *medium confidence* in the large carbon stocks of tropical peat forests (1,956-14,757 tCO_2-eq ha^{-1}) and large rates of carbon loss associated with land cover change (640-1,650 tCO_2-eq ha^{-1}) (Novita et al. 2021; Goldstein et al. 2020). However, large-scale implementation of tropical peatland restoration will likely be limited by costs and other demands for these tropical lands.

7.4.2.8. Reduce conversion of coastal wetlands

Activities, co-benefits, risks and implementation barriers. Reducing conversion of coastal wetlands, including mangroves, marshes and seagrass ecosystems, avoids emissions from above and below ground biomass and soil carbon through avoided degradation and/or loss. Coastal wetlands occur mainly in estuaries and deltas, areas that are often densely settled, with livelihoods closely linked to coastal ecosystems and resources (Moser et al. 2012). The carbon stocks of these highly productive ecosystems are sometimes referred to as "blue carbon". Loss of existing stocks cannot be easily reversed over decadal timescales (Goldstein et al. 2020). The main drivers of conversion include intensive aquaculture, agriculture, salt ponds, urbanisation and infrastructure development, the extensive use of fertilisers, and extraction of water resources (Lovelock et al. 2018). Reduced conversion of coastal wetlands has many co-benefits, including biodiversity conservation, fisheries production, soil stabilisation, water flow and water quality regulation, flooding and storm surge prevention, and increased resilience to cyclones (UNEP 2020; Windham-Myers et al. 2018a). Risks associated with the mitigation potential of coastal wetland conservation include uncertain permanence under future climate scenarios, including the effects of coastal squeeze, where coastal wetland area may be lost if upland area is not available for migration as sea levels rise (IPCC WGII Ch. 3.4.2.5; (Lovelock and Reef 2020). Preservation of coastal wetlands also conflicts with other land use in the coastal zone, including aquaculture, agriculture, and human development; economic incentives are needed to prioritise wetland preservation over more profitable short-term land use. Integration of policies and efforts aimed at coastal climate mitigation, adaptation, biodiversity conservation, and fisheries, for example through Integrated Coastal Zone Management and Marine Spatial Planning, will bundle climate mitigation with co-benefits and optimise outcomes (Herr et al. 2017).

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. Coastal wetlands contain high, yet variable, organic carbon stocks, leading to a range of estimates of the global mitigation potential of reduced conversion. The SRCCL (Chapter 2) and SROCCC (Chapter 5), report a technical mitigation potential of 0.15–5.35 $GtCO_2$-eq yr^{-1} by 2050 (Lovelock et al. 2017; Pendleton et al. 2012; Howard et al. 2017; Griscom et al. 2017)**.** The mitigation potential is derived from quantification of losses of carbon stocks in vegetation and soil due to land conversion, shifts in GHG fluxes associated with land use, and alterations in net ecosystem productivity. The wide range in estimates mostly relate to the scope (all coastal ecosystems vs. mangroves only) and different assumptions on decomposition rates. Loss rates of coastal wetlands have been estimated at 0.2-3% yr-1, depending on the vegetation type and location (Atwood et al. 2017; Howard et al. 2017).

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). Global technical mitigation potential for conservation of coastal wetlands from recent literature have focused on protection of mangroves; estimates range from 0.06–2.25 $GtCO_2$-eq yr^{-1} (Griscom et al. 2020; Bossio et al. 2020) with 80% of the mitigation potential derived from improvements to soil carbon (Bossio et al. 2020). Regional potentials (Roe et al. 2021) reflect mangrove protection; marsh and seagrass protection were not included due to lack of country-level data on marsh and seagrass distribution and conversion.

Global estimates show mangroves have the largest per hectare carbon stocks (see IPCC WGII AR6 Box 3.4 for estimates of carbon stocks, burial rates and ecosystem extent for coastal wetland ecosystems). Mean ecosystem carbon stock in mangroves is 3131 tCO_2-eq ha^{-1} among the largest carbon stocks on Earth. Recent studies emphasize the variability in total ecosystem carbon stocks for each wetland type, based on species and climatic and edaphic conditions (Kauffman et al. 2020; Bedulli et al. 2020; Ricart et al. 2020; Wang et al. 2021; Alongi et al. 2020), and highlight the vulnerability of soil carbon below 1 m depth (Arifanti et al. 2019). Sea level strongly influences coastal wetland distribution, productivity, and sediment accretion; therefore, sea level rise will impact carbon accumulation and persistence of existing carbon stocks (Macreadie et al. 2019, IPCC WGII AR6 Box 3.4).

Recent loss rates of mangroves are 0.16-0.39% y^{-1} and are highest in Southeast Asia (Friess et al. 2019; Hamilton and Casey 2016). Assuming loss of soil C to 1 m depth after deforestation, avoiding mangrove conversion has the technical potential to mitigate approximately 23.5-38.7 $MtCO_2$-eq y^{-1} (Ouyang and Lee 2020); note, this potential is additional to reduced conversion of forests (Griscom et al. 2020, 7.4.2.1). Regional estimates show that about 85% of mitigation potential for avoided mangrove conversion is in Southeast Asia and Developing Pacific (32 $MtCO_2$-eq yr^{-1} at USD100 tCO_2^{-1}), 10% is in Latin American and the Caribbean (4 $MtCO_2$-eq y^{-1}), and approximately 5% in other regions (Griscom et al. 2020; Roe et al. 2021).

Key uncertainties remain in mapping extent and conversion rates for salt marshes and seagrasses (McKenzie et al. 2020). Seagrass loss rates were estimated at 1-2% y^{-1} (Dunic et al. 2021) with stabilization in some regions (IPCC WGII Ch. 3.4.2.5; (de los Santos et al. 2019); however, loss occurs non-linearly and depends on site-specific context. Tidal marsh extent and conversion rates remains poorly estimated, outside of the USA, Europe, South Africa, and Australia (Mcowen et al. 2017; Macreadie et al. 2019).

Critical assessment and conclusion. There is *medium confidence* that coastal wetland protection has a technical potential of 0.8 (0.06–5.4) $GtCO_2$-eq yr^{-1} of which 0.17 (0.06–0.27) $GtCO_2$-eq yr^{-1} is available up to USD100 tCO_2^{-1}. There is a *high certainty* (robust evidence, high agreement) that coastal ecosystems have among the largest carbon stocks of any ecosystem. As these ecosystems provide many important services, reduced conversion of coastal wetlands is a valuable mitigation strategy with numerous co-benefits. However, the vulnerability of coastal wetlands to climatic and other anthropogenic stressors may limit the permanence of climate mitigation.

7.4.2.9. Coastal wetland restoration

Activities, co-benefits, risks and implementation barriers. Coastal wetland restoration involves restoring degraded or damaged coastal wetlands including mangroves, salt marshes, and seagrass ecosystems, leading to sequestration of 'blue carbon' in wetland vegetation and soil (SRCCL Ch 6, SROCCC Ch 5). Successful approaches to wetland restoration include: (1) passive restoration, the removal of anthropogenic activities that are causing degradation or preventing recovery; and (2) active restoration, purposeful manipulations to the environment in order to achieve recovery to a naturally functioning system (Elliott et al. 2016; IPCC WGII Ch 3). Restoration of coastal wetlands delivers many valuable co-benefits, including enhanced water quality, biodiversity, aesthetic values, fisheries production (food security), and protection from rising sea levels and storm impacts (Barbier et al. 2011; Hochard et al. 2019; Sun and Carson 2020; Duarte et al. 2020). Of the 0.3 Mkm^2 coastal wetlands globally, 0.11 Mkm^2 of mangroves are considered feasible for restoration (Griscom et al. 2017). Risks associated with coastal wetland restoration include uncertain permanence under future climate scenarios (IPCC WGII AR6 Box 3.4), partial offsets of mitigation through enhanced methane and nitrous oxide release and carbonate formation, and competition with other land uses, including aquaculture and human settlement and development in the coastal zone (SROCCC, Chapter 5). To date, many coastal wetland restoration efforts do not succeed due to failure to address the drivers of degradation (van Katwijk et al. 2016). However, improved frameworks for implementing and assessing coastal wetland restoration are emerging that emphasize the recovery of ecosystem functions (Cadier et al. 2020; Zhao et al. 2016). Restoration projects that involve local communities at all stages and consider both biophysical and socio-political context are more likely to succeed (Brown et al. 2014; Wylie et al. 2016).

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. The SRCCL reported that mangrove restoration has the technical potential to mitigate 0.07 $GtCO_2$ yr^{-1} through rewetting (Crooks et al. 2011) and take up 0.02–0.84 $GtCO_2$ yr^{-1} from vegetation biomass and soil enhancement through 2030 (*medium confidence*) (Griscom et al. 2017). The SROCCC concluded that cost-effective coastal blue carbon restoration had a potential of ~0.15-0.18 $GtCO_2$-eq yr^{-1}, a low global potential compared to other ocean-based solutions but with extensive co-benefits and limited adverse side effects (Gattuso et al. 2018).

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). Recent studies emphasise the timeframe needed to achieve the full mitigation potential (Duarte et al. 2020; Taillardat et al. 2020). The first project-derived estimate of the net GHG benefit from seagrass restoration found 1.54 tCO_2-eq (0.42 MgC) ha^{-1} yr^{-1} 10 years after restoration began (Oreska et al. 2020); comparable to the default emission factor in the Wetlands Supplement (IPCC 2014). Recent studies of rehabilitated mangroves also indicate that annual carbon sequestration rates in biomass and soils can return to natural levels within decades of restoration (Cameron et al. 2019; Sidik et al. 2019). A meta-analysis shows increasing carbon sequestration rates over the first 15 years of mangrove restoration with rates stabilising at 25.7 ± 7.7 tCO_2-eq (7.0 ± 2.1 MgC) ha^{-1} yr^{-1} through forty years, although success depends on climate, sediment type, and restoration methods (Sasmito et al. 2019). Overall, 30% of mangrove soil carbon stocks and 50-70% of marsh and seagrass carbon stocks are unlikely to recover within 30 years of restoration, underscoring the importance of preventing conversion of coastal wetlands (7.4.2.8) (Goldstein et al. 2020).

According to recent data, the technical mitigation potential for global coastal wetland restoration is 0.04-0.84 $GtCO_2$-eq yr^{-1} (Griscom et al. 2020; Bossio et al. 2020; Roe et al. 2021) with 60% of the mitigation potential derived from improvements to soil carbon (Bossio et al. 2020). Regional potentials based on country-level estimates from Griscom et al. (2020) show the technical and economic (up to USD100 tCO_2^{-1}) potential of mangrove restoration; seagrass and marsh restoration was not included due to lack of country-level data on distribution and conversion (but see (McKenzie et al. (2020) for updates on global seagrass distribution). Although global potential is relatively moderate, mitigation can be quite significant for countries with extensive coastlines (e.g., Indonesia, Brazil) and for small island states where coastal wetlands have been shown to comprise 24-34% of their total national carbon stock (Donato et al. 2012). Furthermore, non-climatic co-benefits can strongly motivate coastal wetland restoration worldwide (UNEP 2021a). Major successes in both active and passive restoration of seagrasses have been documented in North America and Europe (Lefcheck et al. 2018; Orth et al. 2020; de los Santos et al. 2019); passive restoration may also be feasible for mangroves (Cameron et al. 2019).

There is high site-specific variation in carbon sequestration rates and uncertainties regarding the response to future climate change (Jennerjahn et al. 2017; Nowicki et al. 2017; IPCC WGII AR6 Box 3.4). Changes in distributions (Kelleway et al. 2017; Wilson and Lotze 2019)**,** methane release (Al-Haj and Fulweiler 2020), carbonate formation (Saderne et al. 2019), and ecosystem responses to interactive climate stressors are not well-understood (Short et al. 2016; Fitzgerald and Hughes 2019; Lovelock and Reef 2020).

Critical assessment and conclusion. There is *medium confidence* that coastal wetland restoration has a technical potential of 0.3 (0.04–0.84) $GtCO_2$-eq yr^{-1} of which 0.1 (0.05–0.2) $GtCO_2$-eq yr^{-1} is available up to USD100 tCO_2^{-1}. There is *high confidence* that coastal wetlands, especially mangroves, contain large carbon stocks relative to other ecosystems and *medium confidence* that restoration will reinstate pre-disturbance carbon sequestration rates. There is *low confidence* on the response of coastal wetlands to climate change; however, there is *high confidence* that coastal wetland restoration will provide a suite of valuable co-benefits.

7.4.3. Agriculture

7.4.3.1. Soil carbon management in croplands and grasslands

Activities, co-benefits, risks and implementation opportunities and barriers. Increasing soil organic matter in croplands are agricultural management practices that include (1) crop management: for example, high input carbon practices such as improved crop varieties, crop rotation, use of cover crops, perennial cropping systems (including agroforestry see Section 7.4.3.3), integrated production systems, crop diversification, agricultural biotechnology, (2) nutrient management including fertilization with organic amendments / green manures (Section 7.4.3.6), (3) reduced tillage intensity and residue retention, (4) improved water management: including drainage of waterlogged mineral soils and irrigation of crops in arid / semi-arid conditions, (5) improved rice management (Section 7.4.3.5) and (6) biochar application (Section 7.4.3.2) (Smith et al. 2019d). For increased soil organic matter in grasslands, practices include (1) *management of vegetation*: including improved grass varieties/sward composition, deep rooting grasses, increased productivity, and nutrient management, (2) *livestock management*: including appropriate stocking densities fit to carrying capacity, fodder banks, and fodder diversification, and (3) *fire management*: improved use of fire for sustainable grassland management, including fire prevention and improved prescribed burning (Smith et al. 2014, 2019d). All these measures are recognized as Sustainable Soil Management Practices by FAO (Baritz et al. 2018). Whilst there are co-benefits for livelihoods, biodiversity, water provision and food security Smith et al. 2019b , and impacts on leakage, indirect land-use change and foregone sequestration do not apply (since production in not displaced), the climate benefits of soil carbon sequestration in croplands can be negated if achieved through additional fertiliser inputs (potentially causing increased N_2O emissions; (Guenet et al. 2021), and both saturation and permanence are relevant concerns. When considering implementation barriers, soil carbon management in croplands and grasslands is a low-cost option at a high level of technology readiness (it is already widely deployed globally) with low socio-cultural and institutional barriers, but with difficulty in monitoring and verification proving a barrier to implementation (Smith et al. 2020a).

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. Building on AR5, the SRCCL reported the global mitigation potential for soil carbon management in croplands to be 1.4–2.3 $GtCO_2$-eq yr^{-1} (Smith et al. 2014), though the full literature range was 0.3-6.8 $GtCO_2$-eq yr^{-1} (Frank et al. 2017; Sommer and Bossio 2014; Conant et al. 2017; Dickie et al. 2014b; Fuss et al. 2018; Griscom et al. 2017; Hawken 2017; Henderson et al. 2015; Herrero et al. 2016; Paustian et al. 2016; Powlson et al. 2014; Sanderman et al. 2017; Zomer et al. 2016; Roe et al. 2019). The global mitigation potential for soil organic carbon management in grasslands was assessed to be 1.4–1.8 $GtCO_2$-eq yr^{-1}, with the full literature range being 0.1-2.6 $GtCO_2$-eq yr^{-1} (Conant et al. 2017; Herrero et al. 2016;2013; Roe et al. 2019). Lower values in the range represented economic potentials, whilst higher values represented technical potentials – and uncertainty was expressed by reporting the whole range of estimates. The SR1.5 outlined associated costs reported in literature to range from USD -45 to 100 tCO_2^{-1}, describing enhanced soil carbon sequestration as a cost-effective measure (IPCC 2018). Despite significant mitigation potential, there is limited inclusion of soil carbon sequestration as a response option within IAM mitigation pathways (Rogelj et al. 2018a).

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). No recent literature has been published which conflict with the mitigation potentials reported in the SRCCL. Relevant papers include Lal et al. (2018) which estimated soil carbon sequestration potential to be 0.7-4.1 $GtCO_2$-eq yr^{-1} for croplands and 1.1-2.9 $GtCO_2$-eq yr^{-1} for grasslands. Bossio et al. (2020) assessed the contribution of soil carbon sequestration to natural climate solutions and found the potential to be 5.5 $GtCO_2$ yr^{-1} across all ecosystems, with only small portions of this (0.41 $GtCO_2$-eq yr^{-1} for cover cropping in croplands; 0.23, 0.15, 0.15 $GtCO_2$-eq yr^{-1} for avoided grassland conversion, optimal grazing intensity and legumes in pastures, respectively) arising from croplands and grasslands. Regionally, soil carbon management in croplands is feasible anywhere, but effectiveness can be limited in very dry regions (Sanderman et al. 2017). For soil carbon management in grasslands the feasibility is greatest in areas where grasslands have been degraded (e.g. by overgrazing) and soil organic carbon is depleted. For well managed grasslands, soil carbon stocks are already high and the potential for additional carbon storage is low (Roe et al. (2021) estimete greatest economic (up to USD100 tCO_2^{-1}) potential between

2020 and 2050 for croplands to be in Asia and the developing Pacific (339.7 $MtCO_2$ yr^{-1}) and for grasslands, in Developed Countries (253.6 $MtCO_2$ yr^{-1}).

Critical assessment and conclusion. In conclusion, there is *medium confidence* that enhanced soil carbon management in croplands has a global technical mitigation potential of 1.9 (0.4-6.8) $GtCO_2$ yr^{-1}, and in grasslands of 1.0 (0.2-2.6) $GtCO_2$ yr^{-1}, of which, 0.6 (04-0.9) and 0.9 (0.3-1.6) $GtCO_2$ yr^{-1} is estimated to be available at up to USD100 tCO_2^{-1} respectively. Regionally, soil carbon management in croplands and grasslands is feasible anywhere, but effectiveness can be limited in very dry regions, and for grasslands it is greatest in areas where degradation has occurred (e.g. by overgrazing) and soil organic carbon is depleted. Barriers to implementation include regional capacity for monitoring and verification (especially in developing countries), and more widely through concerns over saturation and permanence.

7.4.3.2. Biochar

Activities, co-benefits, risks and implementation opportunities and barriers. Biochar is produced by heating organic matter in oxygen-limited environments (pyrolysis and gasification) (Lehmann and Joseph 2012). Feedstocks include forestry and sawmill residues, straw, manure and biosolids. When applied to soils, biochar is estimated to persist from decades to thousands of years, depending on feedstock and production conditions (Singh et al. 2015; Wang et al. 2016). Biochar systems producing biochar for soil application plus bioenergy, generally give greater mitigation than bioenergy alone and other uses of biochar, and are recognised as a CDR strategy. Biochar persistence is increased through interaction with clay minerals and soil organic matter (Fang et al. 2015). Additional CDR benefits arise through "negative priming" whereby biochar stabilises soil carbon and rhizodeposits (Archanjo et al. 2017; Hagemann et al. 2017; Weng et al. 2015; Han Weng et al. 2017; Weng et al. 2018; Wang et al. 2016). Besides CDR, additional mitigation can arise from displacing fossil fuels with pyrolysis gases, lower soil N_2O emissions (Cayuela et al. 2014, 2015; Song et al. 2016; He et al. 2017; Verhoeven et al. 2017; Borchard et al. 2019), reduced nitrogen fertiliser requirements due to reduced nitrogen leaching and volatilisation from soils (Liu et al. 2019; Borchard et al. 2019), and reduced GHG emissions from compost when biochar is added (Agyarko-Mintah et al. 2017; Wu et al. 2017). Biochar application to paddy rice has resulted in substantial reductions (20-40% on average) in N_2O (Awad et al. 2018; Liu et al. 2018; Song et al. 2016) (Section 7.4.3.5) and smaller reduction in CH_4 emissions (Kammann et al. 2017; Kim et al. 2017a; Song et al. 2016; He et al. 2017; Awad et al. 2018). Potential co-benefits include yield increases particularly in sandy and acidic soils with low cation exchange capacity (Woolf et al. 2016; Jeffery et al. 2017); increased soil water-holding capacity (Omondi et al. 2016), nitrogen use efficiency (Liu et al. 2019; Borchard et al. 2019), biological nitrogen fixation (Van Zwieten et al. 2015); adsorption of organic pollutants and heavy metals (e.g. Silvani et al. 2019); odour reduction from manure handling (e.g. Hwang et al. 2018) and managing forest fuel loads (Puettmann et al. 2020). Due to its dark colour, biochar could decrease soil albedo (Meyer et al. 2012), though this is insignificant under recommended rates and application methods. Biochar could reduce enteric CH_4 emissions when fed to ruminants (Section 7.4.3.4). Barriers to upscaling include insufficient investment, limited large-scale production facilities, high production costs at small scale, lack of agreed approach to monitoring, reporting and verification, and limited knowledge, standardisation and quality control, restricting user confidence (Gwenzi et al. 2015).

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. Biochar is discussed as a mitigation option in AR5 and CDR strategy in the SR1.5. Consideration of potential was limited as biochar is not included in IAMs. The SRCCL estimated mitigation potential of 0.03-6.6 $GtCO_2$-eq yr^{-1} by 2050 based on studies with widely varying assumptions, definitions of potential, and scope of mitigation processes included (SRCCL, Chapters 2 and 4: (Roberts et al. 2010; Pratt and Moran 2010; Hristov; Lee and Day 2013; Dickie et al. 2014a; Hawken 2017; Fuss et al. 2018; Powell and Lenton 2012; Woolf et al. 2010).

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). Developments include mechanistic understanding of 'negative priming' and biochar-soil-microbes-plant interactions (DeCiucies et al. 2018; Fang et al. 2019). Indirect climate benefits are associated with persistent yield response to biochar (Kätterer et al. 2019; Ye et al. 2020), improved crop water use efficiency (Du et al. 2018; Gao et al. 2020) and reduced GHG and ammonia emissions from compost and manure (Sanchez-Monedero et al. 2018; Bora et al. 2020a,b; Zhao et al. 2020). A quantification method based on biochar properties is included in the IPCC guidelines for NGHGIs (IPCC 2019b). Studies report a range of biochar responses, from positive to occasionally adverse impacts, including on GHG emissions, and identify risks (Tisserant and Cherubini 2019). This illustrates the expected variability (Lehmann and Rillig 2014) of responses, which depend on the biochar type and climatic and edaphic characteristics of the site (Zygourakis 2017). Biochar properties vary with feedstock, production conditions and post-production treatments, so mitigation and agronomic benefits are maximised when biochars are chosen to suit the application context (Mašek et al. 2018). A recent assessment finds greatest economic potential (up to USD100 tCO_2^{-1}) between 2020 and 2050 to be in Asia and the developing Pacific (793 $MtCO_2$ yr^{-1}) followed by Developed Countries (447 $MtCO_2$ yr^{-1}) (Roe et al. 2021). Mitigation through biochar will be greatest where biochar is applied to responsive soils (acidic, low fertility), where soil N_2O emissions are high (intensive horticulture, irrigated crops), and where the syngas co-product displaces fossil fuels. Due to the early stage of commercialisation, mitigation estimates are based pilot-scale facilities, leading to uncertainty. However, the long-term persistence of biochar carbon in soils has been widely studied (e.g. Singh et al. 2012; Fang et al. 2019; Zimmerman and Ouyang 2019). The greatest uncertainty is the availability of sustainably-sourced biomass for biochar production.

Critical assessment and conclusion. Biochar has significant mitigation potential through CDR and emissions reduction, and can also improve soil properties, enhancing productivity and resilience to climate change (*medium agreement, robust evidence*). There is *medium evidence* that biochar has a technical potential of 2.6 (0.2–6.6) $GtCO_2$-eq yr^{-1}, of which 1.1 (0.3–1.8) $GtCO_2$-eq yr^{-1} is available up to USD100 tCO_2^{-1}. However mitigation and agronomic co-benefits depend strongly on biochar properties and the soil to which biochar is applied (*strong agreement, robust evidence*). While biochar could provide moderate to large mitigation potential, it is not yet included in IAMs, which has restricted comparison and integration with other CDR strategies.

7.4.3.3. Agroforestry

Activities, co-benefits, risks and implementation opportunities and barriers. Agroforestry is a set of diverse land management systems that integrate trees and shrubs with crops and/or livestock in space and/or time. Agroforestry accumulates carbon in woody vegetation and soil (Ramachandran Nair et al. 2010) and offers multiple co-benefits such as increased land productivity, diversified livelihoods, reduced soil erosion, improved water quality, and more hospitable regional climates (Ellison et al. 2017; Kuyah et al. 2019; Mbow et al. 2020; Zhu et al. 2020). Incorporation of trees and shrubs in agricultural systems, however, can affect food production, biodiversity, local hydrology and contribute to social inequality (Amadu et al. 2020; Fleischman et al. 2020; Holl and Brancalion 2020). To minimise risks and maximise co-benefits, agroforestry should be implemented as part of support systems that deliver tools, and information to increase farmers' agency. This may include reforming policies, strengthening extension systems and creating market opportunities that enable adoption (Jamnadass et al. 2020, Sendzimir et al. 2011, Smith et al. 2019b). Consideration of carbon sequestration in the context of food and fuel production, as well as environmental co-benefits at the farm, local, and regional scales can further help support decisions to plant, regenerate and maintain agroforestry systems (Miller et al. 2020; Kumar and Nair 2011). In spite of the advantages, biophysical and socioeconomic factors can limit the adoption (Pattanayak et al. 2003). Contextual factors may include, but are not limited to; water availability, soil fertility, seed and germplasm access, land policies and tenure systems affecting farmer agency, access to credit, and to information regarding the optimum species for a given location.

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. The SRCCL estimated the global technical mitigation potential of agroforestry, with medium confidence, to be between 0.08 and 5.6 $GtCO_2$-eq yr^{-1} by 2050 (Griscom et al. 2017; Dickie et al. 2014a; Zomer et al. 2016; Hawken 2017). Estimates are derived from syntheses of potential area available for various agroforestry systems e.g., windbreaks, farmer managed natural regeneration, and alley cropping and average annual rates of carbon accumulation. The cost-effective economic potential, also with medium confidence, is more limited at 0.3-2.4 $GtCO_2$-eq yr^{-1} (Zomer et al. 2016; Griscom et al. 2017; Roe et al. 2019). Despite this potential, agroforestry is currently not considered in integrated assessment models used for mitigation pathways (Section 7.5).

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). Updated estimates of agroforestry's technical mitigation potential and synthesised estimates of carbon sequestration across agroforestry systems have since been published. The most recent global analysis estimates technical potential of 9.4 $GtCO_2$-eq yr^{-1} (Chapman et al. 2020) of agroforestry on 1.87 and 1.89 billion ha of crop and pasture lands below median carbon content, respectively. This estimate is at least 68% greater than the largest estimate reported in the SRCCL (Hawken 2017) and represents a new conservative upper bound as Chapman et al. (2020) only accounted for aboveground carbon. Considering both above- and belowground carbon of windbreaks, alley cropping and silvopastoral systems at a more limited areal extent (Griscom et al. 2020), the economic potential of agroforestry was estimated to be only about 0.8 $GtCO_2$-eq yr^{-1}. Variation in estimates primarily result from assumptions on the agroforestry systems including, extent of implementation and estimated carbon sequestration potential when converting to agroforestry.

Regional estimates of mitigation potential are scant with agroforestry options differing significantly by geography (Feliciano et al. 2018). For example, multi-strata shaded coffee and cacao are successful in the humid tropics (Somarriba et al. 2013; Blaser et al. 2018), silvopastoral systems are prevalent in Latin American (Peters et al. 2013; Landholm et al. 2019) while agrosilvopastoral systems, shelterbelts, hedgerows, and windbreaks are common in Europe (Joffre et al. 1988; Rigueiro-Rodriguez 2009). At the field scale, agroforestry accumulates between 0.59 and 6.24 t ha^{-1} yr^{-1} of carbon aboveground. Belowground carbon often constitutes 25% or more of the potential carbon gains in agroforestry systems (De Stefano and Jacobson 2018; Cardinael et al. 2018). Roe et al. (2021) estimate greatest regional economic (up to USD100 tCO_2^{-1}) mitigation potential for the period 2020-2050 to be in Asia and the developing Pacific (368.4 $MtCO_2$-eq yr^{-1}) and Developed Countries (264.7 $MtCO_2$-eq yr^{-1}).

Recent research has also highlighted co-benefits and more precisely identified implementation barriers. In addition to aforementioned co-benefits, evidence now shows that agroforestry can improve soil health, regarding infiltration and structural stability (Muchane et al. 2020); reduces ambient temperatures and crop heat stress (Arenas-Corraliza et al. 2018; Sida et al. 2018); increases groundwater recharge in drylands when managed at moderate density (Ilstedt et al. 2016; Bargués-Tobella et al. 2020); positively influences human health (Rosenstock et al. 2019); and can improve dietary diversity (McMullin et al. 2019). Along with previously mentioned barriers, low social capital, assets, and labour availability have been identified as pertinent to adoption. Practically all barriers are interdependent and subject to the context of implementation.

Critical assessment and conclusion. There is medium confidence that agroforestry has a technical potential of 4.1 (0.3-9.4) $GtCO_2$-eq yr^{-1} for the period 2020-2050, of which 0.8 (0.4-1.1) $GtCO_2$-eq yr^{-1} is available at USD100 tCO_2^{-1}. Despite uncertainty around global estimates due to regional preferences for management systems, suitable land availability, and growing conditions, there is high confidence in agroforestry's mitigation potential at the field scale. With countless options for farmers and land managers to implement agroforestry, there is medium confidence in the feasibility of achieving estimated regional mitigation potential. Appropriately matching agroforestry options, to local biophysical and social contexts is important in maximising mitigation and co-benefits, while avoiding risks (Sinclair and Coe 2019).

[START BOX 7.3 HERE]

Box 7.3 Case study: agroforestry in Brazil – CANOPIES

Summary

Brazilian farmers are integrating trees into their croplands in various ways, ranging from simple to highly complex agroforestry systems. While complex systems are more effective in the mitigation of climate change, trade-offs with scalability need to be resolved for agroforestry systems to deliver on their potential. The Brazilian-Dutch CANOPIES project (Janssen 2020) is exploring transition pathways to agroforestry systems optimised for local ecological and socio-economic conditions

Background

The climate change mitigation potential of agroforestry systems is widely recognised (FAO 2017b; Zomer et al. 2016) and Brazilian farmers and researchers are pioneering diverse ways of integrating trees into croplands, from planting rows of eucalyptus trees in pastures up to highly complex agroforests consisting of >30 crop and tree species. The degree of complexity influences the multiple functions that farmers and societies can attain from agroforestry: the more complex it is, the more it resembles a natural forest with associated benefits for its C storage capacity and its habitat quality for biodiversity (Santos et al. 2019). However, trade-offs exist between the complexity and scalability of agroforestry as complex systems rely on intensive manual labour to achieve high productivity (Tscharntke et al. 2011). To date, mechanisation of structurally diverse agroforests is scarce and hence, efficiencies of scale are difficult to achieve.

Case description

These synergies and trade-offs between complexity, multifunctionality and scalability are studied in the CANOPIES (*Co-existence of Agriculture and Nature: Optimisation and Planning of Integrated Ecosystem Services*) project, a collaboration between Wageningen University (NL), the University of São Paulo and EMBRAPA (both Brazil). Soil and management data are collected on farms of varying complexity to evaluate C sequestration and other ecosystem services, economic performance and labour demands.

Interactions and limitations

The trade-off between complexity and labour demand is less pronounced in EMBRAPA's integrated crop-livestock-forestry (ICLF) systems, where grains and pasture are planted between widely spaced tree rows. Here, barriers for implementation relate mostly to livestock and grain farmers' lack of knowledge on forestry management and financing mechanisms[5] (Gil et al. 2015). Additionally, linking these financing mechanisms to C sequestration remains a Monitoring, Reporting and Verification challenge (Smith et al. 2020b).

Lessons

Successful examples of how more complex agroforestry can be upscaled do exist in Brazil. For example, on farm trials and consistent investments over several years have enabled Rizoma Agro to develop a citrus production system that integrates commercial and native trees in a large-scale multi-layered agroforestry system. The success of their transition resulted in part from their corporate structure that allowed them to tap into the certified Green Bonds market (CBI 2020). However, different transition strategies need to be developed for family farmers and their distinct socio-economic conditions.

[END BOX 7.3 HERE]

7.4.3.4. Enteric fermentation

Activities, co-benefits, risks and implementation opportunities and barriers. Mitigating CH_4 emissions from enteric fermentation can be direct (i.e. targeting ruminal methanogenesis and emissions per animal or unit of feed consumed) or indirect, by increasing production efficiency (i.e. reducing emission intensity per unit of product). Measures can be classified as those relating to (1) feeding, (2) supplements, additives and vaccines, and (3) livestock breeding and wider husbandry (Jia et al. 2019). Co-benefits include enhanced climate change adaptation and increased food security associated with improved livestock breeding (Smith et al. 2014). Risks include mitigation persistence, ecological impacts associated with improving feed quality and supply, or potential toxicity and animal welfare issues concerning feed additives. Implementation barriers include feeding/administration constraints, the stage of development of measures, legal restrictions on emerging technologies and negative impacts, such as the previously described risks (Smith et al. 2014; Jia et al. 2019; Smith et al. 2019b).

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. AR5 indicated medium (5-15%) technical mitigation potential from both feeding and breeding related measures (Smith et al. 2014). More recently, the SRCCL estimated with *medium confidence*, a global potential of 0.12-1.18 $GtCO_2$-eq yr^{-1} between 2020 and 2050, with the range reflecting technical, economic and sustainability constraints (SRCCL, Chapter 2: Hristov et al. 2013; Dickie et al. 2014a; Herrero et al. 2016; Griscom et al. 2017). The underlying literature used a mixture of IPCC GWP_{100} values for CH_4, preventing conversion of CO_2-eq to CH_4. Improved livestock feeding and breeding were included in IAM emission pathway scenarios within the SRCCL and SR1.5, although it was suggested that the full mitigation potential of enteric CH_4 measures is not captured in current models (Rogelj et al. 2018b; IPCC 2018).

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). Recent reviews generally identify the same measures as those outlined in the SRCCL, with the addition of early life manipulation of the ruminal biome (Grossi et al. 2019; Eckard and Clark 2020; Thompson and Rowntree 2020; Beauchemin et al. 2020; Ku-Vera et al. 2020; Honan et al. 2021). There is *robust evidence* and *high agreement* that chemically synthesised inhibitors are promising emerging near-term measures (Patra 2016; Jayanegara et al. 2018; Van Wesemael et al. 2019; Beauchemin et al. 2020) with high (e.g. 16-70% depending on study) mitigation potential reported (e.g. Hristov et al. 2015; McGinn et al. 2019; Melgar et al. 2020) and commercial availability expected within two years in some countries (Reisinger et al. 2021). However, their mitigation persistence (McGinn et al. 2019), cost (Carroll and Daigneault 2019; Alvarez-Hess et al. 2019) and public acceptance (Jayasundara et al. 2016) or regulatory approval is currently unclear while administration in pasture-based systems is likely to be challenging (Patra et al. 2017; Leahy et al. 2019). Research into other inhibitors/feeds containing inhibitory compounds, such as macroalga or seaweed (Chagas et al. 2019; Kinley et al. 2020; Roque et al. 2019), shows promise, although concerns have been raised regarding palatability, toxicity, environmental impacts and the development of industrial-scale supply chains (Abbott et al. 2020; Vijn et al. 2020). In the absence of CH_4 vaccines, which are still under development (Reisinger et al. 2021) pasture-based and non-intensive systems remain reliant on increasing production efficiency (Beauchemin et al. 2020). Breeding of low emitting animals may play an important role and is a subject under on-going research (Pickering et al. 2015; Jonker et al. 2018; López-Paredes et al. 2020).

Approaches differ regionally, with more focus on direct, technical options in developed countries, and improved efficiency in developing countries (Caro Torres et al. 2016; Mottet et al. 2017b; MacLeod et al. 2018; Frank et al. 2018). A recent assessment finds greatest economic (up to USD100 tCO_2-eq^{-1}) potential (using the IPCC AR4 GWP_{100} value for CH_4) for 2020-2050 in Asia and the developing Pacific (32.9 $MtCO_2$-eq yr^{-1}) followed by Developed Countries (25.5 $MtCO_2$-eq yr^{-1}) (Roe et al. 2021). Despite numerous country and sub-sector specific studies, most of which include cost analysis (Hasegawa and Matsuoka 2012; Hoa et al. 2014; Jilani et al. 2015; Eory et al. 2015; Pradhan et al. 2017; Pellerin et al. 2017; Ericksen and Crane 2018; Habib and Khan 2018; Kashangaki and Ericksen 2018; Salmon et al. 2018; Brandt et al. 2019b; Dioha and Kumar 2020; Kiggundu et al. 2019; Kavanagh et al. 2019; Mosnier et al. 2019; Pradhan et al. 2019; Sapkota et al. 2019; Carroll and Daigneault 2019; Leahy et al. 2019), sectoral assessment of regional technical and notably economic (Beach et al. 2015; USEPA 2019) potential is restricted by lack comprehensive and comparable data. Therefore, verification of regional estimates indicated by global assessments is challenging. Feed quality improvement, which may have considerable potential in developing countries (Mottet et al. 2017a; Caro et al. 2016), may have negative wider impacts. For example, potential land use change and greater emissions associated with production of concentrates (Brandt et al. 2019b).

Critical review and conclusion. Based on studies to date, using a range of IPCC GWP_{100} values for CH_4, there is *medium confidence* that activities to reduce enteric CH_4 emissions have a global technical potential of 0.8 (0.2–1.2) $GtCO_2$-eq yr^{-1}, of which 0.2 (0.1–0.3) $GtCO_2$-eq yr^{-1} is available up to USD100 tCO_2-eq^{-1} (Figure 7.11). The CO_2-eq value may also slightly differ if the GWP_{100} IPCC AR6 CH_4 value was uniformly applied within calculations. Lack of comparable country and sub-sector studies to assess the context applicability of measures, associated costs and realistic adoption likelihood, prevents verification of estimates.

7.4.3.5. Improve rice management

Activities, co-benefits, risks and implementation opportunities and barriers. Emissions from rice cultivation mainly concern CH_4 associated with anaerobic conditions, although N_2O emission also occur via nitrification and denitrification processes. Measures to reduce CH_4 and N_2O emissions include (1) improved water management (e.g. single drainage and multiple drainage practices), (2) improved residue management, (3) improved fertiliser application (e.g. using slow release fertiliser and nutrient specific application), and (4) soil amendments (including biochar and organic amendments) (Pandey et al. 2014; Yagi et al. 2020; Sriphirom et al. 2020; Kim et al. 2017b). These measures not only have mitigation potential but can improve water use efficiency, reduce overall water use, enhance drought adaptation and overall system resilience, improve yield, reduce production costs from seed, pesticide, pumping and labour, increase farm income, and promote sustainable development (Sriphirom et al. 2019; Tran et al. 2018; Yamaguchi et al. 2017; Quynh and Sander 2015). However, in terms of mitigation of CH_4 and N_2O, antagonistic effects can occur, whereby water management can enhance N_2O emissions due to creation of alternate wet and dry conditions (Sriphirom et al. 2019), with trade-offs between CH_4 and N_2O during the drying period potentially off-setting some mitigation benefits. Barriers to adoption may include site-specific limitations regarding soil type, percolation and seepage rates or fluctuations in precipitation, water canal or irrigation infrastructure, paddy surface level and rice field size, and social factors including farmer perceptions, pump ownership, and challenges in synchronising water management between neighbours and pumping stations (Yamaguchi et al. 2019; Yamaguchi et al. 2017; Quynh and Sander 2015).

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. AR5 outlined emissions from rice cultivation of 0.49-0.723 $GtCO_2$-eq yr^{-1} in 2010 with an average annual growth of 0.4% yr^{-1}. The SRCCL estimated a global mitigation potential from improved rice cultivation of 0.08-0.87 $GtCO_2$-eq yr^{-1} between 2020 and 2050, with the range representing the difference between technical and economic constraints, types of activities included (e.g. improved water management and straw residue management) and GHGs considered (SRCCL, Chapter 2: Dickie et al. 2014a; Paustian et al. 2016; Beach et al. 2015; Griscom et al. 2017; Hawken 2017).

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). Since AR5 and the SRCCL, studies on mitigation have principally focused on water and nutrient management practices with the aim of improving overall sustainability as well as measurements of site-specific emissions to help improve the resolution of regional estimates. Intensity of emissions show considerable spatial and temporal variation, dependent on site specific factors including degradation of soil organic matter, management of water levels in the field, the types and amount of fertilisers applied, rice variety and local cultivation practices. Variation in CH_4 emissions have been found to range from 0.5-41.8 $mg/m^2/hr$ in Southeast Asia (Sander et al. 2014; Chidthaisong et al. 2018; Setyanto et al. 2018; Sibayan et al. 2018; Wang et al. 2018; Maneepitak et al. 2019), 0.5-37.0 $mg/m^2/hr$ in Southern and Eastern Asia (Zhang et al. 2010; Wang et al. 2012; Oo et al. 2018; Takakai et al. 2020; Wang et al. 2018), and 0.5-10.4 $mg/m^2/hr$ in North America (Wang et al. 2018). Current studies on emissions of N_2O also showed high variation in the range of 0.13-654 $ug/m^2/hr$ (Akiyama et al. 2005; Islam et al. 2018; Kritee et al. 2018; Zschornack et al. 2018; Oo et al. 2018).

Recent studies on water management have highlighted the potential to mitigate GHG emissions, while also enhancing water use efficiency (Tran et al. 2018). A meta-analysis on multiple drainage systems found that Alternative Wetting and Drying (AWD) with irrigation management, can reduce CH_4 emissions by 20-30% and water use by 25.7 %, though this resulted in a slight yield reduction (5.4%) (Carrijo et al. 2017). Other studies have described improved yields associated with AWD (Tran et al. 2018). Water management for both single and multiple drainage can (most likely) reduce methane emissions by ~35 % but increase N_2O emissions by about 20% (Yagi et al. 2020). However, N_2O emissions occur only under dry conditions, therefore total reduction in terms of net GWP is approximately 30%. Emissions of N_2O are higher during dry seasons (Yagi et al. 2020) and depend on site specific factors as well as the quantity of fertiliser and organic matter inputs into the paddy rice system. Variability of N_2O emissions from single and multiple drainage can range from 0.06-33 kg/ha (Hussain et al. 2015; Kritee et al. 2018). AWD in Vietnam was found to reduce both CH_4 and N_2O emissions by 29-30 and 26-27% respectively with the combination of net GWP about 30% as compared to continuous flooding (Tran et al. 2018). Overall, greatest average economic mitigation potential (up to USD100 tCO_2-eq^{-1}) between 2020 and 2050 is estimated to be in Asia and the developing Pacific (147.2 $MtCO_2$-eq yr^{-1}) followed by Latin America and the Caribbean (8.9 $MtCO_2$-eq yr^{-1}) using the IPCC AR4 GWP_{100} value for CH_4 (Roe et al. 2021).

Critical assessment and conclusion. There is *medium confidence* that improved rice management has a technical potential of 0.3 (0.1-0.8) $GtCO_2$-eq yr^{-1} between 2020 and 2050, of which 0.2 (0.05-0.3) $GtCO_2$-eq yr^{-1} is available up to USD100 tCO_2-eq^{-1} (Figure 7.11). Improving rice cultivation practices will not only reduce GHG emissions, but also improve production sustainability in terms of resource utilisation including water consumption and fertiliser application. However, emission reductions show high variability and are dependent on site specific conditions and cultivation practices.

7.4.3.6. Crop nutrient management

Activities, co-benefits, risks and implementation opportunities and barriers. Improved crop nutrient management can reduce N_2O emissions from cropland soils. Practices include optimising fertiliser application delivery, rates and timing, utilising different fertiliser types (i.e. organic manures, composts and synthetic forms), and using slow or controlled-released fertilisers or nitrification inhibitors (Smith et al. 2014; Griscom et al. 2017; Smith et al. 2019b). In addition to individual practices, integrated nutrient management that combines crop rotations including intercropping, nitrogen biological fixation, reduced tillage, use of cover crops, manure and bio-fertilizer application, soil testing and comprehensive nitrogen management plans, is suggested as central for optimising fertiliser use, enhancing nutrient uptake and potentially reducing N_2O emissions (Bationo et al. 2012; Lal et al. 2018; Bolinder et al. 2020; Jensen et al., 2020; Namatsheve et al., 2020). Such practices may generate additional mitigation by indirectly reducing synthetic fertilizer manufacturing requirements and associated emissions, though such mitigation is accounted for in the Industry Sector and not considered in this chapter. Tailored nutrient management approaches, such as 4R nutrient stewardship, are implemented in contrasting farming systems and contexts and supported by best management practices to balance and match nutrient supply with crop requirements, provide greater stability in fertilizer performance and to minimize N_2O emissions and nutrient losses from fields and farms (Fixen 2020; Maaz et al. 2021). Co-benefits of improved nutrient management can include enhanced soil quality (notably when manure, crop residues or compost is utilised), carbon sequestration in soils and biomass, soil water holding capacity, adaptation capacity, crop yields, farm incomes, water quality (from reduced nitrate leaching and eutrophication), air quality (from reduced ammonia emissions) and in certain cases, it may facilitate land sparing (Sapkota et al. 2014; Johnston and Bruulsema 2014; Zhang et al. 2017; Smith et al. 2019b; Mbow et al. 2019).

A potential risk under certain circumstances, is yield reduction, while implementation of practices should consider current soil nutrient status. There are significant regional imbalances, with some regions experiencing nutrient surpluses from over fertilization and others, nutrient shortages and chronic deficiencies (FAO 2021e). Additionally, depending on context, practices may be inaccessible, expensive or require expertise to implement (Hedley 2015; Benson and Mogues 2018) while impacts of climate change may influence nutrient use efficiency (Amouzou et al. 2019) and therefore, mitigation potential.

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. The SRCCL broadly identified the same practices as outlined in AR5 and estimated that improved cropland nutrient management could mitigate between 0.03 and 0.71 $GtCO_2$-eq yr^{-1} between 2020 and 2050 (SRCCL Chapter 2: Dickie et al. 2014a; Beach et al. 2015; Paustian et al. 2016; Griscom et al. 2017; Hawken 2017).

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). Research since the SRCCL highlights the mitigation potential and co-benefits of adopting improved nutrient management strategies, notably precision fertiliser application methods and nutrient expert systems, and applicability in both large-scale mechanised and small-scale systems (Aryal et al. 2020; USEPA 2019; Hijbeek et al. 2019; Griscom et al. 2020; Tian et al. 2020; Sapkota et al. 2021). Improved crop nutrient management is feasible in all regions, but effectiveness is context dependent. Sub-Saharan Africa has one of the lowest global fertiliser consumption rates, with increased fertiliser use suggested as necessary to meet projected future food requirements (Mueller et al. 2012; Adam et al. 2020; ten Berge et al. 2019; Falconnier et al. 2020). Fertiliser use in Developed Countries is already high (Figure 7.10) with increased nutrient use efficiency among the most promising mitigation measures (Roe et al. 2019; Hijbeek et al. 2019). Considering that Asia and developing Pacific, and Developed Countries accounted for the greatest share of global nitrogen fertiliser use, it is not surprising that these regions are estimated to have greatest economic mitigation potential (up to USD100 tCO_2-eq^{-1}) between 2020 and 2050, at 161.8 and 37.1 $MtCO_2$-eq yr^{-1} respectively (using the IPCC AR4 GWP_{100} value for N_2O) (Roe et al. 2021).

Critical assessment and conclusion. There is *medium confidence* that crop nutrient management has a technical potential of 0.3 (0.06–0.7) $GtCO_2$-eq yr^{-1} of which 0.2 (0.05–0.6) $GtCO_2$-eq yr^{-1} is available up to USD100 tCO_2-eq^{-1}. This value is based on GWP100 using a mixture of IPCC values for N2O and may slightly differ if calculated using AR6 values. The development of national roadmaps for sustainable fertilizer (nutrient) management can help in scaling-up related practices and in realising this potential. Crop nutrient management measures can contribute not only to mitigation, but food and nutrition security and wider environmental sustainability goals.

[START BOX 7.4 HERE]

Box 7.4 Case study: the climate-smart village approach

Summary

The climate-smart villages (CSV) approach aims to generate local knowledge, with the involvement of farmers, researchers, practitioners, and governments, on climate change adaptation and mitigation while improving productivity, food security, and farmers' livelihoods (Aggarwal et al. 2018). This knowledge feeds a global network that includes 36 climate-smart villages in South and Southeast Asia, West and East Africa, and Latin America.

Background

It is expected that agricultural production systems across the world will change in response to climate change, posing significant challenges to the livelihoods and food security of millions of people (IPCC 2014). Maintaining agricultural growth while minimising climate shocks is crucial to building a resilient food production system and meeting sustainable development goals in vulnerable countries.

Case description

The CSV approach seeks an integrated vision so that sustainable rural development is the final goal for rural communities. At the same time, it fosters the understanding of climate change with the implementation of adaptation and mitigation actions, as much as possible. Rural communities and local stakeholders are the leaders of this process, where scientists facilitate their knowledge to be useful for the communities and learn at the same time about challenges but also the capacity those communities have built through time. The portfolio includes weather-smart activities, water-smart practices, seed/breed smart, carbon/nutrient-smart practices, and institutional/market smart activities.

Interactions and limitations

The integration of technologies and services that are suitable for the local conditions resulted in many gains for food security and adaptation and for mitigation where appropriate. It was also shown that, in all regions, there is considerable yield advantage when a portfolio of technologies is used, rather than the isolated use of technologies (Govaerts et al. 2005; Zougmoré et al. 2014). Moreover, farmers are using research results to promote their products as climate-smart leading to increases in their income (Acosta-Alba et al. 2019). However, climatic risk sites and socioeconomic conditions together with a lack of resource availability are key issues constraining agriculture across all five regions.

Lessons

1. **1.** Understanding the priorities, context, challenges, capacity, and characteristics of the territory and the communities regarding climate, as well as the environmental and socioeconomic dimensions, is the first step. Then, understanding climate vulnerability in their agricultural systems based on scientific data but also listening to their experience will set the pathway to identify climate-smart agriculture (CSA) options (practices and technologies) to reduce such vulnerability.
2. **2.** Building capacity is also a critical element of the CSV approach, rural families learn about the practices and technologies in a neighbour's house, and as part of the process, families commit to sharing their knowledge with other families, to start a scaling-out process within the communities. Understanding the relationship between climate and their crop is key, as well as the use of weather forecasts to plan their agricultural activities.
3. **3.** The assessment of the implementation of the CSA options should be done together with community leaders to understand changes in livelihoods and climate vulnerability. Also, knowledge appropriation by community leaders has led to farmer-to-farmer knowledge exchange within and outside the community (Ortega Fernandez and Martínez-Barón 2018).

[END BOX 7.4 HERE]

7.4.3.7. Manure management

Activities, co-benefits, risks and implementation opportunities and barriers. Manure management measures aim to mitigate CH_4 and N_2O emissions from manure storage and deposition. Mitigation of N_2O considers both direct and indirect (i.e. conversion of ammonia and nitrate to N_2O) sources. According to the SRCCL, measures may include (1) anaerobic digestion, (2) applying nitrification or urease inhibitors to stored manure or urine patches, (3) composting, (4) improved storage and application practices, (5) grazing practices and (6) alteration of livestock diets to reduce nitrogen excretion (Mbow et al. 2019; Jia et al. 2019). Implementation of manure management with other livestock and soil management measures can enhance system resilience, sustainability, food security and help prevent land degradation (Smith et al. 2014; Mbow et al. 2019; Smith et al. 2019d), while potentially benefiting the localised environment, for example, regarding water quality (Di and Cameron 2016). Risks include increased N_2O emission from the application of manure to poorly drained or wet soils, trade-offs between N_2O and ammonia emissions and potential eco-toxicity associated with some measures.

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. AR5 reported manure measures to have high (> 10%) mitigation potential. The SRCCL estimated a technical global mitigation potential between 2020 and 2050 of 0.01-0.26 $GtCO_2$-eq yr^{-1}, with the range depending on economic and sustainable capacity (SRCCL, Chapter 2: (Dickie et al. 2014a; Herrero et al. 2016). Conversion of estimates to native units is restricted as a mixture of GWP_{100} values was used in underlying studies. Measures considered were typically more suited to confined production systems (Jia et al. 2019; Mbow et al. 2019), while improved manure management is included within IAM emission pathways (Rogelj et al. 2018b).

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). Research published since SRCCL broadly focuses on measures relevant to intensive or confined systems (e.g. (Hunt et al. 2019; Sokolov et al. 2020; Im et al. 2020; Adghim et al. 2020; Mostafa et al. 2020; Kavanagh et al. 2019), highlighting co-benefits and risks. For example, measures may enhance nutrient recovery, fertiliser value (Sefeedpari et al. 2019; Ba et al. 2020; Yao et al. 2020) and secondary processes such as biogas production (Shin et al. 2019). However, the potential antagonistic relationship between GHG and ammonia mitigation and need for appropriate management is emphasised (Aguirre-Villegas et al.

2019; Kupper et al. 2020; Grossi et al. 2019; Ba et al. 2020). In some circumstances, fugitive emissions may reduce the potential mitigation benefits of biogas production (Scheutz and Fredenslund 2019; Bakkaloglu et al. 2021), while high implementation cost is identified as an adoption barrier, notably of anaerobic digestion (Liu and Liu 2018; Niles and Wiltshire 2019; Ndambi et al. 2019; Ackrill and Abdo 2020; Adghim et al. 2020). Nitrification inhibitors have been found to be effective at reducing N_2O emissions from pasture deposited urine (López-Aizpún et al. 2020), although the use of nitrification inhibitors is restricted in some jurisdictions due to concerns regarding residues in food products (Di and Cameron 2016; Eckard and Clark 2020) while *limited evidence* suggests eco-toxicity risk under certain circumstances (Kösler et al. 2019). Some forage crops may naturally contain inhibitory substances (Simon et al. 2019, 2020; de Klein et al. 2020), though this warrants further research (Podolyan et al. 2020; Gardiner et al. 2020).

Country specific studies provide insight into regionally applicable measures, with emphasis on small-scale anaerobic digestion (e.g. dome digesters), solid manure coverage and daily manure spreading in Asia and the developing Pacific, and Africa (Hasegawa et al. 2016; Hasegawa and Matsuoka 2012; Hoa et al. 2014; Jilani et al. 2015; Pradhan et al. 2017; Ericksen and Crane 2018; Pradhan et al. 2019; Kiggundu et al. 2019; Dioha and Kumar 2020). Tank/lagoon covers, large-scale anaerobic digestion, improved application timing, nitrogen inhibitor application to urine patches, soil-liquid separation, reduced livestock nitrogen intake, trailing shoe, band or injection slurry spreading and acidification are emphasised in developed countries (Kaparaju and Rintala 2011; Pape et al. 2016; Liu and Liu 2018; Lanigan et al. 2018; Eory et al. 2015; Jayasundara et al. 2016; Pellerin et al. 2017; Carroll and Daigneault 2019; Eckard and Clark 2020). Using IPCC AR4 GWP_{100} values for CH_4 and N_2O, a recent assessment finds 69% (63.4 $MtCO_2$-eq yr^{-1}) of economic potential (up to USD100 tCO_2-eq^{-1}) between 2020-2050, to be in Developed Countries (Roe et al. 2021).

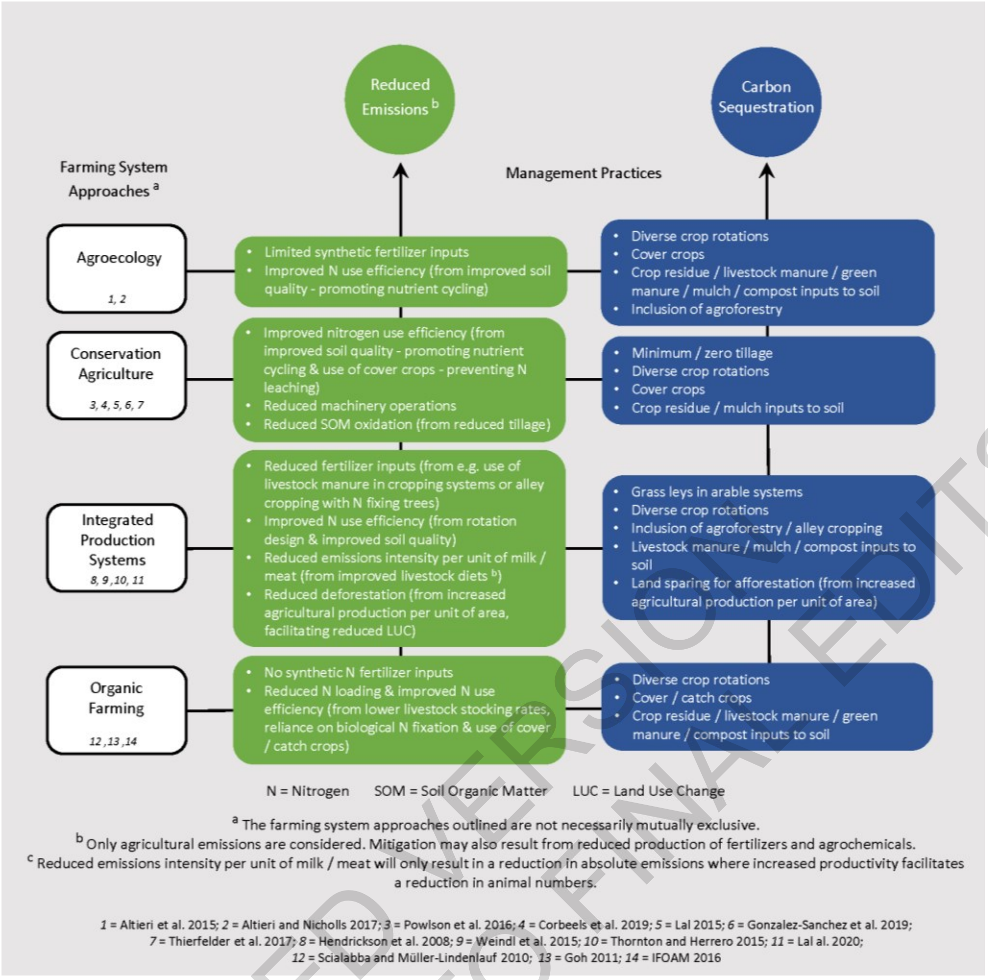
Critical assessment and conclusion. There is *medium confidence* that manure management measures have a global technical potential of 0.3 (0.1-0.5) $GtCO_2$-eq yr^{-1}, (using a range of IPCC GWP_{100} values for CH_4 and N_2O), of which 0.1 (0.09-0.1) $GtCO_2$-eq yr^{-1} is available at up to USD100 tCO_2-eq^{-1} (Figure 7.11). As with other non-CO_2 GHG mitigation estimates, values may slightly differ depending upon which IPCC GWP_{100} values were used. There is *robust evidence and high agreement* that there are measures that can be applied in all regions, but greatest mitigation potential is estimated in developed countries in more intensive and confined production systems.

[START BOX 7.5 HERE]

Box 7.5 Farming system approaches and mitigation

Introduction

There is *robust evidence* and *high agreement* that agriculture needs to change to facilitate environment conservation while maintaining and where appropriate, increase overall production. The SRCCL identified several farming system approaches, deemed alternative to conventional systems (Olsson et al. 2019; Mbow et al. 2019; Smith et al. 2019a). These may incorporate several of the mitigation measures described in 7.4.3, while potentially also delivering environmental co-benefits. This Box assesses evidence specifically on the mitigation capacity of some such system approaches. The approaches are not mutually exclusive, may share similar principles or practices and can be complimentary. In all cases, mitigation may result from either (1) emission reductions or (2) enhanced carbon sequestration, via combinations of management practices as outlined in Figure 1 within this Box. The approaches will have pros and cons concerning multiple factors, including mitigation, yield and co-benefits, with trade-offs subject to the diverse contexts and ways in which they are implemented.



Box 7.5, Figure 1 Potential mitigation mechanisms and associated management practices

Is there evidence that these approaches deliver mitigation?

Agroecology (AE) including Regenerative Agriculture (RA)

There is limited discussion on the mitigation potential of AE (Gliessman 2013; Altieri and Nicholls 2017), but *robust evidence* that AE can improve system resilience and bring multiple co-benefits (Aguilera et al. 2020; Tittonell 2020; Wanger et al. 2020; Altieri et al. 2015; Mbow et al. 2019) (IPCC WGII AR6 Box 5.10). *Limited evidence* concerning the mitigation capacity of AE at a system level (Saj et al. 2017; Snapp et al. 2021) makes conclusions difficult, yet studies into specific practices that may be incorporated, suggest AE may have mitigation potential (Section 7.4.3) (*medium confidence*). However, AE, that incorporates management practices used in organic farming (see below), may result in reduced yields, driving compensatory agricultural production elsewhere. Research into GHG mitigation by AE as a system and impacts of wide-scale implementation is required. Despite absence of a universally accepted definition (see Annex I), RA is gaining increasing attention and shares principles of AE. Some descriptions include carbon sequestration as a specific aim (Elevitch et al. 2018). Few studies have assessed mitigation potential of RA at a system level (e.g. Colley et al. 2020). Like AE, it is *likely* that RA can contribute to mitigation, the extent to which is currently unclear and by its case-specific design, will vary (*medium confidence*).

Conservation Agriculture (CA)

The SRCCL noted both positive and inconclusive results regarding CA and soil carbon, with sustained sequestration dependent on productivity and residue returns (Jia et al. 2019; Mirzabaev et al. 2019; Mbow et al. 2019). Recent research is in broad agreement (Ogle et al. 2019; Corbeels et al. 2020, 2019; Gonzalez-Sanchez et al. 2019; Munkholm et al. 2020) with greatest mitigation potential suggested in dry regions (Sun et al. 2020). Theoretically, CA may facilitate improved nitrogen use efficiency (Lal 2015; Powlson et al. 2016) (*limited evidence*), though CA appears to have mixed effects on soil N_2O emission (Six et al. 2004; Mei et al. 2018). CA is noted for its adaptation benefits, with *wide agreement* that CA can enhance system resilience to climate related stress, notably in dry regions. There is evidence that CA can contribute to mitigation, but its contribution is depended on multiple factors including climate and residue returns (*high confidence*).

Integrated Production Systems (IPS)

The integration of different enterprises in space and time (e.g. diversified cropping, crop and livestock production, agroforestry), therefore facilitating interaction and transfer of recourses between systems, is suggested to enhance sustainability and adaptive capacity (Franzluebbers et al. 2014; Lemaire et al. 2014; Gil et al. 2017; Peterson et al. 2020; Walkup et al. 2020; Garrett et al. 2020; Hendrickson et al. 2008; Weindl et al. 2015; Olseen et al. 2019). Research indicates some mitigation potential, including by facilitating sustainable intensification (Box 7.11), though benefits are likely to be highly context specific (e.g. (Herrero et al. 2013; Carvalho et al. 2014; Piva et al. 2014; de Figueiredo et al. 2017; Guenet et al. 2021; Rosenstock et al. 2014; Weindl et al. 2015; Thornton and Herrero 2015; Lal 2020; Descheemaeker et al. 2016). The other systems outlined within this Box may form or facilitate IPS.

Organic Farming (OF)

OF can be considered a form of AE (Lampkin et al. 2017) though is discussed separately here as it is guided by specific principles and associated regulations (Annex I). OF is perhaps noted more for potential co-benefits, such as enhanced system resilience and biodiversity promotion, than mitigation. Several studies have reviewed the emissions footprint of organic compared to conventional systems (e.g. Mondelaers et al. 2009; Tuomisto et al. 2012; Skinner et al. 2014; Meier et al. 2015; Seufert and Ramankutty 2017; Clark and Tilman 2017; Meemken and Qaim 2018; Bellassen et al. 2021). Acknowledging potential assessment limitations (Meier et al. 2015; van der Werf et al. 2020), evidence suggests organic production to typically generate lower emissions per unit of area, while emissions per unit of product vary and depend on the product (*high agreement, medium evidence*). OF has been suggested to increase soil carbon sequestration (Gattinger et al. 2012), though definitive conclusions are challenging (Leifeld et al. 2013). Fewer studies consider impacts of large-scale conversion from conventional to organic production globally. Though context specific (Seufert and Ramankutty 2017), OF is reported to typically generate lower yields (Seufert et al. 2012; De Ponti et al. 2012; Kirchmann 2019; Biernat et al. 2020). Large-scale conversion, without fundamental changes in food systems and diets (Muller et al. 2017; Theurl et al. 2020), may lead to increases in absolute emissions from land use change, driven by greater land requirements to maintain production (e.g. Leifeld 2016; Meemken and Qaim 2018). OF may have mitigation capacity in certain instances though impacts of large-scale conversion require further research.

[END BOX 7.5 HERE]

[START BOX 7.6 HERE]

Box 7.6 Case study: Mitigation Options and Costs in the Indian Agricultural Sector

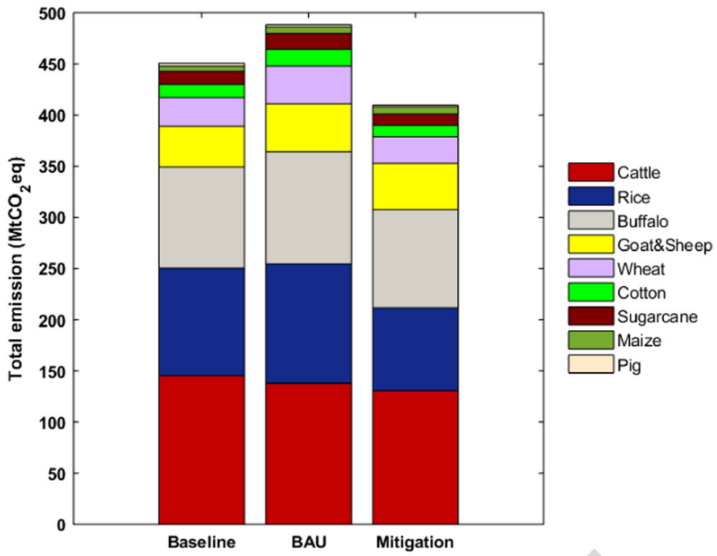
Objective

To assess the technical mitigation potentials of Indian agriculture and costs under a Business as Usual scenario (BAU) and Mitigation scenario up to 2030 (Sapkota et al. 2019).

Results

The study shows that by 2030 under BAU scenario GHG emissions from the agricultural sector in India would be 515 $MtCO_2$-eq yr^{-1} (using GWP_{100} and IPCC AR4 values) with a technical mitigation potential of 85.5 $MtCO_2$-eq yr^{-1} through the adoption of various mitigation practices. About 80% of the technical mitigation potential could be achieved by adopting cost-saving measures. Three mitigation options, i.e., efficient use of fertiliser, zero-tillage, and rice-water management, could deliver more than 50% of the total technical abatement potential. Under the BAU scenario the projected GHG emissions from major crop and livestock species is estimated at 489 $MtCO_2$-eq in 2030, whereas under mitigation scenario GHG emissions are estimated at 410 $MtCO_2$-eq implying a technical mitigation option of about 78.67 $MtCO_2$-eq yr^{-1} (Box 7.6, Figure 1). Major sources of projected emissions under the BAU scenario, in order of importance, were cattle, rice, buffalo, and small ruminants. Although livestock production and rice cultivation account for a major share of agricultural emissions, the highest mitigation potential was observed in rice (about 36 $MtCO_2$-eq yr^{-1}) followed by buffalo (about 14 $MtCO_2$-eq yr^{-1}), wheat (about 11 $MtCO_2$-eq yr^{-1}) and cattle (about 7 $MtCO_2$-eq yr^{-1}). Crops such as cotton and sugarcane each offered mitigation potential of about 5 $MtCO_2$-eq yr^{-1} while the mitigation potential from small ruminants (goat/sheep) was about 2 $MtCO_2$-eq yr^{-1}.

Sapkota et al. (2019) also estimated the magnitude of GHG savings per year through adoption of various mitigation measures, together with the total cost and net cost per unit of CO_2-eq abated. When the additional benefits of increased yield due to adoption of the mitigation measures were considered, about 80% of the technical mitigation potential (67.5 out of 85.5 $MtCO_2$-eq) could be achieved by cost-saving measures. When yield benefits were considered, green fodder supplements to ruminant diets were the most cost-effective mitigation measure, followed by vermicomposting and improved diet management of small ruminants. Mitigation measures such as fertigation and micro-irrigation, various methods of restoring degraded land and feed additives in livestock appear to be cost-prohibitive, even when considering yield benefits, if any. The study accounted for GHG emissions at the farm level and excluded emissions arising due to processing, marketing or consumption post farm-gate. It also did not include emissions from feed production, since livestock in India mostly rely on crop by-products and concentrates. Further the potential of laser land levelling seems exaggerated which may also be redundant with already accounted potential from ‘improved water management in rice’. The mitigation potential of agro-ecological approaches/technologies such as natural farming which is picking up in India in recent years has also been overlooked.



Box 7.6, Figure 1 Contribution of various crops and livestock species to total agricultural emission in 2012 (baseline) and by 2030 under business as usual (BAU) and mitigation scenarios for Indian Agricultural sector. Source: Sapkota et al. (2019).

[END BOX 7.6 HERE]

7.4.4. Bioenergy and BECCS

Activities, co-benefits, risks and implementation opportunities and barriers. Bioenergy refers to energy products (solid, liquid and gaseous fuels, electricity, heat) derived from multiple biomass sources including organic waste, harvest residues and by-flows in the agriculture and forestry sectors, and biomass from tree plantations, agroforestry systems, lignocellulosic crops, and conventional food/feed crops. It may reduce net GHG emissions by displacing the use of coal, oil and natural gas with renewable biomass in the production of heat, electricity, and fuels. When combined with carbon capture and storage (BECCS) and biochar production, bioenergy systems may provide CDR by durably storing biogenic carbon in geological, terrestrial, or ocean reservoirs, or in products, further contributing to mitigation (Section 7.4.3.2, Chapters 3, 4, 6 and 12) (Chum et al. 2011; Hammar and Levihn 2020; Emenike et al. 2020; Cabral et al. 2019; Moreira et al. 2020b; Wang et al. 2020: Johnsson et al. 2020).

This section addresses especially aspects related to land use and biomass supply for bioenergy and BECCS. The mitigation potential presented here and in Table 7.3, includes only the CDR component of BECCS. The additional mitigation achieved from displacing fossil fuels is covered elsewhere (Chapters 6, 8, 9, 10, 11 and 12).

Modern bioenergy systems (as opposed to traditional use of fuelwood and other low-quality cooking and heating fuels) currently provide approximately 30 EJ yr^{-1} of primary energy, making up 53% of total renewable primary energy supply (IEA 2019). Bioenergy systems are commonly integrated within forest and agriculture systems that produce food, feed, lumber, paper and other biobased products. They can also be combined with other AFOLU mitigation options: deployment of energy crops, agroforestry and A/R can provide biomass while increasing land carbon stocks (Sections 7.4.2.2 and 7.4.3.3) and anaerobic digestion of manure and wastewater, to reduce methane emissions, can produce biogas and CO2 for storage (Section 7.4.3.7). But ill-deployment of energy crops can also cause land carbon losses (Hanssen et al. 2020) and increased biomass demand for energy could hamper other mitigation measures such as reduced deforestation and degradation (Sections 7.4.2.1).

Bioenergy and BECCS can be associated with a range of co-benefits and adverse side-effects (Section 12.5; Jia et al. 2019; Calvin et al. 2021; Smith et al. 2016). It is difficult to disentangle bioenergy development from the overall development in the AFOLU sector given its multiple interactions with food, land, and energy systems. It is therefore not possible to precisely determine the scale of bioenergy and BECCS deployment at which negative impacts outweigh benefits. Important uncertainties include governance systems, future food and biomaterials demand, land use practices, energy systems development, climate impacts, and time scale considered when weighing negative impacts against benefits (SRCCL, Cross-Chapter Box 7; Box 7.7). (Turner et al. 2018b; Daioglou et al. 2019; Kalt et al. 2020; Wu et al. 2019; Robledo-Abad et al. 2017; Hanssen et al. 2020; Calvin et al, 2021;Cowie et al. 2021). The use of municipal organic waste, harvest residues, and biomass processing by-products as feedstock is commonly considered to have relatively lower risk, provided that associated land use practices are sustainable (Cowie et al. 2021). Deployment of dedicated biomass production systems can have positive and negative implications on mitigation and other sustainability criteria, depending on location and previous land use, feedstock, management practice, and deployment strategy and scale (Sections 12.5 and 17.3.3.1;(Popp et al. 2017; Humpenöder et al. 2018; Rulli et al. 2016; Brondizio et al. 2019; Hasegawa et al. 2020; Fujimori et al. 2019; Drews et al. 2020; Schulze et al. 2020; Stenzel et al. 2020; Daioglou et al. 2017; Staples et al. 2017; Carvalho et al. 2017; Mouratiadou et al. 2020; Buchspies et al. 2020; Hanssen et al. 2020).

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. Many more stringent mitigation scenarios in AR5 relied heavily on bioenergy and BECCS. The SR1.5 reported a range for the CDR potential of BECCS (2100) at 0.5 to 5 $GtCO_2$-eq yr^{-1} when applying constraints reflecting sustainability concerns, at a cost of 100-200 USD tCO_2^{-1} (Fuss et al. 2018). The SRCCL reported a technical CDR potential for BECCS at 0.4-11.3 $GtCO_2$ yr^{-1} (*medium confidence*), noting that most estimates do not include socio-economic barriers, the impacts of future climate change, or non-GHG climate forcing (IPCC. 2019a). The SR1.5 and SRCCL highlighted that bioenergy and BECCS can be associated with multiple co-benefits and adverse side-effects that are context specific.

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). The role of bioenergy and BECCS in mitigation pathways has been reduced as IAM-based studies have incorporated broader mitigation portfolios and have explored non-CO2 emissions reduction and a wider variation of underlying assumptions about socio-economic drivers and associated energy and food demand, as well as deployment limits such as land availability for A/R and for cultivation of crops used for bioenergy and BECCS (Grubler et al. 2018; Van Vuuren et al. 2018).

Increased availability of spatially explicit data and advances in the modelling of crop productivity and land use, land carbon stocks, hydrology, and ecosystem properties, have enabled more comprehensive analyses of factors that influence the contribution of bioenergy and BECCS in IAM-based mitigation scenarios, and also associated co-benefits and adverse side-effects (Wu et al, 2019, Li et al. 2020, Turner et al 2018a, Hanssen et al. 2020; Ai et al. 2021; Drews et al. 2020; Hasegawa et al. 2021). Yet, IAMs are still coarse in local land use practices. (Daioglou et al. 2019; Wu et al. 2019; Moreira et al. 2020b). Literature complementary to IAM studies indicate opportunities for integration of biomass production systems into agricultural landscapes (e.g., agroforestry, double cropping) to produce biomass while achieving co-benefits (Section 12.5). Similarly, climate-smart forestry puts forward measures (Box 7.3) adapted to regional circumstances in forest sectors, enabling co-benefits in nature conservation, soil protection, employment and income generation, and provision of wood for buildings, bioenergy and other biobased products (Nabuurs et al. 2017).

Studies have also investigated the extent and possible use of marginal, abandoned, and degraded lands, and approaches to help restore the productive value of these lands (Elbersen et al. 2019; Awasthi et al.

2017; Chiaramonti and Panoutsou, 2018; Fernando et al. 2018; Rahman et al. 2019; Fritsche et al. 2017; Næss et al. 2021). In the SRCCL, the presented range for degraded or abandoned land was 32 - 1400 Mha (Jia et al. 2019). Recent regional assessments not included in the SRCCL found up to 69 Mha in EU-28, 185 Mha in China, 9.5 Mha in Canada, and 127 Mha in the USA (Elbersen et al. 2019; Zhang et al 2020; Emery et al. 2017; Liu et al. 2017;Vera et al. 2021). The definition of marginal/abandoned/degraded land, and the methods used to assess such lands remain inconsistent across studies (Jiang et al. 2019), causing large variation amongst them (Jiang et al. 2021). Furthermore, the availability of such lands has been contested since they may serve other functions (subsistence, biodiversity protection, etc.) (Baka 2014).

[START BOX 7.7 HERE]

Box 7.7 Climate change mitigation value of bioenergy and BECCS

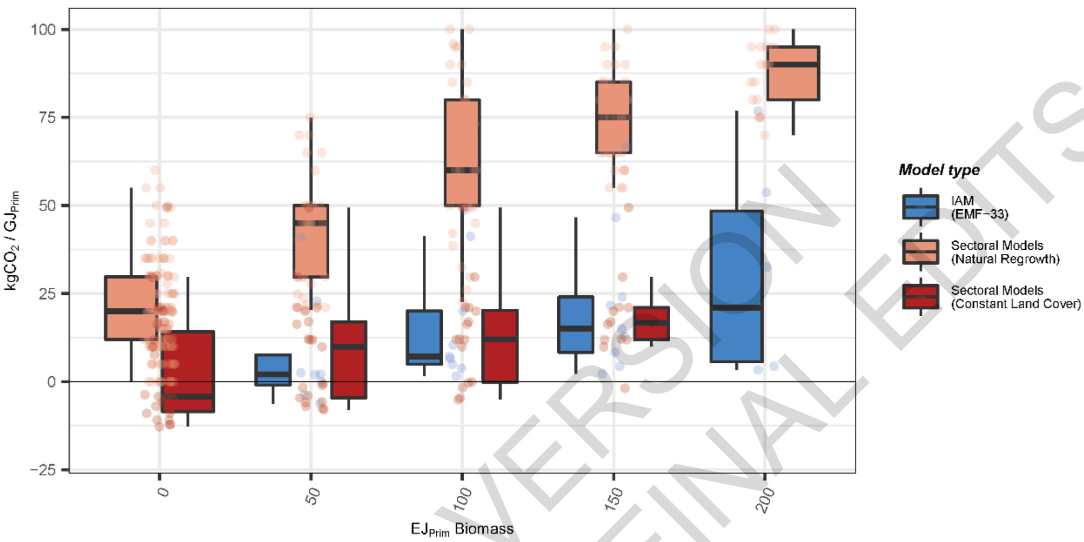
Besides emissions, and possible avoided emissions, related to the supply chain, the GHG effects of using bioenergy depend on: (i) change in GHG emissions when bioenergy substitutes another energy source; and (ii) how the associated land use and possible land use change influence the amount of carbon that is stored in vegetation and(Calvin et al. 2021) soils over time. Studies arrive at varying mitigation potentials for bioenergy and BECCS due to the large diversity of bioenergy systems, and varying conditions concerning where and how they are deployed (Cowie et al. 2021; Elshout 2015; Harper et al 2018; Kalt et al 2019; Muri 2018; Brandão et al. 2019; Buchspies et al. 2020; Calvin et al. 2021). Important factors include feedstock type, land management practice, energy conversion efficiency, type of bioenergy product (and possible co-products), emissions intensity of the products being displaced, and the land use/cover prior to bioenergy deployment (Zhu et al. 2017; Hanssen et al. 2020; Staples et al. 2017; Daioglou et al. 2017; Carvalho et al. 2017; Mouratiadou et al. 2020). Studies arrive at contrasting conclusions also when similar bioenergy systems and conditions are analysed, due to different methodologies, assumptions, and parameterisation (Harper et al 2018; Kalt et al 2019; Brandão et al. 2019; Albers et al. 2019; Buchspies et al. 2020; Bessou et al. 2020; Rolls and Forster 2020; Cowie et al. 2021).

Box 7.7 Figure 1 shows emissions associated with biomass supply (residues and crops grown on cropland not needed for food) in 2050, here designated emission-supply curves. The curves are constructed assuming that additional biomass supply consistently comes from the available land/biomass resource that has the lowest GHG emissions, i.e., the marginal GHG emissions increase with increasing biomass use for bioenergy. Net negative emissions indicate cases where biomass production increases land carbon stocks.

One curve (*EMF-33*) is determined from stylised scenarios using IAMs (Rose et al. 2020). One of the two curves determined from sectoral models, *Constant Land Cover*, reflects supply chain emissions and changes in land carbon storage caused by the biomass supply system itself. These two curves are obtained with modelling approaches compatible with the modelling protocol used for the scenarios in the AR6 database, which accounts for the land-use change and all other GHG emissions along a given transformation trajectory, enabling assessments of the warming level incurred.

The *Natural Regrowth* curve attribute additional "counterfactual emissions" to the bioenergy system, corresponding to estimated uptake of CO_2 in a counterfactual scenario where land is not used for bioenergy but instead subject to natural vegetation regrowth. This curve does not show actual emissions from the bioenergy system, but it provides insights in the mitigation value of the bioenergy option compared to alternative land-use strategies. To illustrate, if biomass is used instead of a primary energy source with emission factor 75 kg CO_2 GJ^{-1}, and the median values in the *Natural Regrowth* curve are adopted, then the curve indicates that up to about 150 EJ of biomass can be produced and used for energy while achieving higher net GHG savings than the alternative to set aside the same land for natural vegetation regrowth (assuming same conversion factor).

The large ranges in the bars signify the importance of uncertainties and how the biomass is deployed. Variation in energy conversion efficiencies and uncertainty about magnitude, timing, and permanence of land carbon storage further complicate the comparison. Finally, not shown in Box 7.7 Figure 1, the emission-supply curves would be adjusted downwards if displacement of emission intensive energy was included or if the bioenergy is combined with CCS to provide CDR.



Box 7.7, Figure 1 Emissions associated with primary biomass supply in 2050 (residues and crops grown on cropland not needed for food), as determined from sectoral models (Daioglou et al. 2017; Kalt et al. 2020), and stylised scenarios from the EMF-33 project using Integrated Assessment Models (Rose et al. 2020). All methods include LUC (direct and indirect) emissions. Emissions associated with *Natural Regrowth* include counterfactual carbon fluxes (see text). The sectoral models include a more detailed representation of the emissions, including Life-Cycle emissions from fertiliser production. IAM models may include economic feedbacks such as intensification as a result of increasing prices. As an indication: for natural gas the emission factor is around 56, for coal around 95 kg CO_2 GJ^{-1}.

[END BOX 7.7 HERE]

Critical assessment and conclusion. Recent estimates of technical biomass potentials constrained by food security and environmental considerations fall within previous ranges corresponding to *medium agreement*, (e.g., Turner et al. 2018b; Daioglou et al. 2019; Wu et al. 2019, Hansen et al 2020; Kalt et al. 2020) arriving at 4-57 and 46-245 EJ yr^{-1} by 2050 for residues and dedicated biomass crops, respectively. Based on studies to date, the technical net CDR potential of BECCS (including LUC and other supply chain emissions, but excluding energy carrier substitution) by 2050 is 5.9 (0.5-11.3) $GtCO_2$ yr^{-1} globally, of which 1.6 (0.5-3.5) $GtCO_2$ yr^{-1} is available at below USD100 tCO_2^{-1} (*medium confidence)* (Figure 7.11) (Lenton 2010; Koornneef et al. 2012; McLaren 2012; Powell and Lenton 2012; Fuss et al. 2018; Turner et al. 2018a; Hanssen et al. 2020; Roe et al. 2021). The equivalent economic potential as derived from IAMs is 1.8 (0.2 - 9.9) $GtCO_2$ yr^{-1} (Table 7.3).

Technical land availability does not imply that dedicated biomass production for bioenergy and BECCS is the most effective use of this land for mitigation. Further, implications of deployment for climate change mitigation and other sustainability criteria are context dependent and influenced by many factors, including rate and total scale. While governance has a critical influence on outcome, larger scale and higher expansion rate generally translates into higher risk for negative outcomes for GHG emissions, biodiversity, food security and a range of other sustainability criteria (Rochedo et al. 2018; Daioglou et al. 2019; Junginger et al. 2019; Galik et al. 2020; Searchinger 2017; Vaughan et al. 2018; de Oliveira Garcia et al. 2018; Stenzel et al. 2020).

However, literature has also highlighted how the agriculture and forestry sectors may respond to increasing demand by devising management approaches that enable biomass production for energy in conjunction with supply of food, construction timber, and other biobased products, providing climate change mitigation while enabling multiple co-benefits including for nature conservation (Parodi et al. 2018; Springmann et al. 2018; Nabuurs et al. 2017; Rosenzweig et al. 2020; Clark et al. 2020; Favero et al. 2020; Hanssen et al. 2020; Section 7.4 and Cross-Working Group Box 3 in Chapter 12).

Strategies to enhance the benefits of bioenergy and BECCS include (i) management practices that protect carbon stocks and the productive and adaptive capacity of lands, as well as their environmental and social functions (van Ittersum et al. 2013, Gerssen-Gondelach et al. 2015; Moreira et al. 2020b) (ii) supply chains from primary production to final consumption that are well managed and deployed at appropriate levels (Donnison et al. 2020; Fajardy et al. 2018); and (iii) development of a cross-sectoral agenda for biobased production within a circular economy, and international cooperation and governance of global trade in products to maximize synergies while limiting trade-offs concerning environmental, economic and social outcomes (*very high confidence*). Finally, the technical feasibility of BECCS depends on investments in and the roll-out of advanced bioenergy technologies currently not widely available (Daioglou et al. 2020b, Baker et al 2015).

7.4.5. Demand-side measures

7.4.5.1. Shift to sustainable healthy diets

Activities, co-benefits, risks and implementation opportunities and barriers. The term 'Sustainable healthy diets' refers to dietary patterns that 'promote all dimensions of individuals' health and wellbeing; have low environmental pressure and impact; are accessible, affordable, safe and equitable; and are culturally acceptable' (FAO and WHO 2019). In addition to climate mitigation gains, a transition towards more plant-based consumption and reduced consumption of animal-based foods, particularly from ruminant animals, could reduce pressure on forests and land used for feed, support the preservation of biodiversity and planetary health (Theurl et al. 2020; FAO 2018c), and contribute to preventing forms of malnutrition (i.e. undernutrition, micronutrient deficiency, and obesity) in developing countries (Chapter 12, Section 12.4.). Other co-benefits include lowering the risk of cardiovascular disease, type 2 diabetes, and reducing mortality from diet-related non-communicable diseases (Toumpanakis et al. 2018; Satija and Hu 2018; Faber et al. 2020; Magkos et al. 2020). However, transition towards sustainable healthy diets could have adverse impacts on the economic stability of the agricultural sector (MacDiarmid 2013; Aschemann-Witzel 2015; Van Loo et al. 2017). Therefore, shifting toward sustainable and healthy diets requires effective food-system oriented reform policies that integrate agriculture, health, and environment policies to comprehensively address synergies and conflicts in co-lateral sectors (agriculture, trade, health, environment protection etc.) and capture spill-over effects (climate change, biodiversity loss, food poverty) (Galli et al. 2020; FAO and WHO 2019).

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. According to the AR5, changes in human diets and consumption patterns can reduce emissions 5.3 to 20.2 $GtCO_2$-eq yr^{-1} by 2050 from diverted agricultural production and avoided land-use change (Smith et al. 2014). In the SRCCL, a "contract and converge" model of transition to sustainable healthy diets was suggested as an effective approach, reducing food consumption in over-consuming populations and increasing consumption of some food groups in populations where minimum nutritional needs are not met (Smith et al. 2019b). The total technical mitigation potential of changes in human diets was estimated as 0.7 - 8 $GtCO_2$-eq yr^{-1} by 2050 (SRCCL, Chapter 2 and 6; (Springmann et al. 2016; Hawken 2017; Tilman and Clark 2014), ranging from a 50% adoption of healthy diets (<60g of animal-based protein) and only accounting for diverted agricultural production, to the global adoption of a vegetarian diet.

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). Since the SRCCL, global studies continue to find high mitigation potential from reducing animal-source foods and increasing proportions of plant-rich foods in diets. Springmann et al. (2018) estimated that diet changes in line with global dietary guidelines for total energy intake and consumption of red meat, sugar, fruits, and vegetables, could reduce GHG emissions by 29% and other environmental impacts by 5–9% compared with the baseline in 2050. Poore and Nemecek (2018) revealed that shifting towards diets that exclude animal-source food could reduce land use by 3.1 billion ha, decrease food-related GHG emissions by 6.5 $GtCO_2$-eq yr^{-1}, acidification by 50%, eutrophication by 49%, and freshwater withdrawals by 19% for a 2010 reference year. Frank et al. (2019) estimated non-CO_2 emissions reductions of 0.4 $GtCO_2$-eq yr^{-1} at a carbon price of USD100 tCO_2^{-1} and 0.6 $GtCO_2$-eq yr^{-1} at USD20 tCO_2^{-1} in 2050 from shifting to lower animal-source diets (430 kcal of livestock calorie intake) in developed and emerging countries. From a systematic literature review, Ivanova et al. (2020) found mitigation potentials of 0.4-2.1 tCO_2-eq $capita^{-1}$ for a vegan diet, of 0.01-1.5 for a vegetarian diet, and of 0.1-2.0 for Mediterranean or similar healthy diet.

Regionally, mitigation potentials for shifting towards sustainable healthy diets (50% convergence to <60g of meat-based protein, only accounting for diverted production) vary across regions. A recent assessment finds greatest economic (up to USD100 tCO_2^{-1}) potential for 2020-2050 in Asia and the developing Pacific (609 $MtCO_2$-eq yr^{-1}) followed by Developed Countries (322 $MtCO_2$-eq yr^{-1}) based on IPCC AR4 GWP_{100} values for CH_4 and N_2O) (Roe et al. 2021). In the EU, (Latka et al. 2021) found that moving to healthy diets through price incentives could bring about annual reductions of non-CO_2 emissions from agriculture of 12-111 $MtCO_2$-eq yr^{-1}. At the country level, recent studies show that following National Dietary Guidelines (NDG) would reduce food system GHG emissions by 4–42%, confer large health gains (1.0–1.5 million quality-adjusted life-years) and lower health care system costs (NZD 14–20 billion) in New Zealand Drew et al. (2020); reduce 28% of GHG emissions in Argentina Arrieta and González (2018); about 25% in Portugal Esteve-Llorens et al. (2020) and reduce GHG emissions, land use and blue water footprint by 15–60% in Spain Batlle-Bayer et al. (2020). In contrast, Aleksandrowicz et al. (2019) found that meeting healthy dietary guidelines in India required increased dietary energy intake overall, which slightly increased environmental footprints by about 3–5% across GHG emissions, blue and green water footprints and land use.

Critical assessment and conclusion. Shifting to sustainable healthy diets has large potential to achieve global GHG mitigation targets as well as public health and environmental benefits (*high confidence*). Based on studies to date, there is *medium confidence* that shifting toward sustainable healthy diets has a technical potential including savings in the full value chain of 3.6 (0.3-8.0) $GtCO_2$-eq yr^{-1} of which 2.5 (1.5-3.9) $GtCO_2$-eq yr^{-1} is considered plausible based on a range of GWP_{100} values for CH_4 and N_2O. When accounting for diverted agricultural production only, the feasible potential is 1.7 (1 – 2.7) $GtCO_2$-eq yr^{-1}. A shift to more sustainable and healthy diets is generally feasible in many regions (*medium confidence*). However, potential varies across regions as diets are location- and community- specific, and thus may be influenced by local production practices, technical and financial barriers and associated livelihoods, everyday life and behavioural and cultural norms around food consumption (Meybeck and Gitz 2017; Creutzig et al. 2018; FAO 2018b). Therefore, a transition towards low-GHG emission diets and achieving their mitigation potential requires a combination of appropriate policies, financial and non-financial incentives and awareness-raising campaigns to induce changes in consumer behaviour with potential synergies between climate objectives, health and equity (Rust et al. 2020).

7.4.5.2. Reduce food loss and waste

Activities, co-benefits, risks and implementation opportunities and barriers. Food loss and waste (FLW) refer to the edible parts of plants and animals produced for human consumption that are not ultimately consumed (UNEP 2021b). Food loss occurs through spoilage, spilling or other unintended consequences due to limitations in agricultural infrastructure, storage and packaging (Parfitt et al. 2010). Food waste typically takes place at the distribution (retail and food service) and consumption stages in the food supply chain and refers to food appropriate for human consumption that is discarded or left to spoil (HLPE 2014). Options that could reduce FLW include: investing in harvesting and post-harvesting technologies in developing countries, taxing and other incentives to reduce business and consumer-level waste in developed countries, mandatory FLW reporting and reduction targets for large food businesses, regulation of unfair trading practices, and active marketing of cosmetically imperfect products (van Giesen and de Hooge 2019; Sinclair Taylor et al. 2019). Other studies suggested providing options of longer-lasting products and behavioural changes (e.g. through information provision) that cause dietary and consumption changes and motivate consumers to actively make decisions that reduce FLW. Reductions of FLW along the food chain bring a range of benefits beyond GHG mitigation, including reducing environmental stress (e.g. water and land competition, land degradation, desertification), safeguarding food security, and reducing poverty (Galford et al. 2020; Venkat et al. 2020). Additionally, FLW reduction is crucial for achieving SDG 12 which calls for ensuring 'sustainable consumption and production patterns' through lowering per capita global food waste by 50% at the retail and consumer level and reducing food losses along food supply chains by 2030. In line with these SDG targets, it is estimated that reducing FLW can free up several million km^2 of land (*high confidence*). The interlinkages between reducing FLW and food system sustainability are discussed in Chapter 12. Recent literature identifies a range of barriers to climate change mitigation through FLW reduction, which are linked to technological, biophysical, socio-economic, financial and cultural contexts at regional and local levels (Blok et al. 2020; Vogel and Meyer 2018; Gromko and Abdurasalova 2019; Rogissart et al. 2019). Examples of these barriers include infrastructural and capacity limitations, institutional regulations, financial resources, constraining resources (e.g. energy), information gaps (e.g. with retailers), and consumers' behaviour (Blok et al. 2020; Gromko and Abdurasalova 2019).

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. In AR5, reduced FLW was considered as a mitigation measure that could substantially lower emissions, with estimated mitigation potential of 0.6–6.0 $GtCO_2$-eq yr^{-1} in the food supply chain (Smith et al. 2014). In the SRCCL, the technical mitigation potential of reducing food and agricultural waste was estimated at 0.76-4.5 $GtCO_2$-eq yr^{-1} (SRCCL, Chapter 2 and 6: Bajželj et al. 2014; Dickie et al. 2014b; Hawken 2017).

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). Since the SRCCL, there have been very few quantitative estimates of the mitigation potential of FLW reductions. Evidence suggests that reducing FLW together with overall food intake could have substantial mitigation potential, equating to an average of 0.3 tCO_2-eq $capita^{-1}$ (Ivanova et al. 2020). Some regional sectoral studies indicate that reducing FLW in the EU can reduce emissions by 186 $MtCO_2$-eq yr^{-1}, the equivalent of around 15% of the environmental impacts (climate, acidification, and eutrophication) of the entire food value chain (Scherhaufer et al. 2018). In the UK, disruptive low-carbon innovations relating to FLW reduction were found to be associated with potential emissions reductions ranging between 2.6 and 3.6 $MtCO_2$-eq (Wilson et al. 2019). Other studies investigated the effect of tax mechanisms, such as 'pay as you throw' for household waste, on the mitigation potential of reducing FLW. Generally, these mechanisms are recognised as particularly effective in reducing the amount of waste and increasing the recycling rate of households (Carattini et al. 2018; Rogissart et al. 2019). Technological FWL mitigation opportunities exist throughout the food supply chain; post-harvest opportunities for FLW reductions are discussed in Chapter 12. Based on IPCC AR4 GWP_{100} values for CH_4 and N_2O, greatest economic mitigation potential (up to USD100 tCO_2^{-1}) for the period 2020-2050 from FLW reduction is estimated to be in Asia and developing Pacific (192.3 $GtCO_2$-eq yr^{-1}) followed by Developed Countries (101.6 $GtCO_2$-eq yr^{-1}) (Roe et al. 2021). These estimates reflect diverted agricultural production and do not capture potential from avoided land-use changes.

Critical assessment and conclusion. There is *medium confidence* that reduced FLW has large global technical mitigation potential of 2.1 (0.1–5.8) $GtCO_2$-eq yr^{-1} including savings in the full value chain and using GWP_{100} and a range of IPCC values for CH_4 and N_2O. Potentials at 3.7 (2.2–5.1) $GtCO_2$-eq yr^{-1} are considered plausible. When accounting for diverted agricultural production only, the feasible potential is 0.5 (0.0–0.9) $GtCO_2$-eq yr^{-1}. See the section above for the joint land use effects of food related demand-side measures which increases three-fold when accounting for the land-use effects as well. But this would overlap with other measures and is therefore not additive. Regionally, FLW reduction is feasible anywhere but its potential needs to be understood in a wider and changing socio-cultural context that determines nutrition (*high confidence*).

7.4.5.3. Improved and enhanced use of wood products

Activities, co-benefits, risks and implementation opportunities and barriers. The use of wood products refers to the fate of harvested wood for material uses and includes two distinctly different components t affecting the carbon cycle, including carbon storage in wood products and material substitution. When harvested wood is used for the manufacture of wood products, carbon remains stored in these products depending on their end use and lifetime. Carbon storage in wood products can be increased through enhancing the inflow of products in use, or effectively reducing the outflow of the products after use. This can be achieved through additional harvest under sustainable management (Pilli et al. 2015; Johnston and Radeloff 2019), changing the allocation of harvested wood to long-lived wood products or by increasing products' lifetime and increasing recycling (Brunet-Navarro et al. 2017; Jasinevičius et al. 2017; Xu et al. 2018; Xie et al. 2021). Material substitution involves the use of wood for building, textiles, or other applications instead of other materials (e.g. concrete, steel which consume more energy to produce) to avoid or reduce emissions associated with the production, use and disposal of those products it replaces.

The benefits and risks of improved and enhanced improved use of wood products are closely linked to forest management. First of all, the enhanced use of wood products could potentially activate or lead to improved sustainable forest management that can mitigate and adapt (Verkerk et al. 2020). Secondly, carbon storage in wood products and the potential for substitution effects can be increased by additional harvest, but with the risk of decreasing carbon storage in forest biomass when not done sustainably (Smith et al. 2019b). Conversely, reduced harvest may lead to gains in carbon storage in forest ecosystems locally, but these gains may be offset through international trade of forest products causing increased harvesting pressure or even degradation elsewhere (Pendrill et al. 2019b; Kastner et al. 2011; Kallio and Solberg 2018). There are also environmental impacts associated with the processing, manufacturing, use and disposal of wood products (Adhikari and Ozarska 2018; Baumgartner 2019). See Section 9.6.4 of this report for additional discussion on benefits and risks.

Conclusions from AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL); mitigation potential, costs, and pathways. There is strong evidence at the product level that wood products from sustainably managed forests are associated with less greenhouse emissions in their production, use and disposal over their life-time compared to products made from emission-intensive and non-renewable materials. However, there is still limited understanding of the substitution effects at the level of markets, countries (Leskinen et al. 2018). AR5 did not report on the mitigation potential of wood products. The SRCCL (Chapters 2 and 6) finds that some studies indicate significant mitigation potentials for material substitution, but concludes that the global, technical mitigation potential for material substitution for construction applications ranges from 0.25-1 $GtCO_2$-eq yr^{-1} (*medium confidence*) (McLaren 2012; Miner 2010; Roe et al. 2019).

Developments since AR5 and IPCC Special Reports (SR1.5, SROCCC and SRCCL). Since the SRCCL, several studies have examined the mitigation potential of the enhanced and improved use of wood products. A global forest sector modelling study (Johnston and Radeloff 2019) estimated that carbon storage in wood products represented a net carbon stock increase of 0.34 $GtCO_2$-eq yr^{-1} globally in 2015 and which could provide an average mitigation potential (by increasing the HWP pool) of 0.33–0.41 $GtCO_2$-eq yr^{-1} for the period 2020–2050, based on the future socio-economic development (SSP scenarios) and its effect on the production and consumption of wood products. Traded feedstock provided another 0.071 $GtCO_2$ yr^{-1} of carbon storage in 2015 and 0.12 $GtCO_2$ yr^{-1} by 2065. These potentials exclude the effect of material substitution. Another recent study estimated the global mitigation potential of mid-rise urban buildings designed with engineered wood products at 0.04-3.7 $GtCO_2$ yr^{-1} (Churkina et al. 2020). Another study (Oliver et al. 2014) estimated that using wood to substitute for concrete and steel as building materials could provide a technical mitigation potential of 0.78-1.73 $GtCO_2$ yr^{-1} achieved through carbon storage in wood products and through material and energy substitution.

The limited availability or absence of estimates of the future mitigation potential of improved use of wood products for many world regions represents an important knowledge gap, especially with regards to material substitution effects. At the product level, wood products are often associated with lower fossil-based emissions from production, use and disposal, compared to products made from emission-intensive and non-renewable materials (Sathre and O'Connor 2010; Geng et al. 2017; Leskinen et al. 2018).

Critical assessment and conclusion. Based on studies to date, there is *strong evidence and medium agreement* that the improved use of wood products has a technical potential of 1.0 (0.04–3.7) $GtCO_2$-eq yr^{-1} and economic potential of 0.4 (0.3–0.5) $GtCO_2$-eq yr^{-1}.There is *strong evidence* and *high agreement* at the product level that material substitution provides on average benefits for climate change mitigation as wood products are associated with less fossil-based GHG emissions over their lifetime compared to products made from emission-intensive and non-renewable materials. However, the evidence at the level of markets or countries is uncertain and fairly limited for many parts of the world. There is *medium confidence* that material substitution and carbon storage in wood products contribute to climate change mitigation when also the carbon balances of forest ecosystems are considered of sustainably managed large areas of forests in medium term. The total future mitigation potential will depend on the forest system considered, the type of wood products that are produced and substituted and the assumed production technologies and conversion efficiencies of these products.

7.5. AFOLU Integrated Models and Scenarios

This section assesses the literature and data available on potential future GHG dynamics in the AFOLU sector, the cost-effectiveness of different mitigation measures, and consequences of climate change mitigation pathways on land-use dynamics as well as relevant sustainable development indicators at the regional and global level based on global integrated models.

Land-based mitigation options interact and create various trade-offs, and thus need to be assessed together as well as with mitigation options in other sectors, and in combination with other sustainability goals (Popp et al. 2014; Obersteiner et al. 2016; Roe et al. 2019; Van Vuuren et al. 2019; Prudhomme et al. 2020; Strefler et al. 2021). The assessments of individual mitigation measures or sectoral estimates used to estimate mitigation potential in Section 7.4, when aggregated together, do not account for interactions and trade-offs. Integrative land-use models (ILMs) combine different land-based mitigation options and are partially included in Integrated Assessment Models (IAMs) which combine insights from various disciplines in a single framework and cover the largest sources of anthropogenic GHG emissions from different sectors. Over time, ILMs and IAMs have extended their system coverage (Johnson et al. 2019). However, the explicit modelling and analysis of integrated land-use systems is relatively new compared to other sectoral assessments such as the energy system (Jia et al. 2019). Consequently, ILMs as well as IAMs differ in their portfolio and representation of land-based mitigation options, the representation of sustainability goals other than climate action as well as the interplay with mitigation in other sectors (van Soest et al. 2019; Johnson et al. 2019). These structural differences have implications for the regional and global deployment of different mitigation options as well as their sustainability impacts.

As a consequence of the relative novelty of land-based mitigation assessment in ILMs and IAMs, the portfolio of land-based mitigation options does not cover the full option space as outlined in Section 7.4. The inclusion and detail of a specific mitigation measure differs across models. Land based mitigation options are only partially included in ILM and IAM analyses, which mostly rely on afforestation/reforestation and bioenergy with CCS (BECCS). Most ILM and IAM scenarios are based on the Shared Socio-economic Pathways (SSPs) (Riahi et al. 2017), which is a set of contrasting future scenarios widely used in the research community such as in the CMIP6 exercise, the SRCCL and the IPBES global assessment. However, the coverage of land-based mitigation options in these scenarios is mostly limited to dietary changes, higher efficiency in food processing (especially in livestock production systems), reduction of food waste, increasing agricultural productivity, methane reductions in rice paddies, livestock and grazing management for reduced methane emissions from enteric fermentation, manure management, improvement of N-efficiency, international trade, first generation of biofuels, avoided deforestation, afforestation, bioenergy and BECCS (Van Meijl et al. 2018; Popp et al. 2017; Frank et al. 2019). Hence, there are mitigation options not being broadly included in integrated pathway modelling as soil carbon, forest management, agroforestry or wetland management (Humpenöder et al. 2020) which have the potential to alter the contribution of land-based mitigation in terms of timing, potential and sustainability consequences (Frank et al. 2017).

7.5.1. Regional GHG emissions and land dynamics

In most of the assessed mitigation pathways, the AFOLU sector is of great importance for climate change mitigation as it (i) turns from a source into a sink of atmospheric CO_2 due to large-scale afforestation and reforestation, (ii) provides high amounts of biomass for bioenergy with or without CCS and (iii), even under improved agricultural management, still causes residual non-CO_2 emissions from agricultural production and (iv) interplays with sustainability dimensions other than climate action

(Popp et al. 2017; Rogelj et al. 2017; Van Vuuren et al. 2018; Frank et al. 2018; van Soest et al. 2019; Hasegawa et al. 2018). Regional AFOLU GHG emissions in scenarios with <4°C warming in 2100 (scenario category C7), as shown in Figure 7.13, are shaped by considerable CH_4 and N_2O emissions throughout 2050 and 2100, mainly from ASIA and AFRICA. CH_4 emissions from enteric fermentation are largely caused by ASIA, followed by AFRICA, while CH_4 emissions from paddy rice production are almost exclusively caused by ASIA. N_2O emissions from animal waste management and soils are more equally distributed across region.

In most regions, CH_4 and N_2O emission are both lower in mitigation pathways that limit warming to <1.5°C, < 2°C and <3°C (C1-C6) compared to scenarios with <4°C (Popp et al. 2017; Rogelj et al. 2018a). In particular, the reduction of CH_4 emissions from enteric fermentation in ASIA and AFRICA is profound. Land-related CO_2 emissions, which include emissions from deforestation as well as removals from afforestation, are slightly negative (i.e. AFOLU systems turn into a sink) in <1.5°C, < 2°C and <3°C mitigation pathways compared to <4°C scenarios. Carbon sequestration via BECCS is most prominent in ASIA, LAM, AFRICA and OECD90+EU, which are also the regions with the highest bioenergy area.

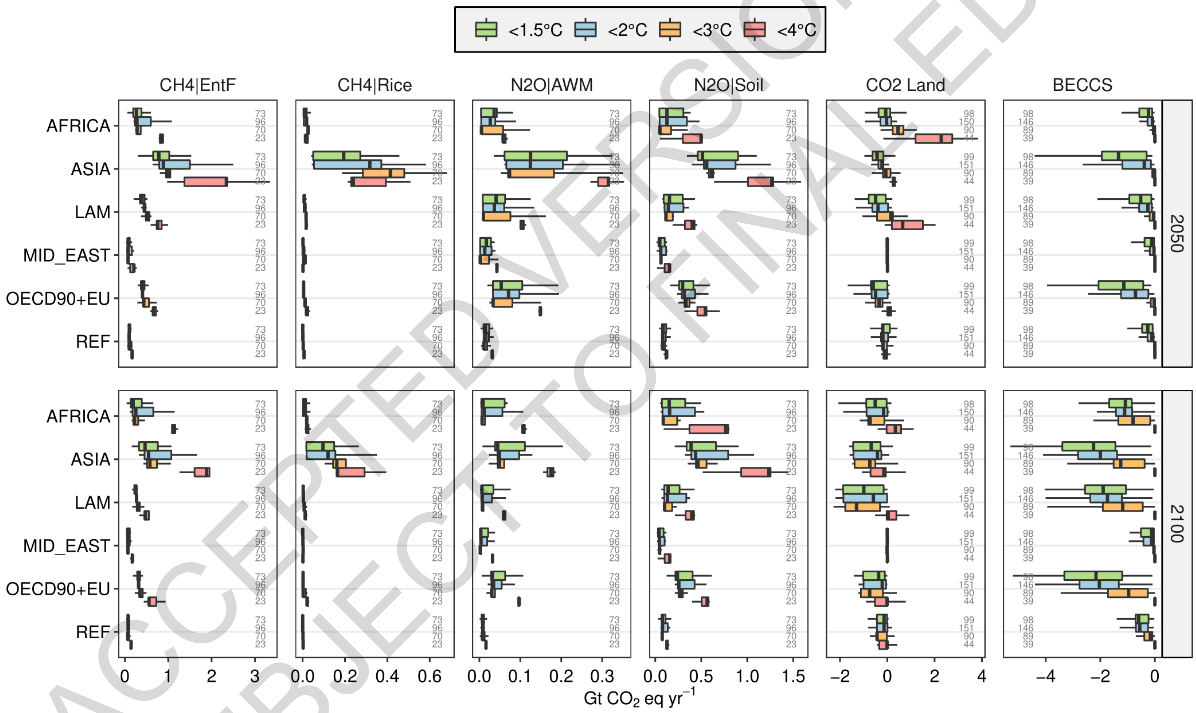


Figure 7.13 Land-based regional GHG emissions and removals in 2050 (top) and 2100 (bottom) for scenarios from the AR6 Database with <1.5°C (C1, C2), < 2°C (C3, C4), <3°C (C5, C6) and <4°C (C7) global warming in 2100 (scenario type is indicated by colour). The categories shown include CH_4 emissions from enteric fermentation (EntF) and rice production (Rice), N_2O emissions from animal waste management (AWM) and fertilisation (Soil). The category CO_2 Land includes CO_2 emissions from land-use change as well as removals due to afforestation/reforestation. BECCS reflects the CO_2 emissions captured from bioenergy use and stored in geological deposits. The annual GHG emission data from various models and scenarios is converted to CO_2 equivalents using GWP factors of 27 for CH_4 and 273 for N_2O. The data is summarised in boxplots (Tukey style), which show the median (vertical line), the interquartile range (IQR box) and the range of values within 1.5 x IQR at either end of the box (horizontal lines) across all models and scenarios.

The number of data points available for each emission category, scenario type, region and year is shown at the edge of each panel. Regional definitions: AFRICA = Sub-Saharan Africa, ASIA = Asia, LAM = Latin America and Caribbean, MID_EAST = Middle East, OECD90+EU = OECD 90 and EU, REF = Reforming Economies of Eastern Europe and the Former Soviet Union.

Figure 7.14 indicates that regional land use dynamics in scenarios with <4°C warming in 2100 are characterised by rather static agricultural land (i.e. cropland and pasture) in ASIA, LAM, OECD90+EU and REF, and increasing agricultural land in AFRICA. Bioenergy area is relatively small in all regions. Agricultural land in AFRICA expands at the cost of forests and other natural land.

The overall land dynamics in <1.5°C, < 2°C and <3°C mitigation pathways are shaped by land-demanding mitigation options such as bioenergy and afforestation, in addition to the demand for other agricultural and forest commodities. Bioenergy production and afforestation take place largely in the (partly) tropical regions ASIA, LAM and AFRICA, but also in OECD90+EU. Land for dedicated second generation bioenergy crops and afforestation displace agricultural land for food production (cropland and pasture) and other natural land. For instance, in the <1.5°C mitigation pathway in ASIA, bioenergy and forest area together increase by about 2.1 million km^2 between 2020 and 2100, mostly at the cost of cropland and pasture (median values). Such large-scale transformations of land use have repercussions on biogeochemical cycles (e.g. fertiliser and water) but also on the economy (e.g. food prices) and potential socio-political conditions.

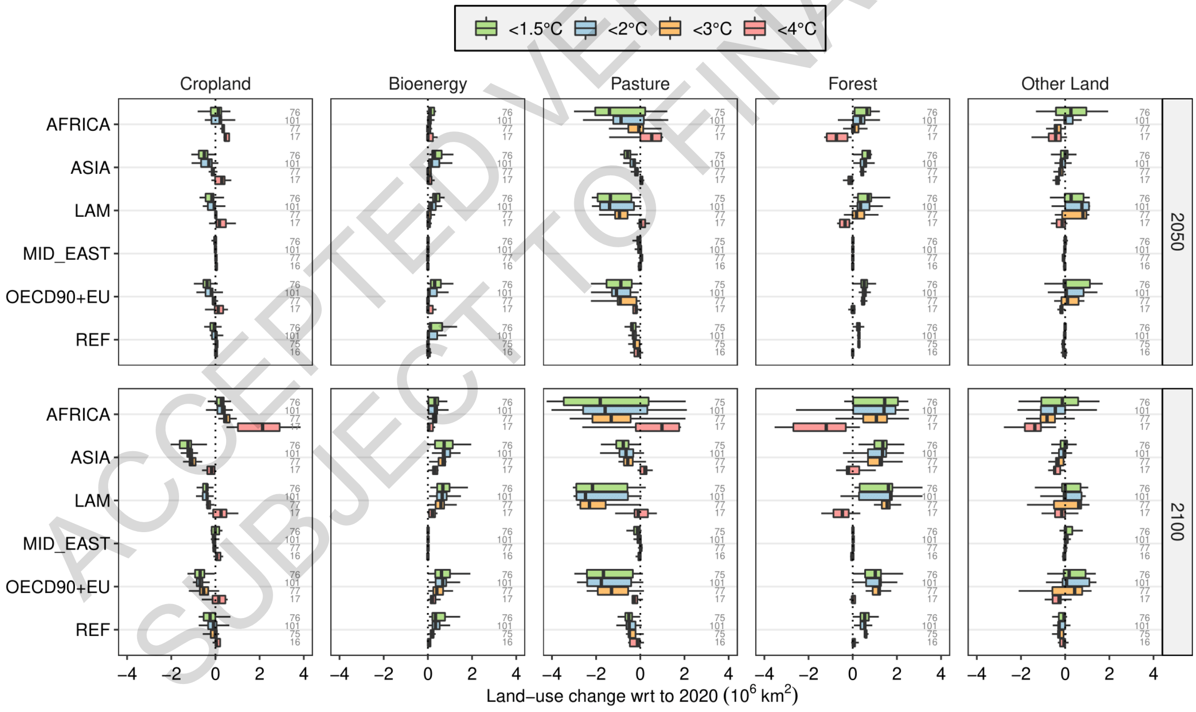


Figure 7.14 Regional change of major land cover types by 2050 (top) and 2100 (bottom) relative to 2020 for scenarios from the AR6 Database with <1.5°C (C1, C2), < 2°C (C3, C4), <3°C (C5, C6) and <4°C (C7) global warming in 2100 (scenario type is indicated by colour). The data is summarised in boxplots (Tukey style), which show the median (vertical line), the interquartile range (IQR box) and the range of values within 1.5 x IQR at either end of the box (horizontal lines) across all models and scenarios. The number of data points available for each land cover type,

scenario type, region and year is shown at the right edge of each panel. Regional definitions: AFRICA = Sub-Saharan Africa, ASIA = Asia, LAM = Latin America and Caribbean, MID_EAST = Middle East, OECD90+EU = OECD 90 and EU, REF = Reforming Economies of Eastern Europe and the Former Soviet Union.

7.5.2. Marginal abatement costs according to integrated assessments

In this section, Integrated Assessment Model (IAM) results from the AR6 database are used to derive marginal abatement costs which indicate the economic mitigation potential for the different gases (N_2O, CH_4, CO_2) related to the AFOLU sector, at the global level and at the level of five world regions. This review provides a complementary view on the economic mitigation potentials estimated in Section 7.4 by implicitly taking into account the interlinkages between the land-based mitigation options themselves as well as the interlinkages with mitigation options in the other sectors such as BECCS. The review systematically evaluates a range of possible economic potential estimates across gases, time, and carbon prices.

For different models and scenarios from the AR6 database, the amount of mitigated emissions is presented together with the respective carbon price (Figure 7.15). To determine mitigation potentials, scenarios are compared to a benchmark scenario which usually assumes business-as-usual trends and no explicit additional mitigation efforts. Scenarios have been excluded, if they do not have an associated benchmark scenario or fail the vetting according to the AR6 scenario database, or if they do not report carbon prices and CO_2 emissions from AFOLU. Scenarios with contradicting assumptions (for example, fixing some of the emissions to baseline levels) are excluded. Furthermore, only scenarios with consistent[3] regional and global level results are considered. Mitigation potentials are computed by subtracting scenario specific emissions and sequestration amounts from their respective benchmark scenario values. This difference accounts for the mitigation that can be credited to the carbon price which is applied in a scenario. A few benchmark scenarios, however, apply already low carbon prices. For consistency reasons, a carbon price that is applied in a benchmark scenario is subtracted from the respective scenario specific carbon price. This may generate a bias because low carbon prices tend to have a stronger marginal impact on mitigation than high carbon prices. Scenarios with carbon prices which become negative due to the correction are not considered. The analysis considers all scenarios from the AR6 database which pass the criteria and should be considered as an ensemble of opportunity (Huppmann et al. 2018).

This approach is close to integrated assessment marginal abatement cost curves (MACCs) as described in the literature (Frank et al. 2018, 2019; Harmsen et al. 2019; Fujimori et al. 2016) in the sense that it incorporates besides the technical mitigation options also structural options, as well as behavioural changes and market feedbacks. Furthermore, indirect emission changes and interactions with other sectors can be highly relevant (Daioglou et al. 2019; Kalt et al. 2020) and are also accounted for in the presented potentials. Hereby, some sequestration efforts can occur in other sectors, while leading to less mitigation in the AFOLU sector. For instance, as an integral part of many scenarios, BECCS deployment will lead to overall emissions reductions, and even provision of CDR as a result of the interplay between three direct components i) LULUCF emissions/sinks, ii) reduction of fossil fuel use/emissions, iii) carbon capture and sequestration. Since the latter two effects can compensate for the LULUCF effect, BECCS deployment in ambitious stabilisation scenarios may lead to reduced

FOOTNOTE: [3] Scenarios are considered consistent between global and regional results (based on R5 regions), if the sum of regional emissions (or sequestration efforts) does not deviate more than 10% from the reported global total. To take into account that small absolute values have a higher sensitivity, a deviation of 90% is allowed for absolute values below 100.

sink/increased emissions in LULUCF (Kalt et al. 2020). The same holds for trade-offs between carbon sequestration in forests versus harvested wood products both for enhancing the HWP pool and for material substitution. The strengths of the competition between biomass use and carbon sequestration will depend on the biomass feedstocks considered (Lauri et al. 2019).

In the individual cases, the accounting of all these effects is dependent on the respective underlying model and its coverage of inter-relations of different sectors and sub-sectors. The presented potentials cover a wide range of models, and additionally, a wide range of background assumptions on macro-economic, technical, and behavioural developments as well as policies, which the models have been fed with. Subsequently, the range of the resulting marginal abatement costs is relatively wide, showing the full range of expected contributions from land use sector mitigation and sequestration in applied mitigation pathways.

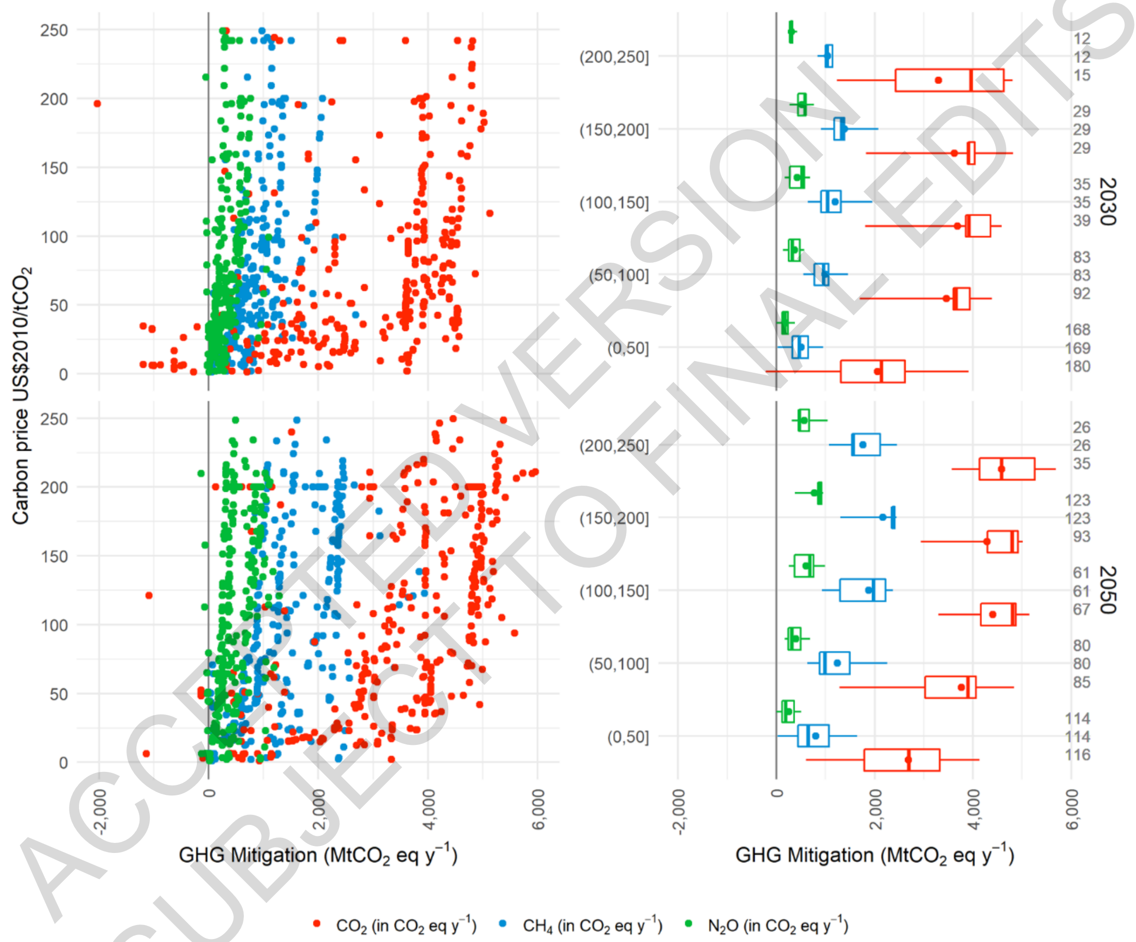


Figure 7.15 Mitigation of CO_2, CH_4 and N_2O emissions (in CO_2-eq yr^{-1} using IPCC AR6 GWP_{100} values) from the AFOLU sector for increasing carbon price levels for 2030 and 2050. In the left side panels, single data points are generated by comparing emissions between a policy scenario and a related benchmark scenario, and mapping these differences with the respective carbon price difference. Plots only show the price range of up to USD(2010)250 tCO_2-eq^{-1} and the mitigation range between -2,000 and 6,000 $MtCO_2$-eq yr^{-1} for better visibility. At the right-hand side, based on the same data as left-hand side panels, Boxplots show Medians (vertical line within the boxes), Means (dots), 33%-66% intervals (Box) and 10%-90% intervals (horizontal lines). Numbers on the very right indicate the number of observations falling into the respective price range per variable. A wide range of carbon price induced mitigation options

(such as technical, structural and behavioural options in the agricultural sector, afforestation, reforestation, natural re-growth or avoided deforestation in the LULUUCF sector, *excluding* carbon capture and sequestration from BECCS) are reflected in different scenarios.

At the global level, the analysis of the economic mitigation potentials from N_2O and CH_4 emissions from AFOLU (which mainly can be related to agricultural activities) and CO_2 emissions (which mainly can be related to LULUCF emissions) reveals a relatively good agreement of models and scenarios in terms of ranking between the gases. On the right-hand side panels of Figure 7.15, only small overlaps between the ranges (showing the 10-90% intervals of observations) and mainly for lower price levels, can be observed, despite all differences in underlying model structure and scenario assumptions.

N_2O emissions show the smallest economic potential of the three different gases in 2030 as well as in 2050. The mitigation potential increases until a price range of USD150-200 and to a median value of around 0.6 $GtCO_2$-eq yr^{-1} mitigation in 2030 and 0.9 $GtCO_2$-eq yr^{-1} in 2050, respectively, while afterwards with higher prices the expansion is very limited. Mitigation of CH_4 emissions has a higher potential, also with increasing mitigation potentials until a price range of USD150-200 in both years, with median mitigation of around 1.3 $GtCO_2$-eq yr^{-1} in 2030 and around 2.4 $GtCO_2$-eq yr^{-1} in 2050, respectively. The highest mitigation potentials are observed for CO_2, but also the highest ranges of observations among the three gases. In 2030, a median of 4 $GtCO_2$-eq yr^{-1} mitigation potential is reported for the price range of USD200–250. In 2050, for the carbon price range of between USD100 and USD200, a median of around 4.8 $GtCO_2$-eq yr^{-1} can be observed.

When compared with the sectoral estimates from Harmsen et al. (2019), the integrated assessment median potentials are broadly comparable for the N_2O mitigation potential; Harmsen et al. 2050 mitigation potential at USD125 is 0.6 $GtCO_2$-eq yr^{-1} while the integrated assessment estimate for the same price range is 0.7 $GtCO_2$-eq yr^{-1}. The difference is substantially larger for the CH4 mitigation potential; 0.9 $GtCO_2$-eq yr^{-1} in Harmsen et al. while 2 $GtCO_2$-eq yr^{-1} the median integrated assessment estimate. While the Harmsen et al. MACCs consider only technological mitigation options, integrated assessments typically include also demand side response to the carbon price and GHG efficiency improvements through structural change and international trade. These additional mitigation options can represent more than 60% of the total non-CO_2 mitigation potential in the agricultural sector, where they are more important in the livestock sector, and thus the difference between sectoral and integrated assessments is more pronounced for the CH_4 emissions (Frank et al. 2019).

Economic CO_2 mitigation potentials from land use change and forestry are larger compared to potentials from non-CO_2 gases, and at the same time reveal high levels of variation in absolute terms. The 66th percentile in 2050 goes up to 5.2 $GtCO_2$-eq yr^{-1} mitigation, while the lowest observations are even negative, indicating higher CO_2 emissions from land use in scenarios with carbon price compared to scenarios without (counterintuitive dynamics explained below).

Land use is at the centre of the interdependencies with other sectors, including energy. Some models see a strong competition between BECCS deployment with its respective demand for biomass, and CO_2 mitigation/sequestration potentials in the land sector. Biomass demand may lead to an increase in CO_2 emissions from land use despite the application of a carbon price when land use expansion for dedicated biomass production, such as energy plantations, comes from carbon rich land use/land cover alternatives, or when increased extraction of biomass from existing land uses, such as forest management, leads to reduction of the carbon sink (Daioglou 2019; Luderer et al. 2018, SI) and can explain the high variety of observations in some cases. Overall, the large variety of observations shows a large variety of plausible results, which can go back to different model structures and assumptions, showing a robust range of plausible outcomes (Kriegler et al. 2015).

7.5.3. Interaction between mitigation in the AFOLU sector and other SDGs in the context of integrated assessments

Besides the level of biomass supply for bioenergy, the adoption of SDGs may also significantly impact AFOLU emissions and the land use sector's ability for GHG abatement (Frank et al. 2021). Selected SDGs are found to have positive synergies for AFOLU GHG abatement and to consistently decrease GHG emissions for both agriculture and forestry, thereby allowing for even more rapid and deeper emissions cuts. In particular, the decreased consumption of animal products and less food waste (SDG12), and the protection of high biodiversity ecosystems such as primary forests (SDG15) deliver high synergies with GHG abatement. On the other hand, protection of highly biodiverse ecosystems from conversion (SDG15) limits the global biomass potentials for bioenergy (Frank et al. 2021), and while several forestry measures enhancing woody biomass supply for bioenergy may have synergies with improving ecosystems conditions, many represent a threat to biodiversity (Camia et al. 2020). See also Section 7.6.5. and Chapter 17 Section 17.3.3.7, Figure 17.1, Supplementary Material Table 17.1.

7.5.4. Regional AFOLU abatement for different carbon prices

Figure 7.16 Regional mitigation efforts for CO_2, CH_4 and N_2O emissions (in CO_2-eq yr^{-1} using IPCC AR6 GWP_{100} values) from the AFOLU sector for increasing carbon price levels for 2030 and 2050. Underlying datapoints are generated by comparing emissions between a policy scenario and a related benchmark

scenario, mapping these differences with the respective carbon price differences. Boxplots show Medians (vertical line within the boxes), Means (dots), 33%-66% intervals (box) and 10%-90% intervals (horizontal lines) for respective scenarios of carbon prices implemented in intervals of USD50 from a price of USD0 to USD250. Regions: Asia (ASIA), Latin America and Caribbean (LAM), Middle East (MIDDLE_EAST),Africa (AFRICA), Developed Countries (OECD 90 and EU) (OECD+EU) and Reforming Economies of Eastern Europe and the Former Soviet Union (REF).

At the regional level (Figure 7.16), the highest potential from non-CO_2 emissions abatement, and mostly from CH_4, is reported for ASIA with the median of mitigation potential observations from CH_4 increasing up to a price of USD200 in the year 2050, reaching a median of 1.2 $GtCO_2$-eq yr^{-1}. In terms of economic potential, ASIA is followed by LAM, AFRICA, and OECD+EU, where emission reduction mainly is achieved in the livestock sector.

The highest potentials from land-related CO_2 emissions, including avoided deforestation as well as afforestation, can be observed in LAM and AFRICA with strong responses of mitigation (indicated by the median value) to carbon prices mainly in the lower range of displayed carbon prices. In general, CO_2 mitigation potentials show a wide range of results in comparison to non-CO_2 mitigation potentials, but mostly also a higher median value. The most extreme ranges are reported for the regions LAM and AFRICA. A medium potential is reported for ASIA and OECD+EU, while REF has the smallest potential according to model submissions. These estimates reflect techno-economic potentials and do not necessarily include feasibility constraints which are discussed in Chapter 7.6.

7.5.5. Illustrative mitigation pathways

Different mitigation strategies can achieve the net emission reductions that would be required to follow a pathway limiting global warming, with very different consequences for the land system. Figure 7.17 shows Illustrative Mitigation Pathways (IMPs) for achieving different climate targets highlighting AFOLU mitigation strategies, resulting GHG and land use dynamics as well as the interaction with other sectors. For consistency this chapter discusses IMPs as described in detail in chapters 1 and 3 of this report but focusing on the land-use sector. All pathways are assessed by different IAM realizations and do not only reduce GHG emissions but also use CDR options, whereas the amount and timing varies across pathways, as do the relative contributions of different land-based CDR options.

The *scenario ModAct* (below 3.0°C warming, C6) is based on the prolongation of current trends (SSP2) but contains measures to strengthen policies for the implementation of National Determined Contributions (NDCs) in all sectors including AFOLU (Grassi et al. 2018). This pathway shows a strong decrease of CO_2 emissions from land-use change in 2030, mainly due to reduced deforestation, as well as moderately decreasing N_2O and CH_4 emissions from agricultural production due to improved agricultural management and dietary shifts away from emissions-intensive livestock products. However, in contrast to CO_2 emissions, which turn net-negative around 2050 due to afforestation/reforestation, CH_4 and N_2O emissions persist throughout the century due to difficulties of eliminating these residual emissions based on existing agricultural management methods (Stevanović et al. 2017; Frank et al. 2017). Comparably small amounts of BECCS are applied by the end of the century. Forest area increases at the cost of other natural vegetation.

IMP Neg-2.0 is similar to *ModAct* scenario in terms of socio-economic setting (SSP2) but differs strongly in terms of the mitigation target (likely 2°C, C3) and its strong focus on the supply side of mitigation measures with strong reliance on net-negative emissions. Consequently, all GHG emission reductions as well as afforestation/reforestation and BECCS-based CDR start earlier in time at a higher rate of deployment. However, in contrast to CO_2 emissions, which turn net-negative around 2030 due to afforestation/reforestation, CH_4 and N_2O emissions persist throughout the century, similar to *ModAct*, due to ongoing increasing demand for total calories and animal-based commodities (Bodirsky et al. 2020) and difficulties of eliminating these residual emissions based on existing agricultural management methods (Stevanović et al. 2017 ; (Frank et al. 2017). In addition to abating land-related GHG emissions as well as increasing the terrestrial sink, this example also shows the potential importance of the land sector in providing biomass for BECCS and hence CDR in the energy sector. Cumulative CDR (2020-2100) amounts to 502 $GtCO_2$ for BECCS and 121 $GtCO_2$ for land-use change (including afforestation and reduced deforestation). In consequence, compared to *ModAct scenario,* competition for land is increasing and much more other natural land as well as agricultural land (cropland and pasture land) is converted to forest or bioenergy cropland with potentially severe consequences for various sustainability dimensions such as biodiversity (Hof et al. 2018) and food security (Fujimori et al. 2019).

IMP Ren is similar to *IMP Neg-2.0* in terms of socio-economic setting (SSP2) but differs substantially in terms of mitigation target and mitigation efforts in the energy sector. Even under the more ambitious climate change mitigation target (1.5°C with no or low OS, C1), the high share of renewable energy in *IMP Ren* strongly reduces the need for large-scale land-based CDR, which is reflected in smaller bioenergy and afforestation areas compared to *IMP Neg-2.0*. However, CH_4 and N_2O emissions from AFOLU persist throughout the century, similar to *ModAct scenario and IMP Neg-2.0*.

In contrast to *IMPs Neg-2.0 and Ren, IMP SP* (Soergel et al. 2021; 1.5°C with no or low OS, C1) displays a future of generally low resource and energy consumption (including healthy diets with low animal-calorie shares and low food waste) as well as significant but sustainable agricultural intensification in combination with high levels of nature protection. This pathway shows a strong near-term decrease of CO_2 emissions from land-use change, mainly due to reduced deforestation, and in difference to all other *IMPs* described in this chapter strongly decreasing N_2O and CH_4 emissions from agricultural production due to improved agricultural management but also based on dietary shifts away from emissions-intensive livestock products as well as lower shares of food waste. In consequence, comparably small amounts of land are needed for land demanding mitigation activities such as BECCS and afforestation. In particular, the amount of agricultural land converted to bioenergy cropland is smaller compared to other mitigation pathways. Forest area increases either by regrowth of secondary vegetation following the abandonment of agricultural land or by afforestation / reforestation at the cost of agricultural land.

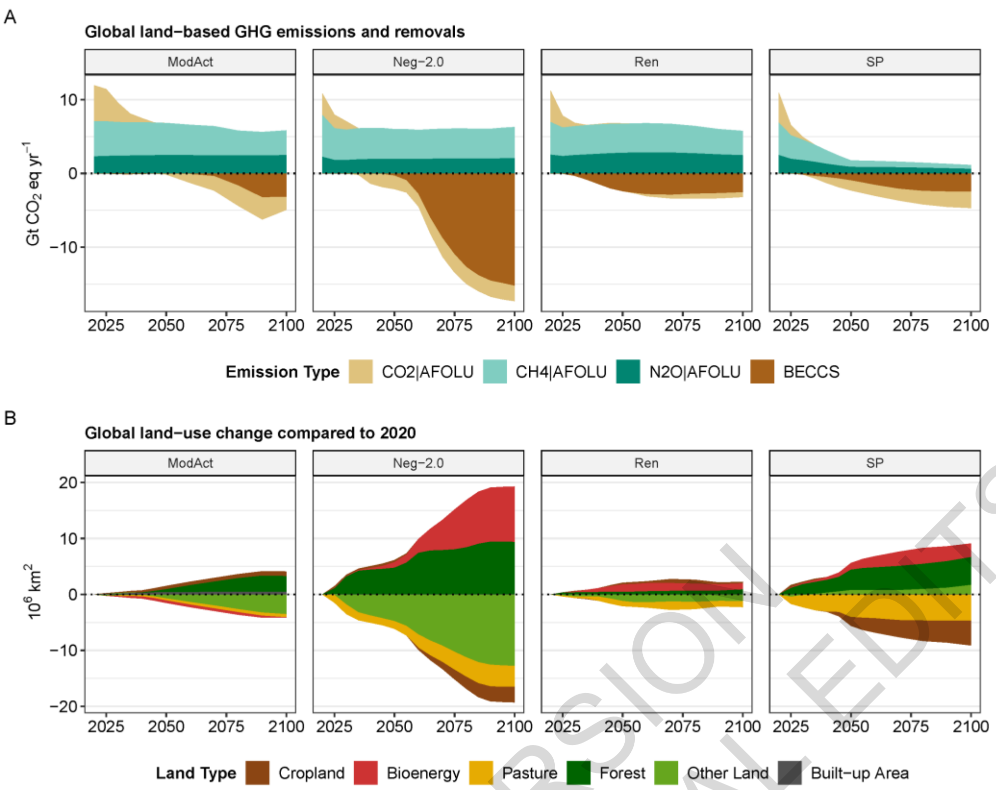


Figure 7.17 Evolution and break down of (A) global land-based GHG emissions and removals and (B) global land use dynamics under four Illustrative Mitigation Pathways, which illustrate the differences in timing and magnitude of land-based mitigation approaches including afforestation and BECCS. All pathways are based on different IAM realisations: *ModAct scenario* (below 3.0°C, C6) from IMAGE 3.0; *IMP Neg-2.0* (likely 2°C, C3) from AIM/CGE 2.2; *IMP Ren* (1.5°C with no or low OS, C1) from REMIND-MAgPIE 2.1-4.3; *IMP SP* (1.5°C with no or low OS, C1) from REMIND-MAgPIE 2.1-4.2; In panel A the categories CO_2 Land, CH_4 Land and N_2O Land include GHG emissions from land-use change and agricultural land use (including emissions related to bioenergy production). In addition, the category CO_2 Land includes removals due to afforestation / reforestation. BECCS reflects the CO_2 emissions captured from bioenergy use and stored in geological deposits. CH_4 and N_2O emissions are converted to CO_2-eq using GWP_{100} factors of 27 and 273 respectively.

7.6. Assessment of economic, social and policy responses

7.6.1. Retrospective in policy efforts and achieved mitigation within AFOLU

Since the establishment of the UNFCCC, international agencies, countries, sub-national units and NGO's have developed policies to facilitate and encourage GHG mitigation within AFOLU (Figure 7.18). Early guidance and policies focused on developing GHG inventory methodology with some emphasis on afforestation and reforestation projects, but the Clean Development Mechanism (CDM) in the Kyoto Protocol focused attention on emission reduction projects, mostly outside of AFOLU. As successive IPCC WGIII reports illustrated large potential for AFOLU mitigation, methods to quantify and verify carbon emission reductions emerged within several projects in the early 2000s, through both voluntary (e.g., the Chicago Climate Exchange (CCX)) and regulated (e.g., New South Wales and California) markets. The CDM dedicated large attention to LULUCF, including dedicated methodologies and bodies. The reasons for limited uptake of CDM afforestation/reforestation projects were multiple and not limited to the regulatory constraints, but also due to the low abatement potential (poor cost/performance ratio) compared to other mitigation opportunities.

Following COP 13 in Bali, effort shifted to advancing policies to reduce deforestation and forest degradation (REDD+) in developing countries. According to Simonet et al. (2019), nearly 65 Mha have been enrolled in REDD+ type programs or projects funded through a variety of sources, including UN REDD, the World Bank Forest Carbon Partnership Facility, and bi-lateral agreements between countries with Norway being the largest donor. While there has been considerable focus on forest and agricultural project-based mitigation actions, national governments were encouraged to incorporate project-based approaches with other sectoral strategies in their Nationally Appropriate Mitigation Strategies (NAMAs) after 2012. NAMAs reflect the country's proposed strategy to reduce net emissions across various sectors within their economy (e.g. forests or agriculture). More recently, Nationally Determined Contributions (NDCs) indicate whether individual countries plan to use forestry and agricultural policies or related projects amongst a set of measures in other sectors, to reduce their net emissions as part of the Paris Agreement (e.g., Forsell et al. 2016; Fyson and Jeffery 2019).

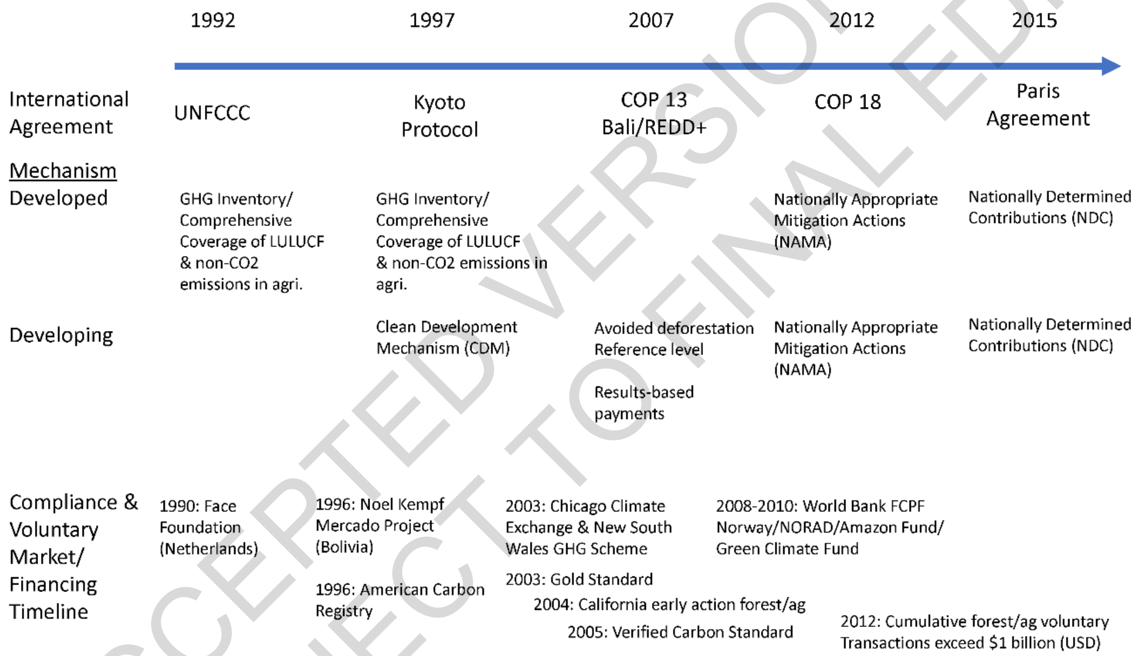


Figure 7.18 Milestones in policy development for AFOLU measures.

The many protocols now available can be used to quantify the potential mitigation to date resulting from various projects or programs. For instance, carbon registries issue credits using protocols that typically account for additionality, permanence and leakage, thus providing evidence that the projects are a net carbon benefit to the atmosphere. Protocol development engages the scientific community, project developers, and the public over a multi-year period. Some protocols have been revised multiple times, such as the USA State of California's forest carbon protocol, which is in its fifth revision, with the latest in 2019 (see http://www.climateactionreserve.org/how/protocols/forest/). Credits from carbon registries feed into regulatory programs, such as the cap and trade program in California, or voluntary offset markets (Hamrick and Gallant 2017a). Although AFOLU measures have been deployed across a range of projects and programs globally to reduce net carbon emissions, debate about the net carbon benefits of some projects continues (e.g. Krug 2018).

A new assessment of projects over the last two decades finds emission reductions or offsets of at least 7.9 $GtCO_2$-eq (using GWP_{100} and a mix of IPCC values for CH_4 and N_2O) over the last 12 years due to agricultural and forestry activities (Table 7.4). More than 80% of these emission reductions or offsets have been generated by forest-based activities. The total amounts to 0.66 $GtCO_2$ yr^{-1} for the period 2010-2019, which is 1.2% of total global, and 5.5% of AFOLU emissions reported in Table 7.1, over the same time period (*high confidence*).

The array of activities in Table 7.4 includes the Clean Development Mechanism, REDD+ activities reported in technical annexes of country biennial update reports to the UNFCCC, voluntary market transactions, and carbon stored as a result of carbon markets in Australia, New Zealand and California in the USA. Although other countries and sub-national units have developed programs and policies, these three regions are presented due to their focus on forest and agricultural carbon mitigation, their use of generally accepted protocols or measures and the availability of data to quantify outcomes.

The largest share of emission reductions or carbon offsets in Table 7.4 has been from slowing deforestation and REDD+, specifically from efforts in Brazil (86% of total), which substantially reduced deforestation rates between 2004 and 2012 (Nepstad et al., 2014), as well as other countries in Latin America. With the exception of Roopsind et al. (2019), estimated reductions in carbon emissions from REDD+ in Table 7.4 are measured relative to a historical baseline. As noted in Brazil's Third Biennial Update Report (Ministry of Foreign Affairs 2019), estimates are made in accordance with established methodologies to determine the benefits of results-based REDD+ payments to Brazil. REDD+ estimates from other countries also have been derived from biennial update reports.

Regulatory markets provide the next largest share of carbon removal to date. Data from the Australia Emissions Reduction Fund is an estimate of carbon credits in agriculture and forestry purchased by the Australian government. In the case of California, offset credits from forest and agricultural activities, using methods approved by a third-party certification authority (Climate Action Reserve), have been allowed as part of their state-wide cap and trade system. Transaction prices for forest and agricultural credits in California were around USD13 tCO_2^{-1} in 2018, and represented 7.4% of total market compliance. By the end of 2018, 80 $MtCO_2$ had been used for compliance purposes.

For New Zealand, the carbon reduction in Table 7.4 represents forest removals that were surrendered from post-1989 forests between 2008 and the 2020. Unlike offsets in voluntary markets or in California, where permanence involves long-term contracts or insurance pools, forests in the New Zealand market liable for emissions when harvested or following land use change. This means sellers account for future emission risks related to harvesting when they enter forests into carbon contracts. Offset prices were around USD13 tCO_2^{-1} in 2016 but have risen to more than USD20 tCO_2^{-1} in 2020.

The voluntary market data in Table 7.4 are offsets developed under the major standard-setting organizations, and issued from 2008-2018 (e.g., Hamrick and Gallant 2018). Note that there is some potential for double counting of voluntary offsets that may have been transacted in the California compliance market, however this would only have applied to transactions of US-issued offsets, and the largest share of annual transactions of voluntary AFOLU credits occurs with credits generated in Latin America, followed by Africa, Asia and North America. Europe and Oceania have few voluntary carbon market transactions. Within forestry and agriculture, most of the voluntary offsets were generated by forestry projects. Using historical transaction data from various *Forest Trends* reports, the offsets generated were valued at USD46.9 million yr^{-1}. Prices for voluntary offset transactions in the period 2014-2016 ranged from USD4.90 to 5.40 tCO_2^{-1} (Hamrick and Gallant 2017a).

Voluntary finance has amounted to USD0.5 billion over a 10-year period for development of forest and agricultural credits. The three regulatory markets quantified amount to USD2.7 billion in funding from 2010 to 2019. For the most part, this funding has focused on forest projects and programs, with agricultural projects accounting for 5-10% of the total. In total, reported funding for AFOLU projects and programs has been USD4.4 billion over the past decade, or about USD569 million yr^{-1} (*low confidence*). The largest share of the total carbon includes efforts in the Amazon by Brazil. Government expenditures on regulatory programs and business expenditures on voluntary programs in Brazil (e.g., the soy or cattle moratoriums) were not included in financing estimates due to difficulties obtaining that data. If Brazil and CDM (for which we have no cost estimates) are left out of the calculation, average cost per ton has been USD3.20 tCO_2^{-1}.

Table 7.4 Estimates of achieved emission offsets or reductions in AFOLU through 2018. Data include CDM, voluntary carbon standards, compliance markets, and reduced deforestation from official UNFCCC reports. Carbon sequestration due to other government policies not included.

Fund / Mechanism	Total Emission Reductions or Offsets (Mt CO_2-eq)	Time Frame	Mt CO_2-eq yr^{-1}	Financing (Million USD yr^{-1})
CDM-forest [a]	11.3	2007-2015	1.3	-
CDM-agriculture [a]	21.8	2007-2015	2.4	-
REDD + (Guyana) [b]	12.8	2010-2015	2.1	33.0
Reduced Deforestation/ REDD + Brazil [c]	6,894.5	2006-2017	574.5	49.2
REDD + Indonesia [c]	244.9	2013-2017	49.0	13.4
REDD + Argentina [c]	165.2	2014-2015	55.1	1.4
REDD + Others [c]	211.8	2010-2017	26.5	46.0
Voluntary Market [d]	95.3	2009-2018	9.5	46.9
Australia ERF [e]	33.7	2012-2018	4.8	50.5
California [f]	122.2	2013-2018	20.4	227.1
New Zealand Carbon Trading [g]	83.9	2010-2019	8.4	101.7
Total	**7,897.4**	**2007-2018**	**658.1** [8]	**569.1**

[a] Clean Development Mechanism Registry: https://cdm.unfccc.int/Registry/index.html (accessed 22/06/2021)
[b] Roopsind et al. 2019.
[c] UNFCCC REDD+ Web Platform (https://redd.unfccc.int/submissions.html) and UNFCCC Biennial Update Report database (https://unfccc.int/BURs)
[d] (Hamrick and Gallant 2017a). State of Forest Carbon Finance. Forest Trends Ecosystem Marketplace. Washington, DC.

[e] Data for Australia carbon credit units (ACCUs) from Australia Emission Reduction Fund Registry for forest agricultural and savanna practices through FY2018/19 (downloaded on 24/10/2019): (http://www.cleanenergyregulator.gov.au/ERF/project-and-contracts-registers/project-register).

[f] Data from the California Air Resources Board Offset Issuance registry (https://ww2.arb.ca.gov/our-work/programs/compliance-offset-program) for forestry and agricultural early action and compliance credits.

[g] Surrendered forest carbon credits from post-1989 forests in New Zealand. Obtained from New Zealand Environmental Protection Authority. ETS Unit Movement interactive report (Excel based). https://www.epa.govt.nz/industry-areas/emissions-trading-scheme/ets-reports/unit-movement/. Obtained 13/08/2020.[8] All non-CO_2 gases are converted to CO_2-eq using IPCC GWP_{100} values recommended at the time the project achieved approval by the relevant organisation or agency.

The large number of policy approaches described in Table 7.4 combined with efforts by other international actors, such as the Global Environmental Facility (GEF), as well as non-state actors (e.g., eco-labelling programs and corporate social responsibility initiatives) illustrate significant policy experimentation over the last several decades. Despite widespread effort, AFOLU measures have thus far failed to achieve the large potential for climate mitigation described in earlier IPCC WG III reports (*high confidence*). The limited gains from AFOLU to date appear largely to result from lack of investment and other institutional and social barriers, rather than methodological concerns (*high confidence*).

7.6.2. Review of observed policies and policy instruments

7.6.2.1. Economic incentives

Emissions Trading/Carbon Taxes. While emissions trading programs have been developed across the globe, forest and agriculture have not been included as part of the cap in any of the existing systems. However, offsets from forestry and agriculture have been included in several of the trading programs. New Zealand has a hybrid program where carbon storage in forests can be voluntarily entered into the carbon trading program, but once entered, forests are counted both as a sink for carbon if net gains are positive, and a source when harvesting occurs. New Zealand is considering rules to include agricultural GHG emissions under a future cap (Henderson et al. 2020; see: https://www.agmatters.nz/topics/he-waka-eke-noa/).

The state of California has developed a formal cap and trade program that allows a limited number of forest and agricultural offset credits to be used under the cap. All offsets must meet protocols to account for additionality, permanence and leakage. Forest projects used as offsets in California currently are located in the USA, but the California Air Resources Board adopted a tropical forest carbon standard, allowing for avoided deforestation projects from outside the USA to enter the California market (CARB 2019).

Canadian provinces have developed a range of policy options that can include carbon offsets. Quebec has an emissions trading program that plans to allow forest and agricultural offsets generated within the province to be utilised. Alberta also allows offsets to be utilised by regulated sectors while British Columbia allows offsets to be utilised by the government for its carbon neutrality goals (Government of Alberta, 2021) . Over 20 countries and regions have adopted explicit carbon taxes on carbon emission sources and fossil fuels, however, the charges have not been applied to non-CO_2 agricultural emissions (OECD 2021a). California may implement regulations on methane emissions from cattle, however, regulations if approved, will not go into effect until 2024. Institutional and trade-related barriers (e.g., leakage) likely will limit widespread implementation of taxes on emissions in the food sector globally. Many countries exempt purchases of fuels used in agricultural or fishery production from fuel or carbon taxes, thus lowering the effective tax rate imposed on those sectors (OECD 2021a). Furthermore, bioenergy, produced from agricultural products, agricultural waste, and wood is often exempted from explicit carbon taxes. Colombia recently implemented a carbon tax on liquid fuels but allowed domestically produced forestry credits to offset the tax. Colombia also is in the process of developing an emissions trading scheme (OECD 2021a).

REDD+/*Payment for Ecosystem Services (PES).* PES programs for a variety of ecosystem services have long been utilised for conservation (e.g. Wunder 2007) and may now be as large as USD42 billion yr^{-1} (Salzman et al. 2018). REDD+ emerged in the early 2000s and is a widely recognized example of PES program focused on conservation of tropical forests (Table 7.4). However, our summation of actually paid funds in Table 7.4 is much smaller than what is portrayed by Salzman et al. (2018). REDD+ may operate at the country level, or for specific programs or forests within a country. As with other PES programs, REDD+ has evolved towards a results-based program that involves payments that are conditioned on meeting certain successes or milestones, such as rates of deforestation (Angelsen 2017).

A large literature has investigated whether PES programs have successfully protected habitats. Studies in the USA found limited additionality for programs that encouraged conservation tillage practices, but stronger additionality for programs that encouraged set-asides for grasslands or forests (Woodward et al. 2016; Claassen et al. 2018;), although the set-asides led to estimated leakage of 20 up to 100% (Wu 2000; Pfaff and Robalino 2017; Kallio and Solberg 2018). Evidence from the EU similarly suggests that payments for some agro-environmental practices may be additional, while others are not (Chabé-Ferret and Subervie 2013). Other studies, in particular in Latin America where many PES programs have been implemented, have found a wide range of estimates of effectiveness (e.g. Honey-Rosés et al. 2011; Robalino and Pfaff 2013; Mohebalian and Aguilar 2016; Jayachandran et al. 2017; Börner et al. 2017; Alix-Garcia et al. 2015; Robalino et al. 2015; Burivalova et al. 2019). Despite concerns, the many lessons learned from PES program implementation provide critical information that will help policymakers refine future PES programs to increase their effectiveness (*medium confidence*).

While expectations that carbon-centred REDD+ would be a simple and efficient mechanism for climate mitigation have not been met (Turnhout et al. 2017; Arts et al. 2019), progress has nonetheless occurred. Measuring, monitoring and verification systems have been developed and deployed, REDD readiness programs have improved capacity to implement REDD+ on the ground in over 50 countries, and a number of countries now have received results-based payments.

Empirical evidence that REDD+ funding has slowed deforestation is starting to emerge. Simonet et al. (2019) showed that a REDD+ project in Brazil reduced deforestation certainly until 2018, while Roopsind et al. (2019) showed that country-level REDD+ payments to Guyana encouraged reduced deforestation and increased carbon storage. Although more impact evaluation (IE) analysis needs to be conducted on REDD+ payments, these studies support the country-level estimates of carbon benefits from REDD+ shown in Table 7.4. Nearly all of the analysis of PES and REDD+ to date has focused on the presence or absence of forest cover, with little to no analysis having been conducted on forest degradation, conservation, or enhancement of forest stocks.

Agro-environmental Subsidy Programs/PES. Climate policy for agriculture has developed more slowly than in other sectors due to concerns with food security and livelihoods, political interests, and difficulties in coordinating diffuse and diverse activities and stakeholders (e.g. nutritional health, rural development, and biodiversity conservation) (Leahy et al. 2020). However, a review of the National Adaptation Programme of Action (NAPAs), National Adaptation Plans (NAPs), NAMAs, and NDCs in the Paris Agreement suggest an increasing focus of policy makers on agriculture and food security. The vast majority of parties to the Paris Agreement recognise the significant role of agriculture in supporting a secure sustainable development pathway (Richards and VanWey 2015) with the inclusion of agriculture mitigation in 103 NDCs from a total of 160 NDC submissions. Livestock is the most frequently cited specific agricultural sub-sector, with mitigation activities generally focusing on increasing efficiency and productivity.

Agriculture is one of the most subsidised industries globally, especially in the European Union and the USA. While subsidy payments over the last 20 years have shifted modestly to programs designed to reduce the environmental impact of the agricultural sector, only 15-20% of the more than USD700 billion spent globally on subsidies are green payments (OECD 2021b). Under the Common Agricultural Policy in the EU, up to 30% of the direct payments to farmers (Pillar 1) have been green payments (Henderson et al. 2020), including some actions that could increase carbon storage or reduce emissions. Similarly, at least 30% of the rural development payments (Pillar 2) are used for measures that reduce environmental impact, including reduction of GHG emissions and carbon storage. There is limited evidence that these policies contributed to the 20% reduction in GHG emissions from the agricultural sector in the EU between 1990 and 2018 (Baudrier et al. 2015) and Eurostat 2020).

The USA spends USD4 billion yr^{-1} on conservation programs, or 12% of net farm income (Departament Of Agriculture 2020). In real terms, this expenditure has remained constant for 15 years, supporting 12 Mha of permanent grass or woodland cover in the Conservation Reserve Program (CRP), which has increased soil carbon sequestration by 3 tCO_2 ha^{-1} yr^{-1} (Paustian et al. 2019; Conant et al. 2017), as well as other practices that could lower net emissions. Gross GHG emissions from the agricultural sector in the US, however, have increased since 1990 (US-EPA 2020) due to reductions in the area of land in the US CRP program and changes in crop rotations, both of which caused soil carbon stocks to decline (US-EPA 2020). When combined with increased non-CO_2 gas emissions, the emission intensity of US agriculture increased from 1.5 to 1.7 tCO_2 ha^{-1} between 2005 and 2018 (*high confidence*).

China has implemented large conservation programs that have influenced carbon stocks. For example, the Sloping Land Conversion Program, combined with other programs, has increased forest cover and carbon stocks, reduced erosion and increased other ecosystem services in China in recent years (Ouyang et al. 2016). Despite increased forest area in China, however, land use change and management potentially were net contributors to carbon emissions from 1990-2010 (Lai et al. 2016). As part of Brazil's national strategy, numerous practices to reduce GHG emissions from agriculture, and in particular from the animal agriculture industry, have been subsidized. Estimates by Manzatto et al. (2020) suggest that the program may have reduced agricultural emissions by 169 $MtCO_2$ between 2010 and 2020. Given the large technical and economic potential for agroforestry to be deployed in Africa, subsidy approaches could be deployed along with other polices to enhance carbon through innovative practices such as regreening (Box 7.10).

7.6.2.2. Regulatory approaches

Regulations on land use include direct controls on how land is used, zoning, or legally set limits on converting land from one use to another. Since the early 2000s, Brazil has deployed various regulatory measures to slow deforestation, including enforcement of regulations on land use change in the legal Amazon area. Enforcement of these regulations, among other approaches is credited with encouraging the large-scale reduction in deforestation and associated carbon emissions after 2004 (Nepstad et al. 2014). Empirical evidence has found that regulations reduced deforestation in Brazil (Arima et al. 2014) but over time, reversals occurred when enforcement was not consistent (Azevedo et al. 2017) (Box 7.9).

Many OECD countries have strong legal frameworks that influence agricultural and forest management on both public and private land. These include for example, legal requirements to protect endangered species, implement conservation tillage, protect riparian areas, replant forests after harvest, maintain historical species composition, forest certification, and other approaches. Increasingly, laws support more widespread implementation of nature-based solutions for a range of environmental issues (e.g. see European Commission 2021) The extent to which the combined influence of these regulations has enhanced carbon storage in ecosystems is not quantified although they are likely to explain some of the persistent carbon sink that has emerged in temperate forests of OECD countries (*high confidence*). In the least developed and developing countries, regulatory approaches face challenges in part because environmental issues are a lower priority than many other socioeconomic issues (e.g., poverty, opportunity, essential services), and weak governance (Mayer Pelicice 2019; Walker et al. 2020); Box 7.2).

Set asides and protected areas have been a widely utilised approach for conservation, and according to (FAO 2020d), 726 Mha (18%) of forests are in protected areas globally. A review of land sparing and land sharing policies in developing countries indicated that most of them follow land sparing models, sometimes in combination with land sharing approaches. However, there is still no clear evidence of which policy provides the best results for ecosystem services provision, conservation, and livelihoods (Mertz and Mertens 2017). The literature contains a wide range of results on the effectiveness of protected areas to reduce deforestation (Burivalova et al. 2019), with studies suggesting that protected areas provide significant protection of forests (e.g., Blackman 2015), modest protection (Andam et al. 2008), as well as increases in deforestation (Blackman 2015) and possible leakage of harvesting to elsewhere (Kallio and Solberg 2018). An estimate of the contributions of protected areas to mitigation between 2000 and 2012, showed that in the tropics, PAs reduced carbon emissions from deforestation by 4.88 Pg C, or around 29%, when compared to the expected rates of deforestation (Bebber and Butt 2017). In that study, the tropical Americas (368.8 TgC y^{-1}) had the largest contribution, followed by Asia (25.0 TgC y^{-1}) and Africa (12.7 TgC y^{-1}). The authors concluded that local factors had an important influence on the effectiveness of protected areas. For example, in the Brazilian Amazon, protected area effectiveness is affected by the government agency controlling the land (federal indigenous lands, federal PAs, and state PAs) (Herrera et al. 2019). Because protected areas limit not just land use change, but also logging or harvesting non-timber forest products, they may be relatively costly approaches for forest conservation (*medium confidence*).

Community forest management (CFM) allows less intensive use of forest resources, while at the same time providing carbon benefits by protecting forest cover. Community forest management provides property rights to communities to manage resources in exchange for their efforts to protect those resources. In many cases, the local communities are indigenous people who otherwise would have insecure tenure due to an advancing agricultural frontier or mining activity. Other examples are forest owner associations like those discussed in Box 7.8. According to the Rights and Resources Initiative (2018), the area of forests under community management increased globally by 152 Mha from 2002 to 2017, with over 500 Mha under community management in 2017. Studies have now shown that improved property rights with community forest management can reduce deforestation and increase carbon storage (Bowler et al. 2012; Alix-Garcia et al. 2005; Blackman 2015; Fortmann et al. 2017; Burivalova et al. 2019; Alix-Garcia 2007; Deininger and Minten 2002). Efforts to expand property rights, especially community forest management, have reduced carbon emissions from deforestation in tropical forests in the last two decades (*high confidence*), although the extent of carbon savings has not been quantified globally.

[START BOX 7.8 HERE]

Box 7.8 Management of native forests by the Menominee people in North America and lessons from forest owner associations

Summary of the case – Indigenous peoples include more than 5 000 different peoples, with over 370 million people, in 70 countries on five continents (UNIPP 2012). Forests cover more than 80% of the area occupied by indigenous peoples (330 million hectares) point to their critical for forest governance

(Garnett et al. 2018; Fa et al. 2020). The Menominee people (Wisconsin, USA) practice sustainable forestry on their reservation according to a land ethic integral to the tribal identity. The Tribe calls themselves "The Forest Keepers," recognizing that the connection of their future to the sustainable management of the forest that allowed the forest volume standing today to be higher than when timber harvesting began more than 160 years ago. Management practices are based on continuous forest inventories (Mausel et al. 2017).

Introduction to the case - Forest management and timber harvesting operations began shortly after the Menominee Indian Reservation was created by treaty in 1854. The Menominee reservation sits on ca. 95000 ha of land in Wisconsin that spans multiple forest types and is more diverse than adjacent forests. The collectively maintained reservation has 87% of its land under sustained yield forestry.

Case description - The Tribe, in the 19th century, had already mastered vegetation manipulation with fire, sustainable forestry, multiple-use, ecosystem, and adaptive management. The centerpiece of the Tribe's economy has been its forest product industry, Menominee Tribal Enterprises (MTE) (Pecore 1992). A balance between growth and removals and continuous forest inventories (CFI) are central for forest management for the past 160 years, aiming not at very large volumes, but at very high quality trees. During this same period, more than 2.3 billion board feet have been harvested from the same area, equivalent to 0.3 m^3 $ha^{-1}y^{-1}$).

Interactions and limitations –In 2013, the Menominee Tribe started a collaboration with the US Forest Service to implement climate adaptation measures. The Tribe actively works to reduce the risk of forest damage and decided to further promote diversity by planting tree seedlings adapted to a warming climate (https://toolkit.climate.gov/case-studies/and-trees-will-last-forever). However, new challenges are related to increasing pressures on forest ecosystems such as non-native insects, pathogens, weed invasions, and the costs for continuous forest inventories to support long-term forest management. **Identified lessons** - The elements of sustainability are intertwined with Menominee history, culture, spirituality, and ethics. The balance between the environment, community, and economy for the short term as well as future generations is an example of protecting the entire environment as the Menominee land is a non-fragmented remnant of the prehistoric Lake States forest which has been dramatically reduced all around the reserve (Schabel and Pecore 1997). These and other types of community forest owner associations exist all over the world. Examples are Södra in Sweden (with 52,000 forest owners) (Södra, 2021) or Waldbauernverband in North-Rhine Westphalia (with 150,000 forest owners and covering 585,000 ha) (AGDW-The Forest Owners, 2021). These are ways for small forest owners to educate, jointly put wood on the market, employ better forest management, use machinery together, and apply certification jointly. In this manner and with all their diversity of goals, they manage to maintain carbon sinks and stocks, while preserving biodiversity and producing wood.

[END BOX 7.8 HERE]

***Bioenergy targets*.** Multiple policies have been enacted at national and supra-national levels to promote the use of bioenergy in the transport sector, and for bioelectricity production. Existing policies mandate or subsidize the production and use of bioenergy. In the past few years, policies have been proposed, put in place or updated in Australia (Renewable Energy Target), Brazil (RenovaBio, Nationally Determined Contribution), Canada (Clean Fuel Standard), China (Biodiesel Industrial Development Policy, Biodiesel Fuel Blend Standard), the European Union (Renewable Energy Directive II), the USA (Renewable Fuel Standards), Japan (FY2030), Russia (Energy Strategy Bill 2035), India (Revised National Policy on Biofuels), and South Africa (Biofuels Regulatory Framework).

While current policies focus on bioenergy to decarbonise the energy system, some also contain provisions to minimise the potential environmental and social trade-offs from bioenergy production. For instance, the EU Renewable Energy Directive (EU-REDII) and US Renewable Energy Standard (US-RFS) assign caps on the use of biofuels, which are associated with indirect land-use change and food-security concerns. The Netherlands has a stringent set of 36 sustainability criteria to which the certified biomass needs to comply. The EU-REDII also sets a timeline for the complete phase-out of high-risk biofuels (Section 7.4.4).

7.6.2.3. Voluntary actions and agreements

Forest certification programs, such as Forest Sustainability Council (FSC) or Programme for the Endorsement of Forest Certification (PEFC), are consumer driven, voluntary programs that influence timber harvesting practices, and may reduce emissions from forest degradation with reduced impact logging and other approaches (*medium confidence*). Forest certification has expanded globally to over 440 Mha (Kraxner et al. 2017). As the area of land devoted to certification has increased, the amount of timber produced from certified land has increased. In 2018, FSC accounted for harvests of 427 million m^3 and jointly FSC and PEFC accounted for 689 million m^3 in 2016 or around 40% of total industrial wood production (FAO 2018c). There is evidence that reduced impact logging can reduce carbon losses in tropical regions (Pearson et al. 2014); (Ellis et al. 2019). However, there is conflicting evidence about whether forest certification reduces deforestation (e.g., Tritsch et al. 2020; Blackman et al. 2018).

Supply chain management in the food sector encourages more widespread use of conservation measures in agriculture (*high confidence*). The number of private commitments to reduce deforestation from supply chains has greatly increased in recent years, with at least 865 public commitments by 447 producers, processors, traders, manufacturers and retailers as of December, 2020 (New York Declaration on Forests 2021). Industry partnerships with NGOs, such as the Roundtable on Sustainable Palm Oil (RSPO), have become more widespread and visible in agricultural production. For example, RSPO certifies members all along the supply chain for palm oil and claims around 19% of total production. Similar sustainability efforts exist for many of the world's major agricultural products, including soybeans, rice, sugar cane, and cattle.

There is evidence that the Amazon Soy Moratorium (ASM), an industry-NGO effort whereby large industry consumers agreed voluntarily not to purchase soybeans grown on land deforested after 2006, reduced deforestation in the legal Amazon (Nepstad et al. 2014; Gibbs et al. 2015). However, recent studies have shown that some deforestation from the Amazon was displaced to the Cerrado (Brazilian savannas) region (Moffette and Gibbs 2021). which is a global hotspot for biodiversity, and has significant carbon stocks. These results illustrate the importance of broadening the scope of supply chain management to minimize or eliminate displacement (Lima et al. 2019). In addition, while voluntary efforts may improve environmental outcomes for a time, it is not clear that they are sufficient to deliver long-term reductions in deforestation, given the increases in deforestation that have occurred in the Amazon in recent years (Box 7.9). Voluntary efforts would be more effective at slowing deforestation if they present stronger linkages to regulatory or other approaches (Lambin et al. 2018).

[START BOX 7.9 HERE]

Box 7.9 Case study: Deforestation control in the Brazilian Amazon

Summary

Between 2000 and 2004, deforestation rates in the Brazilian Legal Amazon (is a socio-geographic division containing all nine Brazilian states in the Amazon basin) increased from 18,226 to 27,772 km^2 yr^{-1} 2008 (INPE, 2021) . A set of public policies designed in participatory process involving federal government, states, municipalities, and civil society successfully reduced deforestation rates until 2012. However, deforestation rates increased after 2013, and particularly between 2019 and 2020. Successful deforestation control policies are being negatively affected by changes in environmental governance, weak law enforcement, and polarisation of the national politics.

Background

In 2004, the Brazilian federal government started the Action Plan for Prevention and Control of Deforestation in the Legal Amazon (PPCDAm) (Ministry of Environment, Government of Brazil, 2018)

. The PPCDAm was a benchmark for the articulation of forest conservation policies that included central and state governments, prosecutor offices, and the civil society. The decline in deforestation after 2008 is mostly attributed to these policy options. In 2012, deforestation rates decreased to 4,571 km^2 yr^{-1}.

Case description

Combating deforestation was a theme in several programs, government plans, and projects not being more restricted to the environmental agenda. This broader inclusion resulted from a long process of insertion and articulation in the government dating back to 2003 while elaborating on the Sustainable Amazon Plan. In May 2003, a historic meeting took place in an Amazonian city, with the President of the Republic, State Governors, Ministers, and various business leaders, civil institutions, and social movements. It was presented and approved the document entitled "Sustainable Amazonia - Guidelines and Priorities of the Ministry of Environment for the Sustainable Development of the Amazon Brazilian," containing several guidelines for conservation and sustainable use in the region. At the meeting, the Union and some states signed a Cooperation Agreement aiming to elaborate a plan for the Amazon, to be widely discussed with the various sectors of the regional and national society (Ministerio do Meio Ambiente. MMA 2013).

Interactions and limitations

The PPCDAm had three main lines of action: 1. territorial management and land use; 2. command and control; and 3. promotion of sustainable practices. During the execution of the 1st and 2nd phases of the PPCDAm (2004-2011), important results in the territorial management and land use component included, for example, the creation of 25 Mha of federal Protected Areas (PAs) located mainly in front of the expansion of deforestation, as well as the homologation of 10 Mha of Indigenous Lands. Also, states and municipalities created approximately 25 Mha, so that all spheres of government contributed to the expansion of PAs in the Brazilian Amazon. In the Command and Control component, agencies performed hundreds of inspection operations against illegal activities (e.g., illegal logging) under strategic planning based on technical and territorial priorities. Besides, there was a significant improvement of the environmental monitoring systems, involving the analysis of satellite images to guide actions on the ground. Another policy was the restriction of public credit to enterprises linked to illegal deforestation following a resolution of the Brazilian Central Bank (2008) (Ministerio do Meio Ambiente. MMA 2013). Also, in 2008, Brazil created the Amazon Fund, a REDD+ mechanism (Government of Brazil, n.d).

However, the country's political polarisation has gradually eroded environmental governance, especially after the Brazilian Forest Code changes in 2012 (major environmental law in Brazil), the presidential impeachment in 2016, presidential elections in 2018, and the start of the new federal administration in 2019. Successful deforestation control policies are being negatively affected by critical changes in the political context, and weakening the environmental rule of law, forest conservation, and sustainable development programs (for example, changes in the Amazon Fund governance in disagreement with the main donors). In 2019, the annual deforestation rate reached 10,129 km^2 being the first time it surpassed 10,000 km^2 since 2008 (INPE, 2021) . Besides, there has been no effective transition from the historical economic model to a sustainable one. The lack of clarity in the ownership of land is still a major unresolved issue in the Amazon.

Lessons

The reduction of deforestation in the Brazilian Amazon was possible due to effective political and institutional support for environmental conservation. The initiatives of the Action Plan included the expansion of the protected areas network (conservation unities and indigenous lands), improvement of deforestation monitoring to the enforcement of environmental laws, and the use of economic instruments, for example, by cutting off public credit for municipalities with higher deforestation rates (Souza et al. 2013; Ricketts et al. 2010; Blackman and Veit 2018; Nepstad et al. 2014; Arima et al. 2014).

The array of public policies and social engagement was a historical and legal breakthrough in global protection. However, the broader political and institutional context and actions to reduce the representation and independent control of civil society movements in decision-making bodies weaken this structure with significant increases in deforestation rates, burnings, and forest fires.

[END BOX 7.9 HERE]

[START BOX 7.10 HERE]

Box 7.10 Regreening the Sahel, Northern Africa

Case description

More than 200 million trees have regenerated on more than 5 Mha in the Sahel (Sendzimir et al. 2011). The Maradi/Zinder region of Niger is the epicentre of experimentation and scale up. This vast geographic extent generates significant mitigation potential despite the relatively modest per unit area increase in carbon of about 0.4 Mg C ha^{-1} a^{-1} (Luedeling and Neufeldt 2012). In addition to the carbon benefits, these agroforestry systems decrease erosion, provide animal fodder, recharge groundwater, generate nutrition and income benefits and act as safety nets for vulnerable rural households during climate and other shocks (Bayala et al. 2014, 2015; Binam et al. 2015; Sinare and Gordon 2015; Ilstedt et al. 2016).

Lessons

A mélange of factors contributed to regreening in the Sahel. Increased precipitation, migration, community development, economic volatility and local policy reform have all likely played a role (Haglund et al. 2011; Sendzimir et al. 2011; Brandt et al. 2019a; Garrity and Bayala 2019); the easing of forestry regulations has been particularly critical in giving farmers greater control over the management and use of trees on their land (Garrity et al. 2010). This policy shift was catalysed by greater regional autonomy resulting from economic decline and coincided with successful pilots and NGO-led experimentation, cash-for-work, and training efforts to support changes in land management (Sendzimir et al. 2011). Participation of farmers in planning and implementation helped align actions with local knowledge and goals as well as market opportunities.

Regreening takes place when dormant seed or tree stumps sprout and are cultivated through the technique, called Farmer Managed Natural Regeneration (FMNR). Without planting new trees, FMNR is presumed to be cheaper than other approaches to restoration, though comparative economic analysis has yet to be conducted (Chomba et al. 2020). Relatively lower investment costs are believed to have contributed to the replication across the landscape. These factors worked together to contribute to a groundswell of action that affected rights, access, and use of local resources (Tougiani et al. 2009).

Regreening in the Sahel and the consequent transformation of the landscape has resulted from the actions of hundreds of thousands of individuals responding to social and biophysical signals (Hanan 2018). This is an example for climate change mitigation, where eliminating regulations – versus increasing them - has led to carbon dioxide removal.

[END BOX 7.10 HERE]

7.6.2.4. Mitigation Effectiveness: Additionality, Permanence and Leakage

Additionality, permanence and leakage have been widely discussed in the forestry and agricultural mitigation literature (Murray et al. 2007), including in AR5 (Section 11.3.2 of the WGIII report) and earlier assessment reports. Since the earlier assessment reports, new studies have emerged to provide new insights on the effect of these issues on the credibility of forest and agricultural mitigation. This assessment also provides additional context not considered in earlier assessments.

Typically, carbon registries will require that project developers show additionality by illustrating that the project is not undertaken as a result of a legal requirement, and that the project achieves carbon reductions above and beyond a business as usual. The protocols developed by the California Air Resources Board to ensure permanence and additionality are strong standards and may even limit participation (e.g. Ruseva et al. 2017). The business as usual is defined as past management actions by the same entity that can be verified. Additionality can thus be observed in the future as a difference from historical actions. This approach has been used by several countries in their UNFCCC Biennial Update Reports to establish reductions in carbon emissions from avoided deforestation (e.g., Brazil and Indonesia).

However, alternative statistical approaches have been deployed in the literature to assess additionality with a quasi-experimental method that rely on developing a counterfactual (e.g. Andam et al. 2008; Blackman 2015; Fortmann et al. 2017; Roopsind et al. 2019; Sills et al. 2015). In several studies, additionality in avoided deforestation was established after the project had been developed by comparing land-use change in treated plots where the policy or program was in effect with land use change in similar untreated plot. Alternatively, synthetic matching statistically compares trends in a treated region (i.e., a region with a policy) to trends in a region without the policy, and has been applied in a region in Brazil (e.g., Sills et al. 2015), and at the country level in Guyana (Roopsind et al. 2019). While these analyses establish that many projects to reduce deforestation have overcome hurdles related to additionality (*high confidence),* there has not been a systematic assessment of the elements of project or program design that lead to high levels of additionality. Such assessment could help developers design projects to better meet additionality criteria.

The same experimental methods have been applied to analyse additionality of the adoption of soil conservation and nutrient management practices in agriculture. Claassen et al. (2018) find that programs to promote soil conservation are around 50% additional across the USA (i.e. 50% of the land enrolled in soil conservation programs would not have been enrolled if not for the programme), while Woodward et al. (2016) find that adoption of conservation tillage is rarely additional. Claassen et al. (2018) find that payments for nutrient management plans are nearly 100% additional, although there is little evidence that farmers reduce nutrient inputs when they adopt plans. It is not clear if the same policy approaches would lead to additionality in other regions.

Permanence focuses on the potential for carbon sequestered in offsets to be released in the future due to natural or anthropogenic disturbances. Most offset registries have strong permanence requirements, although they vary in their specific requirements. VCS/Verra requires a pool of additional carbon credits that provides a buffer against inadvertent losses. The Climate Action Reserve (CAR) protocol for forests requires carbon to remain on the site for 100 years. The carbon on the site will be verified at pre-determined intervals over the life of the project. If carbon is diminished on a given site, the credits for the site have to be relinquished and the project developer has to use credits from their reserve fund (either other projects or purchased credits) to make up for the loss. Estimates of leakage in forestry projects in the AR5 suggest that it can range from 10% to over 90% in the USA (Murray et al. 2004), and 20-50% in the tropics (Sohngen and Brown 2004) for forest set-asides and reduced harvesting. Carbon offset protocols have made a variety of assumptions. The Climate Action Reserve (CAR) assumes it is 20% in the USA. One of the voluntary protocols (Verra) uses specific information about the location of the project to calculate a location specific leakage factor.

More recent literature has developed explicit estimates of leakage based on statistical analysis of carbon projects or programs. The literature suggests that there are two economic pathways for leakage (e.g. (Roopsind et al. 2019), either through a shift in output price that occurs when outputs are affected by the policy or program implementation, as described in (Gan and McCarl 2007; Wear and Murray 2004; Murray et al. 2004; Sohngen and Brown 2004), or through a shift in input prices and markets, such as for labour or capital, as analysed in (Alix-Garcia et al. 2012; Andam et al. 2008; Fortmann et al. 2017; Honey-Rosés et al. 2011). Estimates of leakage through product markets (e.g. timber prices) have suggested leakage of up to 90% (Sohngen and Brown 2004; Murray et al. 2004; Gan and McCarl 2007; I. Kallio and Solberg 2018), while studies that consider shifts in input markets are considerably smaller. The analysis of leakage for the Guyana program by Roopsind et al. (2019) revealed no statistically significant leakage in Suriname. A key design feature for any program to reduce leakage is to increase incentives for complementary mitigation policies to be implemented in areas where leakage may occur. Efforts to continue to draw more forests into carbon policy initiatives will reduce leakage over time Roopsind et al. (2019), suggesting that if NDCs continue to encompass a broader selection of policies, measures and forests over time, leakage will decline.

7.6.3. Assessment of current policies and potential future approaches

The Paris Agreement encourages a wide range of policy approaches, including REDD+, sustainable management of forests, joint mitigation and adaptation, and emphasises the importance of non-carbon benefits and equity for sustainable development (Martius et al. 2016). Around USD 0.7 billion yr^{-1} has been invested in land-based carbon offsets (Table 7.4), but as noted in Streck (2012), there is a large funding gap between these efforts and the scale of efforts necessary to meet 1.5 or 2.0°C targets outlined in SR1.5. As Box 7.12 discusses, forestry actions could achieve up to 5.8 $GtCO_2$ yr^{-1} with costs rising from USD178 billion yr^{-1} to USD400 billion yr^{--1} by 2050. Over half of this investment is expected to occur in Latin America, with 13% in SE Asia and 17% in Sub-Saharan Africa (Austin et al. 2020). Other studies have suggested that similar sized programs are possible, although they do not quantify total costs (e.g. Griscom et al. 2017**;** Busch et al. 2019). The currently quantified efforts to reduce net emissions with forests and agricultural actions are helpful, but society will need to quickly ramp up investments to achieve carbon sequestration levels consistent with high levels of mitigation. Only 2.5% of climate mitigation funding goes to land-based mitigation options, an order of magnitude below the potential proportional contribution (Buchner et al. 2015).

To date, there has been significantly less investment in agricultural projects than forestry projects to reduce net carbon emissions (Table 7.4). For example, the economic potential (available up to USD100 tCO_2^{-1}) for soil carbon sequestration in croplands is 1.9 (0.4–6.8) $GtCO_2$ yr^{-1} (Section 7.4.3.1), however, less than 2% of the carbon in Table 7.4 is derived from soil carbon sequestration projects. While reductions in CH_4 emissions due to enteric fermentation constitute a large share of potential agricultural mitigation reported in Section 7.4, agricultural CH_4 emission reductions so far have been relatively modest compared to forestry sequestration. The protocols to quantify emission reductions in the agricultural sector are available and have been tested, and the main limitation appears to be the lack of available financing or the unwillingness to re-direct current subsidies (*medium confidence*).

Although quantified emission reductions in agricultural projects are limited to date, a number of OECD and economy in transition parties have reduced their net emissions through carbon storage in cropland soils since 2000. These reductions in emissions have typically resulted from policy innovations outside of the climate space, or market trends. For example, in the USA, there has been widespread adoption of conservation tillage in the last 30 years as a labour-saving crop management technique. In Europe, agricultural N_2O and CH_4 emissions have declined due to reductions in nutrient inputs and cattle numbers (Henderson et al. 2020).These reductions may be attributed to mechanism within the Common Agricultural Policy (Section 7.6.2.1), but could also be linked to higher nutrient prices in the 2000-2014 period. Other environmental policies could play a role, for example, efforts to reduce water pollution from phosphorus in The Netherlands, may ultimately reduce cattle numbers, also lowering CH_4 emissions.

Numerous developing countries have established policy efforts to abate agricultural emissions or increase carbon storage. Brazil, for instance, developed a subsidy program in 2010 to promote sustainable development in agriculture, and practices that would reduce GHG emissions. Henderson et al. (2020) report that this program reduced GHG emission in agricultural by up to 170 $MtCO_2$ between 2010 and 2018. However, the investments in low-carbon agriculture in Brazil amounted only 2% of the total funds for conventional agriculture in 2019. Programs on deforestation in Brazil had successes and failures, as described in Box 7.9. Indonesia has engaged in a wide range of programs in the REDD+ space, including a moratorium implemented in 2011 to prevent the conversion of primary forests and peatlands to oil palm and logging concessions (Henderson et al. 2020) (Tacconi and Muttaqin 2019; Wijaya et al. 2017). Efforts to restore peatlands and forests have also been undertaken. Indonesia reports that results based REDD+ programs have been successful and have led to lower rates of deforestation (Table 7.4).

Existing policies focused on GHG management in agriculture and forestry is less advanced in Africa than in Latin American and Asia, however, Henderson et al. (2020) report on 10 countries in Sub Saharan Africa that have included explicit policy proposals for reducing AFOLU GHG emissions through their NDCs. These include efforts to reduce N_2O emission, increase implementation of conservation agriculture, improve livestock management, and implement forestry and grassland practices, including agroforestry (Box 7.10). Within several of the NDCs, countries have explicitly suggested intensification as an approach to reduce emission in the livestock sector. However, it is important to note caveats associated with pursuing mitigation via intensification (Box 7.11)

The agricultural sector throughout the world is influenced by many policies that affect production practices, crop choices and land use. It is difficult to quantify the effect of these policies on reference level GHG emissions from the sector, as well as the cost estimates presented in Sections 7.4 and 7.5. The presence of significant subsidy programs intended to improve farmer welfare and rural livelihoods makes it more difficult to implement regulatory programs aimed at reducing net emissions in agriculture, however, it may increase the potential to implement new subsidy programs that encourage practices aimed at reducing net emissions (*medium confidence*). For instance, in the USA, crop insurance can influence both crop choices and land use (Claassen et al. 2017; Miao et al. 2016), both of which will affect emission trends. Regulations to limit nutrient applications have not been widely considered, however, federal subsidy programs have been implemented to encourage farmers to conduct nutrient management planning.

[START BOX 7.11 HERE]

Box 7.11 Sustainable intensification within agriculture: evidence and caveats

Introduction

Sustainable intensification (SI) has received considerable attention as a suggested means of pursuing increased overall production, reducing associated environmental externalities, and potentially releasing agricultural land for alternative uses, such as forestry or rewilding (Godfray and Garnett 2014; Pretty 2018). The concept was explored within the SRCCL (SRCCL Section 5.6.4.4 and Cross-Chapter Box 6 in Chapter 5; (Mbow et al. 2019)). SI is context specific and dynamic, with no universally prescribed methodology (HLPE 2019). Equal importance is given to enhancing sustainability as to achieving agricultural intensification. The former aspect is often challenging to realise, measure and maintain.

The extent of sustainable intensification

Total global agricultural land area has remained relatively stable while overall production has increased in recent decades (Section 7.3), indicating that agricultural intensification, as judged by production per unit of land (OECD/FAO 2019; Petersen and Snapp 2015) has taken place. Changes in agricultural land use and degradation of natural resources (UN Environment 2019; IPBES 2019) suggests however that not all of this intensification is sustainable. Although agricultural intensification has led to less GHG emissions compared to a scenario where that intensification had not taken place (Burney et al. 2010), absolute agriculture related emissions have continued to increase (Section 7.2). Active pursuit of SI was found to be expanding, with implementation on an increasing area, notably in developing countries (Pretty et al. 2018), yet regional agricultural area expansion at the expense of native habitat also continues in such regions (Section 7.3). Although there are specific examples of SI (Box 7.13) global progress in achieving SI is acknowledged as slow (Cassman and Grassini 2020) with potentially multiple, context specific geophysical and socio-economic barriers to implementation (Silva et al. 2021a; Firbank et al. 2018).

Preconditions to ensure sustainable intensification

Increasing the total amount of product produced by improving production efficiency (output per unit of input) does not guarantee SI. It will only be successful if increased production efficiency translates into reduced environmental and social impacts as well as increased production. For example, AR5 highlighted a growing emphasis on reducing GHG emissions per unit of product via increasing production efficiency (Smith et al. 2014), but reductions in absolute GHG emissions will only occur when production efficiency increases at a greater rate than the rate at which production increases (Clark et al. 2005).

Defined indicators are required. Measurement of SI requires multiple indicators and metrics. It can be assessed at farm, regional or global scales and temporal aspect must be considered. SI may warrant whole system redesign or land reallocation (Garnett et al. 2013; Pretty et al. 2018). Accordingly, there is *high agreement* concerning the need to consider multiple environmental and social outcomes at wider spatial scales, such as catchments or regions (Weltin et al. 2018; Bengochea Paz et al. 2020; Cassman and Grassini 2020). Impacts may be considered in relative terms (per area or product unit), with relationships potentially antagonistic. Both area- and product unit-based metrics are valid, relevant under different contexts and useful in approaching SI, but do not capture overall impacts and trade-offs (Garnett 2014). To reduce the risk of unsustainable intensification, quantitative data and selection of appropriate metrics to identify and guide strategies are paramount (Garnett et al. 2013; Gunton et al. 2016; Cassman and Grassini 2020).

Avoiding unsustainable intensification

It is critical that intensification does not drive expansion of unsustainable practices. Increased productivity with associated economic reward could incentivise and reward agricultural land expansion, or environmentally and socially damaging practices on existing and former agricultural land (Phalan 2018; Ceddia et al. 2013). Accordingly, coordinated policies are crucial to ensuring desired outcomes (Reddy et al. 2020; Kassam and Kassam 2020; Godfray and Garnett 2014;). Barretto et al. (2013) found that in agriculturally consolidated areas, land-use intensification coincided with either a contraction of both cropland and pasture areas, or cropland expansion at the expense of pastures, both resulting in a stable farmed area. In contrast, in agricultural frontier areas, land-use intensification coincided with expansion of agricultural lands.

In conclusion, SI within agriculture is needed given the rising global population and the need to address multiple environmental and social externalities associated with agricultural activities. However, implementation requires strong stakeholder engagement, appropriate regulations, rigorous monitoring and verification and comprehensive outreach and knowledge exchange programmes.

[END BOX 7.11 HERE]

A factor that will influence future carbon storage in so-called land-based reservoirs involves considering short- and long-term climate benefits, as well as interactions among various natural climate solution options. The benefits of various natural climate solutions depend on a variety of spatially dependent issues as well as institutional factors, including their management status (managed or unmanaged systems), their productivity, opportunity costs, technical difficulty of implementation, local willingness to consider, property rights and institutions, among other factors. Biomass energy, as described elsewhere in this chapter and in (Cross-Working Group Box 3 in Chapter 12), is a potential example of an option with trade-offs that emerge when policies favour one type of mitigation strategy over another. Bioenergy production needs safeguards to limit negative impacts on carbon stocks on the land base as is already in place in the EU Renewable Energy Directive and several national schemes in Netherlands, UK and Denmark. (DeCicco and Schlesinger 2018; (Favero et al. 2020; Buchholz et al. 2016; Khanna et al. 2017). It is argued that a carbon tax on only fossil fuel derived emissions, may lead to massive deployment of bioenergy, although the effects of such a policy can be mitigated when combined with policies that encourage sustainable forest management and protection of forest carbon stocks as well as forest management certification (Favero et al. 2020 and Nabuurs et al. 2017, Baker et al, 2019) (*high confidence*).

If biomass energy production expands and shifts to carbon capture and storage (e.g. BECCS) during the century, there could be a significant increase in the area of crop and forestland used for biomass energy production (Sections 7.4 and 7.5). BECCS is not projected to be widely implemented for several decades, but in the meantime, policy efforts to advance land based measures including reforestation and restoration activities (Strassburg et al. 2020) combined with sustainable management and provision of agricultural and wood products are widely expected to increase the terrestrial pool of carbon (Cross-Working Group Box 3 in Chapter 12). Carbon sequestration policies, sustainable land management (forest and agriculture), and biomass energy policies can be complementary (Favero et al. 2017; Baker et al. 2019). However, if private markets emerge for biomass and BECCS on the scale suggested in the SR1.5, policy efforts must ramp up to substantially value, encourage, and protect terrestrial carbon stocks and ecosystems to avoid outcomes inconsistent with many SDGs (*high confidence*).

7.6.4. Barriers and opportunities for AFOLU mitigation

The AR5 and other assessments have acknowledged many barriers and opportunities to effective implementation of AFOLU measures. Many of these barriers and opportunities focus on the context in developing countries, where a significant portion of the world's cost-effective mitigation exists, but where domestic financing for implementation is likely to be limited. The SSPs capture some of this context, and as a result, IAMs (Section 7.5) exhibit a wide range of land-use outcomes, as well as mitigation potential. Potential mitigation, however, will be influenced by barriers and opportunities that are not considered by IAMs or by bottom-up studies reviewed here. For example, more efficient food production systems, or sustainable intensification within agriculture, and globalised trade could enhance the extent of natural ecosystems leading to lower GHG emissions from the land system and lower food prices (Popp et al. 2017), but this (or any) pathway will create new barriers to implementation and encourage new opportunities, negating potential benefits (Box 7.11). It is critically important to consider the current context in any country.

7.6.4.1. Socio-economic barriers and opportunities

***Design and coverage of financing mechanisms*.** The lack of resources thus far committed to implementing AFOLU mitigation, income and access to alternative sources of income in rural households that rely on agriculture or forests for their livelihoods remains a considerable barrier to adoption of AFOLU (*high confidence*). Section 7.6.1 illustrates that to date only USD0.7 billion yr^{-1} has been spent on AFOLU mitigation, well short of the more than USD400 billion yr^{-1} that would be needed to achieve the economic potential described in Section 7.4. Despite long-term recognition that AFOLU can play an important role in mitigation, the *economic incentives* necessary to achieve AFOLU aspirations as part of the Paris Agreement or to maintain temperatures below 2.0 ^{o}C have not emerged. Without quickly ramping up spending, the lack of funding to implement projects remains a substantial barrier (*high confidence*). Investments are critically important in the livestock sector, which has the highest emissions reduction potential among options because actions in the sector influence agriculture specific activities, such as enteric fermentation, as well as deforestation (Mayberry et al. 2019). In many countries with export-oriented livestock industries, livestock farmers control large swaths of forests or re-forestable areas. Incentive mechanisms and funding can encourage adoption of mitigation strategies, but funding is currently too low to make consistent progress.

Scale and accessibility of financing. The largest share of funding to date has been for REDD+, and many of the commitments to date suggest that there will be significant funding in this area for the foreseeable future. Funding for conservation programs in OECD countries and China affects carbon, but has been driven by other objectives such as water quality and species protection. Considerably less funding has been available for agricultural projects aimed at reducing carbon emissions, and outside of voluntary markets, there do not appear to be large sources of funding emerging either through international organisations, or national programs. In the agricultural sector, funding for carbon must be obtained by redirecting existing resources from non-GHG conservation to GHG measures, or by developing new funding streams (Henderson et al. 2020).

Risk and uncertainty. Most approaches to reduce emissions, especially in agriculture, require new or different technologies that involve significant time or financial investments by the implementing landholders. Adoption rates are often slow due to risk aversion among agricultural operators. Many AFOLU measures require carbon to be compensated to generate positive returns, reducing the likelihood of implementation without clear financial incentives. Research to show costs and benefits is lacking in most parts of the world.

[START BOX 7.12 HERE]

Box 7.12 Financing AFOLU mitigation; what are the costs and who pays?

Achieving the large contribution to mitigation that the AFOLU sector can make requires public and private investment. Austin et al. (2020) estimate that in forestry, USD178 billion yr^{-1} is needed over the next decade to achieve 5 $GtCO_2$ yr^{-1}, and investments need to ramp up to USD400 billion yr^{-1} by 2050 to expand effort to 6 $GtCO_2$ yr^{-1}. Other land-based options, such as mangrove protection, peatland restoration, and agricultural options would increase this total cost estimate, but have smaller to negligible opportunity costs.

Financing needs in AFOLU, and in particular in forestry, include both the direct effects of any changes in activities – costs of planting or managing trees, net revenues from harvesting, costs of thinning, costs of fire management, etc. – as well as the opportunity costs associated with land use change. Opportunity costs are a critical component of AFOLU finance, and must be included in any estimate of the funds necessary to carry out projects. They are largest, as share of total costs, in forestry because they play a prominent role in achieving high levels of afforestation, avoided deforestation, and improved forest management. In case of increasing soil carbon in croplands through reduced tillage, there are often cost savings associated with increased residues because there is less effort tilling, but the carbon effects per hectare are also modest. There could, however, be small opportunity costs in cases where residues may otherwise be marketed to a biorefinery. The effect of reduced tillage on yields varies considerably across sites and crop types, but tends to enhance yields modestly in the longer-run.

Opportunity costs are a direct financing costs for activities that require land uses to change. For instance a government can encourage planting forests on agricultural land by (a) requiring it, (b) setting up a market or market-based incentives, or (c) buying the land and doing it themselves. In each case, the required investment is the same – the planting cost plus the net foregone returns of agricultural rents – even though a different entity pays the cost. Private entities that pay for carbon credits will also bear the direct costs of planting plus the opportunity costs. In the case of avoided deforestation, opportunity costs similarly must be paid to individual actors to avoid the deforestation.

[END BOX 7.12 HERE]

Poverty. Mitigation and adaptation can have important implications for vulnerable people and communities, for example, mitigation activities consistent with scenarios examined in the SR1.5 could raise food and fiber prices globally (Section. 7.5). In the NDCs, 82 Parties included references to social issues (e.g. poverty, inequality, human well-being, marginalisation), with poverty the most cited factor (70 Parties). The number of hungry and food insecure people in the world is growing, reaching 821 million in 2017, or one in every nine people (FAO 2018b), and two-thirds live in rural areas (Laborde Debucquet et al. 2020). Consideration of rural poverty and food insecurity is central in AFOLU mitigation because there are a large number of farms in the world (about 570 million), and most are smaller than 2 hectares. It is important to better understand how different mitigation policies affect the poor.

Cultural values and social acceptance. Barriers to adoption of AFOLU mitigation will be strongest where historical practices represent long-standing traditions (*high confidence*). Adoption of new mitigation practices, however, may proceed quickly if the technologies can be shown to improve crop yields, reduce costs, or otherwise improve livelihoods (Ranjan 2019). AR6 presents new estimates of the mitigation potential for shifts in diets and reductions in food waste, but given long-standing dietary traditions within most cultures, some of the strongest barriers exist for efforts to change diets (*medium confidence*). Furthermore, the large number of undernourished who may benefit from increased calories and meat will complicate efforts to change diets. Regulatory or tax approaches will face strong resistance, while efforts to use educational approaches and voluntary measures have limited potential to slow changes in consumption patterns due to free-riders, rebound effects, and other limitations. Food loss and waste occurs across the supply chain, creating significant challenges to reduce it (FAO 2019c). Where food loss occurs in the production stage, i.e. in fields at harvest, there may be opportunities to align reductions in food waste with improved production efficiency, however, adoption of new production methods often requires new investments or changes in labour practices, both of which are barriers.

7.6.4.2. Institutional barriers and opportunities

Transparent and accountable governance. Good governance and accountability are crucial for implementation of forest and agriculture mitigation. Effective nature-based mitigation will require large-scale estimation, modelling, monitoring, reporting and verification of GHG inventories, mitigation actions, as well as their implications for sustainable development goals and their interactions with climate change impacts and adaptation. Efforts must be made to integrate the accounting from projects to the country level. While global datasets have emerged to measure forest loss, at least temporarily (e.g. Hansen et al., 2013), similar datasets do not yet exist for forest degradation and agricultural carbon stocks or fluxes. Most developing countries have insufficient capacity to address research needs, modelling, monitoring, reporting and data requirements (e.g. Ravindranath et al. 2017), compromising transparency, accuracy, completeness, consistency and comparability.

Opportunity for political participation of local stakeholders is barrier in most places where forest ownership rights are not sufficiently documented (Essl et al. 2018). Since incentives for self-enforcement can have an important influence on deforestation rates (Fortmann et al. 2017), weak governance and insecure property rights are significant barriers to introduction of forest carbon offset projects in developing countries, where many of the low-cost options for such projects exist (Gren and Zeleke 2016). Governance challenges exist at all levels of government, with poor coordination, insufficient information sharing, and concerns over accountability playing a prominent role within REDD+ projects and programs (Ravikumar et al. 2015). In some cases, governments are increasingly centralising REDD+ governance and limiting the distribution of governance functions between state and non-state actors (Zelli et al. 2017; Phelps et al. 2010). Overlap and duplication in FLEGT and REDD+ also limits governance effectiveness (Gupta et al. 2016).

Clear land tenure and land-use rights. Unclear property rights and tenure insecurity undermine the incentives to improve forest and agricultural productivity, lead to food insecurity, undermine REDD+ objectives, discourage adoption of farm conservation practices, discourage tree planting and forest management, and exacerbate conflict between different land users (Sunderlin et al. 2018; Antwi-Agyei et al. 2015; Borras and Franco 2018; Felker et al. 2017; Riggs et al. 2018; Kansanga and Luginaah 2019). Some positive signs exist as over 500 million hectares of forests have been converted to community management with clear property rights in the past two decades (Rights and Resources Initiative 2018), but adoption of forest and agricultural mitigation practices will be limited in large remaining areas with unclear property rights (Gupta et al. 2016).

Lack of institutional capacity. Institutional complexity, or lack thereof, represents a major challenge when implementing large and complex mitigation programs (e.g., REDD+) in agriculture, forest and other land uses (Bäckstrand et al. 2017). Without sufficient capacity, many synergies between agricultural and forest programs, or mitigation and adaptation opportunities, may be missed (Duguma et al. 2014). Another aspect of institutional complexity is the different biophysical and socio-economic circumstances as well as the public and private financial means involved in the architecture and implementation of REDD+ and other initiatives (Zelli et al. 2017).

7.6.4.3. Ecological barriers and opportunities

Availability of land and water. Climate mitigation scenarios in the two recent special reports (SR1.5C and SRLCC) that aim to limit global temperature increase to 2°C or less involve carbon dioxide (CO_2)

removal from the atmosphere. To support large-scale CDR, these scenarios involve significant land-use change, due to afforestation/reforestation, avoided deforestation, and deployment of Biomass Energy with Carbon Capture and Storage (BECCS). While a considerable amount of land is certainly available for new forests or new bioenergy crops, that land has current uses that will affect not only the costs, but also the willingness of current users or owners, to shift uses. Regions with private property rights and a history of market-based transactions may be the most feasible for land use change or land management change to occur. Areas with less secure tenure or a land market with fewer transactions in general will likely face important hurdles that limit the feasibility of implementing novel nature-based solutions.

Implementation of nature-based solution may have local or regionally important consequences for other ecosystem services, some of which may be negative (*high confidence*). Land use change has important implications for the hydrological cycle, and the large land use shifts suggested for BECCS when not carried out in a carefully planned manner, are expected to increase water demands substantially across the globe (Stenzel et al. 2019; Rosa et al. 2020). Afforestation can have minor to severe consequences for surface water acidification, depending on site-specific factors and exposure to air pollution and sea-salts (Futter et al. 2019). The potential effects of coastal afforestation on sea-salt related acidification could lead to re-acidification and damage on aquatic biota.

Specific soil conditions, water availability, GHG emission-reduction potential as well as natural variability and resilience. Recent analysis by (Cook-Patton et al. 2020) illustrates large variability in potential rates of carbon accumulation for afforestation and reforestation options, both within biomes/ecozones and across them. Their results suggest that while there is large potential for afforestation and reforestation, the carbon uptake potential in land-based climate change mitigation efforts is highly dependent on the assumptions related to climate drivers, land use and land management, and soil carbon responses to land-use change. Less analysis has been conducted on bioenergy crop yields, however, bioenergy crop yields are also likely to be highly variable, suggesting that bioenergy supply could exceed or fall short of expectations in a given region, depending on site conditions.

The effects of climate change on ecosystems, including changes in crop yields, shifts in terrestrial ecosystem productivity, vegetation migration, wildfires, and other disturbances also will affect the potential for AFOLU mitigation. Climate is expected to reduce crop yields, increase crop and livestock prices, and increase pressure on undisturbed forest land for food production creating new barriers and increasing costs for implementation of many nature-based mitigation techniques (IPCC WGII AR6 Chapter 5) (*medium confidence*).

The observed increase in the terrestrial sink over the past half century can be linked to changes in the global environment, such as increased atmospheric CO_2 concentrations, N deposition, or changes in climate (Ballantyne et al. 2012), though not always proven from ground-based information (Vandersleen et al.2015). While the terrestrial sink relies on regrowth in secondary forests (Houghton and Nassikas 2017), there is emerging evidence that the sink will slow in the northern hemisphere as forests age (Nabuurs et al. 2013), although saturation may take decades (Zhu et al. 2018). Forest management through replanting, variety selection, fertilisation, and other management techniques, has increased the terrestrial carbon sink over the last century (Mendelsohn and Sohngen 2019). Saturation of the sink in situ may not occur when e.g. substitution effects of timber usage are also considered.

Increasing concentrations of CO_2 are expected to increase carbon stocks globally, with the strongest effects in the tropics (Kim et al. 2017a; Schimel et al. 2015; AR6 WGI, Fig SPM7)) and economic models suggest that future sink potential may be robust to the impacts of climate change (Tian et al. 2018). However, it is uncertain if this large terrestrial carbon sink will continue in the future (e.g. Aragão et al. 2018), as it is increasingly recognized that gains due to CO_2 fertilization are constrained by climate and increasing disturbances (Schurgers et al. 2018; Duffy et al. 2021; IPCC WGII AR6 Chapter 5). Further, negative synergies between local impacts like deforestation and forest fires may interact with global drivers like climate change and lead to tipping points (Lovejoy and Nobre 2018;). Factors that reduce permanence or slow forest growth will drive up costs of forest mitigation measures, suggesting that climate change presents a formidable challenge to implementation of nature-based solutions beyond 2030 (*high confidence*).

In addition to climate change, Dooley and Kartha (2018) also note that technological and social factors could ultimately limit the feasibility of agricultural and forestry mitigation options, especially when deployed at large-scale. Concern is greatest with widespread use of bioenergy crops, which could lead to forest losses (Harper et al. 2018).Deployment of BECCS and forest-based mitigation can be complementary (Favero et al. 2017; Baker et al. 2019), but inefficient policy approaches could lead to net carbon emissions if BECCS replaces high-carbon content ecosystems with crops.

Adaptation benefits and biodiversity conservation. Biodiversity may improve resilience to climate change impacts as more-diverse systems could be more resilient to climate change impacts, thereby maintaining ecosystem function and preserving biodiversity (Hisano et al. 2018). However, losses in ecosystem functions due species shifts or reductions in diversity may impair the positive effects of biodiversity on ecosystems. Forest management strategies based on biodiversity and ecosystems functioning interactions can augment the effectiveness of forests in reducing climate change impacts on ecosystem functioning (*high confidence*). In spite of the many synergies between climate policy instruments and biodiversity conservation, however, current policies often fall short of realising this potential (Essl et al. 2018).

7.6.4.4. Technological barriers and opportunities

Monitoring, reporting, and verification. Development of satellite technologies to assess potential deforestation has grown in recent years with the release of 30 m data by Hansen et al. (2013), however, this data only captures tree cover loss, and increasing accuracy over time may limit its use for trend analysis (Ceccherini et al. 2020; Palahí et al. 2021). Datasets on forest losses are less well developed for reforestation and afforestation. As Mitchell et al. (2017) point out, there has been significant improvement in the ability to measure changes in tree and carbon density on sites using satellite data, but these techniques are still evolving and improving and they are not yet available for widespread use.

Ground-based forest inventory measurements have been developed in many countries, most prominently in the northern hemisphere, but more and more countries are starting to develop and collect national forest inventories. Training and capacity building is going on in many developing countries under UNREDD and FAO programmes. Additional efforts to harmonize data collection methods and to make forest inventory data available to the scientific community would improve confidence in forest statistics, and changes in forest statistics over time. To some extent the Global Forest Biodiversity Initiative fills in this data gap (https://gfbi.udl.cat/).

7.6.5. Linkages to ecosystem services, human well-being and adaptation (incl. SDGs)

The linkage between biodiversity, ecosystem services, human well-being and sustainable development is widely acknowledged (Millenium Ecosystem Assesment 2005; UN Environment 2019). Loss of biodiversity and ecosystem services will have an adverse impact on quality of life, human well-being and sustainable development (Díaz et al. 2019). Such losses will not only affect current economic growth but also impede the capacity for future economic growth.

Population growth, economic development, urbanisation, technology, climate change, global trade and consumption, policy and governance are key drivers of global environmental change over recent decades (Kram et al. 2014; UN Environment 2019; WWF 2020). Changes in biodiversity and ecosystem services are mainly driven by habitat loss, climate change, invasive species, over-exploitation of natural resources, and pollution (Millenium Ecosystem Assesment 2005). The relative importance of these drivers varies across biomes, regions, and countries. Climate change is expected to be a major driver of biodiversity loss in the coming decades, followed by commercial forestry and bioenergy production (OECD 2012; UN Environment 2019). Population growth along with rising incomes and changes in consumption and dietary patterns, will exert immense pressure on land and other natural resources (IPCC. 2019a). Current estimates suggest that 75% of the land surface has been significantly anthropogenically altered, with 66% of the ocean area experiencing increasing cumulative impacts and over 85% of wetland area lost (Díaz et al. 2019). As discussed, in section 7.3, land-use change is driven amongst others by agriculture, forestry (logging and fuelwood harvesting), infrastructural development and urbanisation, all of which may also generate localised air, water, and soil pollution (Díaz et al. 2019). Over a third of the world's land surface and nearly three-quarters of available freshwater resources are devoted to crop or livestock production (Díaz et al. 2019). Despite a slight reduction in global agricultural area since 2000, regional agricultural area expansion has occurred in Latin America and the Caribbean, Africa and the Middle East (FAO 2019; (OECD/FAO 2019). The degradation of tropical forests and biodiversity hotspots, endangers habitat for many threatened and endemic species, and reduces valuable ecosystem services. However, trends vary considerably by region. As noted in Section 7.3, global forest area declined by roughly 178 Mha between 1990 and 2020 (FAO 2020a), though the rate of net forest loss has decreased over the period, due to reduced deforestation in some countries and forest gains in others. Between 1990 to 2015, forest cover fell by almost 13% in Southeast Asia, largely due to an increase in timber extraction, large-scale biofuel plantations and expansion of intensive agriculture and shrimp farms, whereas in Northeast Asia and South Asia it increased by 23% and 6% respectively, through policy instruments such as joint forest management, payment for ecosystem services, and restoration of degraded forests (IPBES 2018b). It is lamenting that the area under natural forests which are rich in biodiversity and provide diverse ecosystem services decreased by 301 Mha between 1990 and 2020, decreasing in most regions except Europe and Oceania with largest losses reported in Sub-Saharan Africa (FAO 2020a). The increasing trend of mining in forest and coastal areas, and in river basins for extracting has had significant negative impacts on biodiversity, air and water quality, water distribution, and on human health (Section 7.3). Freshwater ecosystems equally face a series of combined threats including from land-use change, water extraction, exploitation, pollution, climate change and invasive species (Díaz et al. 2019).

7.6.5.1. Ecosystem services

An evaluation of eighteen ecosystem services over the past five decades (1970-2019) found only four (agricultural production, fish harvest, bioenergy production and harvest of materials) to demonstrate increased performance, while the remaining fourteen, mostly concerning regulating and non-material contributions, were found to be in decline (Díaz et al. 2019). The value of global agricultural output (over USD3.54 trillion in 2018) had increased approximately threefold since 1970, and roundwood production (industrial roundwood and fuelwood) by 27%, between 1980 to 2018, reaching some 4 billion m^3 in 2018. However, the positive trends in these four ecosystem services does not indicate long-term sustainability. If increases in agricultural production are realised through forest clearance or through increasing energy-intensive inputs, gains are likely to be unsustainable in the long run. Similarly, an increase in fish production may involve overfishing, leading to local species declines which also impacts fish prices, fishing revenues, and the well-being of coastal and fishing communities (Sumaila and Lam 2020). Climate change and other drivers are likely to affect future fish catch potential, although impacts will differ across regions (Sumaila et al. 2017; IPCC 2019b).

The increasing trend in aquaculture production especially in South and Southeast Asia through intensive methods affects existing food production and ecosystems by diverting rice fields or mangroves

(Bhattacharya and Ninan 2011). Although extensive traditional fish farming of carp in central Europe can contribute to landscape management, enhance biodiversity and provide ecosystem services, there are several barriers to scale up production due to strict EU environmental regulations, vulnerability to extreme weather events, and to avian predators that are protected by EU laws, and disadvantages faced by small-scale enterprises that dominate the sector (European-Commission 2021). Bioenergy production may have high opportunity costs in land-scarce areas and compete with land used for food production which threatens food security and affects the poor and vulnerable. But these impacts will differ across scale, contexts and other factors.

Currently, land degradation is estimated to have reduced productivity in 23% of the global terrestrial area, and between USD235 billion and USD577 billion in annual global crop output is at risk because of pollinator loss (Díaz et al. 2019). The global trends reviewed above are based on data from 2,000 studies. It is not clear whether the assessment included a quality control check of the studies evaluated and suffer from aggregation bias. For instance, a recent meta-analysis of global forest valuation studies noted that many studies reviewed had shortcomings such as failing to clearly mention the methodology and prices used to value the forest ecosystem services, double counting, data errors, etc, (Ninan and Inoue 2013). Furthermore the criticisms against the paper by (Costanza et al. 1997), such as ignoring ecological feedbacks and non-linearities that are central to the processes that link all species to each other and their habitats, ignoring substitution effects may also apply to the global assessment (Smith 1997); Bockstael et al. 2000; Loomis et al. 2000). Land degradation has had a pronounced impact on ecosystem functions worldwide (Scholes et al. 2018). Net primary productivity of ecosystem biomass and of agriculture is presently lower than it would have been under a natural state on 23% of the global terrestrial area, amounting to a 5% reduction in total global net primary productivity (Scholes et al. 2018). Over the past two centuries, soil organic carbon, an indicator of soil health, has seen an estimated 8% loss globally (176 GtC) from land conversion and unsustainable land management practices (Scholes et al. 2018). Projections to 2050 predict further losses of 36 GtC from soils, particularly in Sub-Saharan Africa. These losses are projected to come from the expansion of agricultural land into natural areas (16 GtC), degradation due to inappropriate land management (11 GtC) and the draining and burning of peatlands (9 GtC) and melting of permafrost (Scholes et al. 2018). Trends in biodiversity measured by the global living planet index between 1970 to 2016 indicate a 68% decline in monitored population of mammals, birds, amphibians, reptiles, and fish WWF 2020). FAO's recent report on the state of the world's biodiversity for food and agriculture points to an alarming decline in biodiversity for food and agriculture including associated biodiversity such as pollination services, micro-organisms which are essential for production systems (FAO 2019d). These suggest that overall ecosystem health is consistently declining with adverse consequences for good quality of life, human well-being, and sustainable development.

Although numerous studies have estimated the value of ecosystem services for different sites, ecosystems, and regions, these studies mostly evaluate ecosystem services at a single point in time See (Costanza et al. 1997; Nahuelhual et al. 2007; de Groot et al. 2012; Ninan and Kontoleon 2016; Xue and Tisdell 2001). The few studies that have assessed the trends in the value of ecosystem services provided by different ecosystems across regions and countries indicate a declining trend (Costanza et al. 2014; Kubiszewski et al. 2017). Land use change is a major driver behind loss of biodiversity and ecosystem services in most regions (Archer et al. 2018; Rice et al. 2018; IPBES 2018b; M. Fischer et al. 2018). Projected impacts of land use change and climate change on biodiversity and ecosystem services (material and regulating services) between 2015 to 2050 were assessed to have relatively less negative impacts under global sustainability scenarios as compared to regional competition and economic optimism scenarios (Díaz et al. 2019). The projected impacts were based on a subset of Shared Socioeconomic Pathway (SSP) scenarios and GHG emissions trajectories (RCP) developed in support of IPCC assessments. There are synergies, trade-offs and co-benefits between ecosystem services and mitigation options with impacts on ecosystem services differing by scale and contexts (*high confidence*). Measures such as conservation agriculture, agroforestry, soil and water conservation, afforestation, adoption of silvopastoral systems, can help minimise trade-offs between mitigations options and ecosystem services (Duguma et al. 2014). Climate smart agriculture (CSA) is being promoted to enable farmers to make agriculture more sustainable and adapt to climate change (Box 7.4). However, experience with CSA in Africa has not been encouraging. For instance, a study of climate smart cocoa production in Ghana shows that due to lack of tenure (tree) rights, bureaucratic and legal hurdles in registering trees in cocoa farms, and other barriers small cocoa producers could not realise the project benefits (Box 7.13). Experience of CSA in some other Sub-Saharan African countries and other countries such as Belize too has been constrained by weak extension systems and policy implementation, and other barriers (Arakelyan et al. 2017; Kongsager 2017).

START BOX 7.13 HERE

Box 7.13 Case study: climate smart cocoa production in Ghana

Policy Objectives

1. To promote sustainable intensification of cocoa production and enhance the adaptive capacity of small cocoa producers.
2. To reduce cocoa-induced deforestation and GHG emissions.
3. To improve productivity, incomes, and livelihoods of smallholder cocoa producers.

Policy Mix

The climate smart cocoa (CSC) production programme in Ghana involved distributing shade tree seedlings that can protect cocoa plants from heat and water stress, enhance soil organic matter and water holding capacity of soils, and provide other assistance with agroforestry, giving access to extension services such as agronomic information and agro-chemical inputs. The shade tree seedlings were distributed by NGOs, government extension agencies, and the private sector free of charge or at subsidised prices and was expected to reduce pressure on forests for growing cocoa plants. The CSC programme was mainly targeted at small farmers who constitute about 80% of total farm holdings in Ghana. Although the government extension agency (Cocobod) undertook mass spraying or pruning of cocoa farms they found it difficult to access the 800,000 cocoa smallholders spread across the tropical south of the country. The project brought all stakeholders together i.e., the government, private sector, local farmers and civil society or NGOs to facilitate the sustainable intensification of cocoa production in Ghana. Creation of a community-based governance structure was expected to promote benefit sharing, forest conservation, adaptation to climate change, and enhanced livelihood opportunities.

Governance Context

Critical enablers

The role assigned to local government mechanisms such as Ghana's Community Resource Management Area Mechanisms (CREMAs) was expected to give a voice to smallholders who are an important stakeholder in Ghana's cocoa sector. CREMAs are inclusive because authority and ownership of natural resources are devolved to local communities who can thus have a voice in influencing CSC policy thereby ensuring equity and adapting CSC to local contexts. However, ensuring the long-term sustainability of CREMAs will help to make them a reliable mechanism for farmers to voice their concerns and aspirations, and ensure their independence as a legitimate governance structure in the long run. The private sector was assigned an important role to popularise climate smart cocoa production in Ghana. However, whether this will work to the advantage of smallholder cocoa producers needs to be seen.

Critical barriers

The policy intervention overlooks the institutional constraints characteristic of the cocoa sector in Ghana where small farmers are dominant and have skewed access to resources and markets. Lack of secure tenure (tree rights) where the ownership of shade trees and timber vests with the state, bureaucratic and legal hurdles to register trees in their cocoa farms are major constraints that impede realisation of the expected benefits of the CSC programme. This is a great disincentive for small cocoa producers to implement CSC initiatives and nurture the shade tree seedlings and undertake land improvement measures. The state marketing board has the monopoly in buying and marketing of cocoa beans including exports which impeded CREMAs or farming communities from directly selling their produce to MNCs and traders. However, many MNCs have been involved in setting up of CREMA or similar structures, extending premium prices and non-monetary benefits (access to credit, shade tree seedlings, agro-chemicals) thus indirectly securing their cocoa supply chains. A biased ecological discourse about the benefits of climate smart agriculture and sustainable intensive narrative, complexities regarding the optimal shade levels for growing cocoa, and dependence on agro-chemicals are issues that affect the success and sustainability of the project intervention. Dominance of private sector players especially MNCs in the sector may be detrimental to the interests of smallholder cocoa producers.

Source: Nasser et al. (2020)

END BOX 7.13 HERE

7.6.5.2. Human well-being and Sustainable Development Goals

Conservation of biodiversity and ecosystem services is part of the larger objective of building climate resilience and promoting good quality of life, human well-being and sustainable development. While two of the 17 SDGs directly relate to nature (SDGs 14 and 15 covering marine and terrestrial ecosystems and biodiversity), most other SDGs relating to poverty, hunger, inequality, health and well-being, clean sanitation and water, energy, etc., are directly or indirectly linked to nature (Blicharska et al. 2019). A survey among experts to assess how 16 ecosystem services could help in achieving the SDGs relating to good environment and human well-being suggested that ecosystem services could contribute to achieving about 41 targets across 12 SDGs (Wood et al. 2018). They also indicated cross-target interactions and synergetic outcomes across many SDGs. Conservation of biodiversity and ecosystem services is critical to sustaining the well-being and livelihoods of poor and marginalised people, and indigenous communities who depend on natural resources (high confidence). Nature provides a broad array of goods and services that are critical to good quality of life and human well-being. Healthy and diverse ecosystems can play an important role in reducing vulnerability and building resilience to disasters and extreme weather events (SCBD) Secretariat of the Convention on Biological Diversity 2009; The Royal Society Science Policy Centre 2014; Ninan and Inoue 2017).

Current negative trends in biodiversity and ecosystem services will undermine progress towards achieving 80% (35 out of 44) of the assessed targets of SDGs related to poverty, hunger, health, water, cities, climate, oceans and land (Díaz et al. 2019). However, Reyers and Selig (2020) note that the assessment by (Díaz et al. 2019) could only assess the consequences of trends in biodiversity and ecosystem services for 35 out of the 169 SDG targets due to data and knowledge gaps, and lack of clarity about the relationship between biodiversity, ecosystem services and SDGs.

Progress in achieving the 20 Aichi Biodiversity targets which are critical for realising the SDGs has been poor with most of the targets not being achieved or only partially realised (SCBD 2020). There could be synergies and trade-offs between ecosystem services and human well-being. For instance, a study notes that although policy interventions and incentives to enhance supply of provisioning services (e.g., agricultural production) have led to higher GDP, it may have an adverse effect on the regulatory services of ecosystems (Kirchner et al. 2015). However, we are aware of the inadequacies of traditional GDP as an indicator of well-being. In this context the Dasgupta Biodiversity Review argues for using the inclusive wealth approach to accurately measure social well-being by tracking the changes in produced, human and natural capital (Dasgupta 2021). Targets for nature (biodiversity and ecosystem services) should be refined so as to fit in with the metrics tracked by the SDGs (Ferrier et al. 2016; Rosa et al. 2017).

7.6.5.3. Land-based mitigation and adaptation

Combined mitigation and adaptation approaches have been highlighted throughout Section 7.4 regarding specific measures. Land-based mitigation and adaptation to the risks posed by climate change and extreme weather events can have several co-benefits as well as help promote development and conservation goals. Land-based mitigation and adaptation will not only help reduce GHG emissions in the AFOLU sector, but measures are required to closely link up with adaptation. In the central 2°C scenario, improved management of land and more efficient forest practices, a reduction in deforestation and an increase in afforestation, would account for 10% of the total mitigation effort over 2015–2050 (Keramidas et al. 2018). If managed and regulated appropriately, the Land sector could become carbon-neutral as early as 2030–2035, being a key sector for emissions reductions beyond 2025 (Keramidas et al. 2018). Nature-based solutions (NbS) with safeguards has immense potential for cost-effective adaptation to climate change; but their impacts will vary by scale and contexts (*high confidence*). Griscom et al. 2017 estimate this potential to provide 37% of cost-effective CO_2 mitigation until 2030 needed to meet 2°C goals with likely co-benefits for biodiversity. However, due to the time lag for technology deployment and natural carbon gain this mitigation potential of NbS by 2030 or 2050 can be delayed or much lower than the estimated potential (Qin et al. 2021).

7.7. Knowledge gaps

Closing knowledge gaps and narrowing uncertainties are crucial to advance AFOLU mitigation. Knowledge gaps exist across a range of areas, from emissions accounting and mitigation measure development to integration of scientific and traditional knowledge and development and sustainable implementation strategies. The following are identified as priorities:

- Uncertainty in contemporary emissions and sinks within AFOLU is still high. There is on-going need to develop and refine emission factors, improve activity data and facilitate knowledge exchange, concerning inventories and accounting. For example, insufficient knowledge on CO_2 emissions relating to forest management and burning or draining of organic soils (wetlands and peatlands), limits certainty on CO_2 and CH_4 fluxes.

- Improved monitoring of the land CO_2 balance is urgently needed, including impacts of land degradation and restoration efforts (e.g., in tropical and boreal regions), making use of combined remote sensing, artificial intelligence, ground-based and modelling tools (Grassi et al. 2021). Improved estimates would provide more reliable projections of nationally determined contributions to emissions reduction and enhancement of sinks, and reconciliation of national accounting and modelling results (Nabuurs et al. 2019).

- The future impacts of climate change on land systems are highly uncertain, for example, the role of permafrost thaw, tipping points, increased disturbances and enhanced CO_2 fertilization (Friedlingstein et al. 2020). Further research into these mechanisms is critical to better understand the permanence of mitigation measures in land sector.

- There is need to understand the role of forest management, carbon and nitrogen fertilization and associated interactions in the current forest carbon sink that has emerged in the last 50 to 70 years. These aspects are likely to explain much of the difference between bookkeeping models and other methodologies.

- Continued research into novel and emerging mitigation measures and associated cost efficiency (e.g. CH_4 inhibitors or vaccines for ruminants) is required. In addition to developing specific measures, research is also needed into best practice regarding implementation and optimal agricultural land and livestock management at regional and country level. Further research into the feasible mitigation potential of sustainable intensification in terms of absolute GHG emissions and appropriate policy mechanisms, is required to implement and advance this strategy.

- Research into accounting systems and policy options that will enable agricultural soil and forest carbon to be utilized as offsets (voluntary or regulatory) is needed to increase financing for land-based CDR. Design of incentives that consider local institutions and novel frameworks for cooperation between private finance and public governance can encourage investment. Equally, research to adjust or remove regulations and subsidy schemes that may hamper land-based mitigation efforts, is urgently required.

- Improving mitigation potential estimates, whether derived from sectoral studies or IAMs to account for biophysical climate effects, and impacts of future climate change (e.g. mitigation permanence), biodiversity loss and corresponding feedbacks is needed. IAM 'usability' can be enhanced by integrating a wider set of measures and incorporating sustainability considerations.

- Research into the feasibility of improving and enhancing sustainable agricultural and forestry value chains, provision of renewable products (building with wood) and the sustainability of bioenergy is critically important. Modelled scenarios do not examine many poverty, employment and development trade-offs, which are highly context specific and vary enormously by region. Trade-off analysis and cost-benefit analysis can assist decision making and policy.

- In-depth understanding of mitigation-SDG interactions is critical for identifying mitigation options that maximize synergies and minimize trade-offs. Mitigation measures have important synergies, trade-offs and co-benefits, impacting biodiversity and resource-use, human well-being, ecosystem services, adaptation capacity and many SDGs. In addition to exploring localised economic implementation costs, studies are needed to understand how measures will impact and interact with wider environmental and social factors across localities and contexts.

Frequently Asked Questions (FAQs)

FAQ 7.1 Why is the Agriculture, Forestry and Other Land Uses (AFOLU) sector unique when considering GHG mitigation?

There are three principal reasons that make the AFOLU sector unique in terms of mitigation;

1. In contrast to other sectors, AFOLU can facilitate mitigation in several different ways. Specifically, AFOLU can (a) reduce emissions as a sector in its own right, (b) remove meaningful quantities of carbon from the atmosphere and relatively cheaply, and (c) provide raw materials to enable mitigation within other sectors, such as energy, industry or the built environment.
2. The emissions profile of AFOLU differs from other sectors, with a greater proportion of non-CO_2 gases (N_2O and CH_4). The impacts of mitigation efforts within AFOLU can vary according to which gases are targeted, as a result of the differing atmospheric lifetime of the gases and differing global temperature responses to the accumulation of the specific gases in the atmosphere.
3. In addition to tackling climate change, AFOLU mitigation measures have capacity, where appropriately implemented, to help address some critical, wider challenges, as well as contributing to climate change adaptation. AFOLU is inextricably linked with some of the most serious challenges that are suggested to have ever faced humanity, such as large-scale biodiversity loss, environmental degradation and the associated consequences. As AFOLU concerns land management and utilises a considerable portion of the Earth's terrestrial area, the sector greatly influences soil, water and air quality, biological and social diversity, the provision of natural habitats, and ecosystem functioning, consequently impacting many SDGs.

FAQ 7.2 What AFOLU measures have the greatest economic mitigation potential?

Economic mitigation potential refers to the mitigation estimated to be possible at an annual cost of up to USD100 tCO_2^{-1} mitigated. This cost is deemed the price at which society is willing to pay for mitigation and is used as a proxy to estimate the proportion of technical mitigation potential that could realistically be implemented. Between 2020 and 2050, measures concerning forests and other ecosystem are estimated to have an average annual mitigation potential of 7.3 (3.9 - 13.1) $GtCO_2$-eq yr^{-1} at USD100 tCO_2^{-1}. At the same cost, agricultural measures are estimated to have a potential of 4.1 (1.7-6.7) $GtCO_2$-eq yr^{-1}. Emerging technologies, such as CH_4 vaccines and inhibitors, could sustainably increase agricultural mitigation potential in future. The diverted production effects of changes in demand (reduced food losses, diet changes and improved and enhanced wood products use), is estimated to have an economic potential of 2.2 (1.1–3.6) $GtCO_2$-eq yr^{-1}. However, cost forms only one constraint to mitigation, with realization of economic potential dependent on multiple context-specific environmental and socio-cultural factors.

FAQ 7.3 What are potential impacts of large-scale establishment of dedicated bioenergy plantations and crops and why is it so controversial?

The potential of bioenergy with carbon capture and storage (BECCS) remains a focus of debate with several studies evaluating the level at which BECCS could be sustainably implemented, published since AR5. BECCS involves sequestering carbon through plant growth (i.e. in trees or crops) and capturing the carbon generated when this biomass is processed for power or fuel. The captured carbon then requires long-term storage in for example, geological, terrestrial or ocean reservoirs, or in products. While appearing to create a net removal of carbon from the atmosphere, BECCS requires land, water and energy which can create adverse side-effects at scale. Controversy has arisen because some of the models calculating the energy mix required to keep the temperature to 1.5°C have included BECCS at very large scales as a means of both providing energy and removing carbon from the atmosphere to offset emissions from industry, power, transport or heat. For example, studies have calculated that for BECCS to achieve 11.5 $GtCO_2$-eq per year of carbon removal in 2100, as envisaged in one scenario, 380-700 Mha or 25-46% of all the world's arable and cropland would be needed. In such a situation, competition for agricultural land seriously threatens food production and food security, while also impacting biodiversity, water and soil quality, and landscape aesthetic value. More recently however, the scenarios for BECCS have become much more realistic, though concerns regarding impacts on food security and the environment remain, while the reliability of models is uncertain due to methodological flaws. Improvements to models are required to better capture wider environmental and social impacts of BECCS in order to ascertain its sustainable contribution in emissions pathways. Additionally, the opportunity for other options that could negate very large-scale deployment of BECCS, such as other carbon dioxide removal measures or more stringent emission reductions in other sectors, could be explored within models.

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Chapter 8: Urban Systems and Other Settlements

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Date of Draft: 27/11/2021

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Executive summary

Although urbanization is a global trend often associated with increased incomes and higher consumption, the growing concentration of people and activities is an opportunity to increase resource efficiency and decarbonize at scale *(very high confidence)*. The same urbanization level can have large variations in per capita urban carbon emissions. For most regions, per capita urban emissions are lower than per capita national emissions. {8.1.4, 8.3.3, 8.4, Box 8.1}

Most future urban population growth will occur in developing countries, where per capita emissions are currently low but expected to increase with the construction and use of new infrastructure and the built environment, and changes in incomes and lifestyles *(very high confidence)*. The drivers of urban Greenhouse Gas (GHG) emissions are complex and include an interplay of population size, income, state of urbanization, and how cities are laid out. How new cities and towns are designed, constructed, managed, and powered will lock-in behaviour, lifestyles, and future urban GHG emissions. Low-emission urbanization can improve well-being while minimizing impact on GHG emissions, but there is risk that urbanization can lead to increased global GHG emissions through increased emissions outside the city's boundaries. {8.1.4, 8.3, Box 8.1, 8.4, 8.6}

The urban share of global GHG emissions (including CO_2 and CH_4) is substantive and continues to increase *(high confidence)*. Total urban emissions based on consumption-based accounting were estimated to be 24.5 $GtCO_2$-eq, or 62% of the global total in 2015, excluding aviation, shipping and biogenics, and increased to an estimated 28.5 ± 0.1 $GtCO_2$-eq in 2020, representing about 67-72% of global emissions. About 100 of the highest emitting urban areas account for approximately 18% of the global carbon footprint. {8.1.6, 8.3.3}

The urban share of regional GHG emissions increased between 2000 and 2015, with much inter-region variation in the magnitude of the increase *(high confidence)*. Globally, the urban share of national emissions increased 6 percentage points, from 56% in 2000 to 62% in 2015. For 2000 to 2015, the urban emissions share across WGIII AR6 regions increased from 28% to 38% in Africa, from 46% to 54% in Asia and Developing Pacific, from 62% to 72% in Developed Countries, from 57% to 62% in Eastern Europe and West-Central Asia, from 55% to 66% in Latin America and Caribbean, and from 68% to 69% in the Middle East. {8.1.6, 8.3.3}

Per capita urban GHG emissions increased between 2000 and 2015, with cities in the Developed Countries region producing nearly seven times more per capita than the lowest emitting region *(medium confidence)*. From 2000 to 2015, the global urban GHG emissions per capita increased from 5.5 to 6.2 tCO_2-eq/person (an increase of 11.8%); Africa increased from 1.3 to 1.5 tCO_2-eq per person (22.6%); Asia and Developing Pacific increased from 3.0 to 5.1 tCO_2-eq per person (71.7%); Eastern Europe and West-Central Asia increased from 6.9 to 9.8 tCO_2-eq/person (40.9%); Latin America and the Caribbean increased from 2.7 to 3.7 tCO_2-eq/person (40.4%); and Middle East increased from 7.4 to 9.6 tCO_2-eq/person (30.1%). Albeit starting from the highest level, Developed Countries had a decline of 11.4 to 10.7 tCO_2-eq/person (-6.5%). {8.3.3}

The global share of future urban GHG emissions is expected to increase through 2050 with moderate to no mitigation efforts due to growth trends in population, urban land expansion and infrastructure and service demands, but the extent of the increase depends on the scenario and the scale and timing of urban mitigation action (*medium confidence*). With aggressive and immediate mitigation policies to limit global warming below 1.5°C by the end of the century, including high levels of electrification, energy and material efficiency, renewable energy preferences, and socio-behavioural responses, urban GHG emissions could approach net zero and reach a maximum of 3 $GtCO_2$-eq in 2050.

Under a scenario with aggressive but not immediate urban mitigation policies to limit global warming to 2°C, urban emissions could reach 17 $GtCO_2$-eq in 2050. With no urban mitigation efforts, urban emissions could more than double from 2020 levels and reach 65 $GtCO_2$-eq in 2050, while being limited to 34 $GtCO_2$-eq in 2050 with only moderate mitigation efforts. {8.3.4}

Urban land areas could triple between 2015 and 2050, with significant implications for future carbon lock-in. There is a large range in the forecasts of urban land expansion across scenarios and models, which highlights an opportunity to shape future urban development towards low- or net zero GHG emissions and minimize the loss of carbon stocks and sequestration in the AFOLU sector due to urban land conversion (*medium confidence*). By 2050, urban areas could increase up to 211% over the 2015 global urban extent, with the median projected increase ranging from 43% to 106%. While the largest absolute amount of new urban land is forecasted to occur in Asia and Developing Pacific, and in Developed Countries, the highest rate of urban land growth is projected to occur in Africa, Eastern Europe and West-Central Asia, and in the Middle East. The infrastructure that will be constructed concomitant with urban land expansion will lock-in patterns of energy consumption that will persist for decades if not generations. Furthermore, given past trends, the expansion of urban areas is likely to take place on agricultural lands and forests, with implications for the loss of carbon stocks and sequestration. {8.3.1, 8.3.4, 8.4.1, 8.6}

The construction of new, and upgrading of, existing urban infrastructure through 2030 will result in significant emissions *(very high confidence).* The construction of new and upgrading of existing urban infrastructure using conventional practices and technologies can result in significant committed CO_2 emissions, ranging from 8.5 $GtCO_2$ to 14 $GtCO_2$ annually up to 2030 and more than double annual resource requirements for raw materials to about 90 billion tonnes per year by 2050, up from 40 billion tonnes in 2010 (*medium evidence, high agreement)*.{8.4.1, 8.6}

Given the dual challenges of rising urban GHG emissions and future projections of more frequent extreme climate events, there is an urgent need to integrate urban mitigation and adaptation strategies for cities to address climate change and withstand its effects *(very high confidence).* Mitigation strategies can enhance resilience against climate change impacts while contributing to social equity, public health, and human well-being. Urban mitigation actions that facilitate economic decoupling can have positive impacts on employment and local economic competitiveness.{8.2, Cross-Working Group Box 2, 8.4}

Cities can only achieve net zero or near net zero GHG emissions through deep decarbonisation and systemic transformation *(very high confidence).* Urban deep decarbonisation entails implementing three broad strategies concurrently: (1) reducing urban energy consumption across all sectors, including through compact and efficient urban forms and supporting infrastructure; (2) electrification and switching to net zero emissions resources; and (3) enhancing carbon uptake and stocks (*medium evidence, high agreement*). Given the regional and global reach of urban supply chains, a city cannot achieve net zero GHG emissions by only focusing on reducing emissions within its administrative boundaries. {8.1.6, 8.3.4, 8.4, 8.6}

Packages of mitigation policies that implement multiple urban-scale interventions can have cascading effects across sectors, reduce GHG emissions outside of a city's administrative boundaries, and reduce more emissions than the net sum of individual interventions, particularly if multiple scales of governance are included *(high confidence).* Cities have the ability to implement policy packages across sectors using an urban systems approach, especially those that affect key infrastructure based on spatial planning, electrification of the urban energy system, and urban green and blue infrastructure. The institutional capacity of cities to develop, coordinate, and integrate sectoral mitigation strategies within their jurisdiction varies by context, particularly those related to governance, the regulatory system, and budgetary control. {8.4, 8.5, 8.6}

Integrated spatial planning to achieve compact and resource-efficient urban growth through co-location of higher residential and job densities, mixed land use, and transit-oriented development could reduce GHG emissions between 23-26% by 2050 compared to the business-as-usual scenario *(robust evidence, high agreement, very high confidence).* Compact cities with shortened distances between housing and jobs, and interventions that support a modal shift away from private motor vehicles towards walking, cycling, and low-emissions shared and public transportation, passive energy comfort in buildings, and urban green infrastructure can deliver significant public health benefits and have lower GHG emissions. {8.2, 8.3.4, 8.4, 8.6}

Urban green and blue infrastructure can mitigate climate change through carbon sequestration, avoided emissions, and reduced energy use while offering multiple co-benefits *(robust evidence, high agreement)*. Urban green and blue infrastructure, including urban forests and street trees, permeable surfaces, and green roofs offer potentials to mitigate climate change directly through sequestering and storing carbon, and indirectly by inducing a cooling effect that reduces energy demand and reducing energy use for water treatment. Global urban trees store approximately 7.4 billion tonnes of carbon, and sequester approximately 217 million tonnes of carbon annually, although urban tree carbon storage and sequestration are highly dependent on biome. Among the multiple co-benefits of green and blue infrastructure are reducing the urban heat island (UHI) effect and heat stress, reducing stormwater runoff, improving air quality, and improving mental and physical health of urban dwellers. {8.2, 8.4.4}

The potentials and sequencing of mitigation strategies to reduce GHG emissions will vary depending on a city's land use and spatial form and its state of urbanization, whether it is an established city with existing infrastructure, a rapidly growing city with new infrastructure, or an emerging city with infrastructure build-up *(medium confidence)*. The long lifespan of urban infrastructures locks in behaviour and committed emissions. Urban infrastructures and urban form can enable socio-cultural and lifestyle changes that can significantly reduce carbon footprints. Rapidly growing cities can avoid higher future emissions through urban planning to co-locate jobs and housing to achieve compact urban form, and by leapfrogging to low-carbon technologies. Established cities will achieve the largest GHG emissions savings by replacing, repurposing, or retrofitting the building stock, strategic infilling and densifying, as well as through modal shift and the electrification of the urban energy system. New and emerging cities have unparalleled potential to become low or net zero GHG emissions while achieving high quality of life by creating compact, co-located, and walkable urban areas with mixed land use and transit-oriented design, that also preserve existing green and blue assets {8.2, 8.4, 8.6}

With over 880 million people living in informal settlements, there are opportunities to harness and enable informal practices and institutions in cities related to housing, waste, energy, water, and sanitation to reduce resource use and mitigate climate change *(low evidence, medium agreement).* The upgrading of informal settlements and inadequate housing to improve resilience and well-being offers a chance to create a low-carbon transition. However, there is limited quantifiable data on these practices and their cumulative impacts on GHG emissions. {8.1.4, 8.2.2, Cross-Working Group Box 2, 8.3.2, 8.4, 8.6, 8.7}

Achieving transformational changes in cities for climate change mitigation and adaptation will require engaging multiple scales of governance, including governments and non-state actors, and in connection with substantive financing beyond sectoral approaches *(very high confidence)*. Large and complex infrastructure projects for urban mitigation are often beyond the capacity of local municipality budgets, jurisdictions, and institutions. Partnerships between cities and international institutions, national and region governments, transnational networks, and local stakeholders play a pivotal role in mobilizing global climate finance resources for a range of infrastructure projects with low-carbon emissions and related spatial planning programs across key sectors. {8.4, 8.5}

8.1 Introduction

8.1.1 What is new since AR5

The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) was the first IPCC report that had a standalone chapter on urban mitigation of climate change. The starting point for that chapter was how the spatial organization of urban settlements affects greenhouse gas (GHG) emissions and how urban form and infrastructure could facilitate mitigation of climate change. A main finding in AR5 was that urban form shapes urban energy consumption and GHG emissions.

Since AR5, there has been growing scientific literature and policy foci on urban strategies for climate change mitigation. There are three possible reasons for this. First, according to AR5 Working Group III (WGIII) Chapter 12 on Human Settlements, Infrastructure, and Spatial Planning, urban areas generate between 71–76% of carbon dioxide (CO_2) emissions from global final energy use and between 67–76% of global energy (Seto et al. 2014). Thus, focusing on 'urban systems' (see Glossary and Figure 8.15) addresses one of the key drivers of emissions. Second, more than half of the world population lives in urban areas, and by mid-century 7 out of 10 people on the planet will live in a town or a city (UN DESA 2019). Thus, coming up with mitigation strategies that are relevant to urban settlements is critical for successful mitigation of climate change. Third, beyond climate change, there is growing attention on cities as major catalysts of change and to help achieve the objectives outlined in multiple international frameworks and assessments.

Cities are also gaining traction within the work of the IPCC. The IPCC Special Report on Global Warming of 1.5°C (SR1.5 Chapter 4) identified four systems that urgently need to change in fundamental and transformative ways: urban infrastructure, land use and ecosystems, industry, and energy. Urban infrastructure was singled out but urban systems form a pivotal part of the other three systems requiring change (IPCC 2018a) (see 'infrastructure' in Glossary). The IPCC Special Report on Climate Change and Land (SRCCL) identified cities not only as spatial units for land-based mitigation options but also places for managing demand for natural resources including food, fibre, and water (IPCC 2019).

Other international frameworks are highlighting the importance of cities. For example, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) report on nature's contribution to people is clear: cities straddle the biodiversity sphere in the sense that they present spatial units of ecosystem fragmentation and degradation while at the same time contain spatial units where the concentration of biodiversity compares favourably with some landscapes (IPBES 2019a). Cities are also featured as a key element in the transformational governance to tackle both climate change and biodiversity and ecosystem challenges in the first-ever IPCC-IPBES co-sponsored workshop report (Pörtner et al. 2021) (see Section 8.5 and 'governance' in Glossary).

The UN Sustainable Development Goals (SDGs) further underscore the importance of cities in the international arena with the inclusion of SDG 11 on Sustainable Cities and Communities for 'inclusive, safe, resilient and sustainable' cities and human settlements (United Nations 2015; Queiroz et al. 2017; United Nations 2019). Additionally, UN-Habitat's New Urban Agenda (NUA) calls for various measures, including integrated spatial planning at the city-regional scale, to address the systemic challenges included in greening cities, among which is emissions reduction and avoidance (United Nations 2017).

Since AR5, there has also been an increase in scientific literature on urban mitigation of climate change, including more diversity of mitigation strategies than were covered during AR5 (Lamb et al. 2018), as well as a growing focus on how strategies at the urban scale can have compounding or additive effects beyond urban areas (e.g., in rural areas, land use planning, and the energy sector).

There is also more literature on using a systems approach to understand the interlinkages between mitigation and adaptation, and situating GHG emissions reduction targets within broader social, economic, and human well-being context and goals (Bai et al. 2018; Ürge-Vorsatz et al. 2018; Lin et al. 2021). In particular, the nexus approach, such as the water and energy nexus and the water-energy-food nexus, is increasingly being used to understand potential emissions and energy savings from cross-sectoral linkages that occur in cities (Wang and Chen 2016; Engström et al. 2017; Valek et al. 2017). There is also a growing literature that aims to quantify transboundary urban GHG emissions and carbon footprint beyond urban and national administrative boundaries (Chen et al. 2016; Hu et al. 2016). Such a scope provides a more complete understanding of how local urban emissions or local mitigation strategies can have effects on regions' carbon footprint or GHG emissions.

City Climate Action

Moreover, cities around the world are putting increasing focus on tackling climate change. Since AR5:

- Climate leadership at the local scale is growing with commitment from city decision-makers and policymakers to implement local-scale mitigation strategies (GCoM 2018, 2019; ICLEI 2019a; C40 Cities 2020a).
- More than 360 cities announced at the Paris Climate Conference that the collective impact of their commitments will lead to reducing up to 3.7 $GtCO_2$-eq (CO_2-equivalent) of urban emissions annually by 2030 (Cities for Climate 2015).
- The Global Covenant of Mayors (GCoM), a transnational network comprised of more than 10,000 cities, have made commitments to reduce urban GHG emissions up to 1.4–2.3 $GtCO_2$-eq annually by 2030 and 2.8–4.2 $GtCO_2$-eq annually by 2050, compared to business-as-usual (GCoM 2018, 2019).
- More than 800 cities have made commitments to achieve net zero GHG emissions (see Glossary), either economy-wide or in a particular sector (NewClimate Institute and Data-Driven EnviroLab 2020).

Although most cities and other subnational actors (see Glossary) are yet to meet their net zero GHG or CO_2 emissions commitments, the growing numbers of those commitments, alongside organizations enabled to facilitate reaching those targets, underscore the growing support for climate action by city and other subnational leaders.

Historical and future urban emissions

One major innovation in this assessment report is the inclusion of historical and future urban GHG emissions. Urban emissions based on consumption-based accounting by regions has been put forth for the timeframe 1990–2100 using multiple datasets with projections given in the framework of the Shared Socioeconomic Pathway (SSP) - Representative Concentration Pathway (RCP) scenarios. This advance has provided a time dimension to urban footprints considering different climate scenarios with implications for urban mitigation, allowing a comparison of the way urban emissions and their reduction can evolve given different scenario contexts (see Glossary for definitions of various 'pathways' and 'scenarios' in the context of climate change mitigation, including 'SSPs' and 'RCPs').

Sustainable development linkages and feasibility assessment

Special emphasis is placed on the co-benefits of urban mitigation options, including an evaluation of linkages with the SDGs based on synergies and/or trade-offs. Urban mitigation options are further evaluated based on multiple dimensions according to the feasibility assessment (see Section 8.5.5, Figure 8.19, and SM 8.2) indicating the enablers and barriers of implementation. These advances provide additional guidance for urban mitigation.

8.1.2 Preparing for the Special Report on Cities and Climate Change in AR7

At the 43rd Session of the IPCC in 2016, the IPCC approved a Special Report on Climate Change and Cities during the Seventh Assessment Cycle of the IPCC (AR7). To stimulate scientific research knowledge exchange, the IPCC and nine global partners co-sponsored the IPCC Cities and Climate Change Science Conference, which brought together over 700 researchers, policymakers, and practitioners from 80 countries.

The conference identified key research priorities including the need for an overarching systems approach to understanding how sectors interact in cities as drivers for GHG emissions and the relationship between climate and other urban processes, as well as achieving transformation towards low-carbon and resilient futures (Bai et al. 2018). The subsequent report on global research and action agenda identifies scale, informality, green and blue infrastructure, governance and transformation, as well as financing climate action, as areas for scientific research during the AR6 cycle and beyond (WCRP 2019).

8.1.3 The scope of the chapter: a focus on urban systems

This chapter takes an urban systems approach and covers the full range of urban settlements, including towns, cities, and metropolitan areas. By 'urban system' (see Figure 8.15), this chapter refers to two related concepts. First, an urban systems approach recognizes that cities do not function in isolation. Rather, cities exhibit strong interdependencies across scales, whether it is within a region, a country, a continent, or worldwide. Cities are embedded in broader ecological, economic, technical, institutional, legal, and governance structures that often constrain their systemic function, which cannot be separated from wider power relations (Bai et al. 2016).

The notion of a system of cities has been around for nearly 100 years and recognizes that cities are interdependent, in that significant changes in one city, such as economic activities, income, or population, will affect other cities in the system (Christaller 1933; Berry 1964; Marshall 1989). This perspective of an urban system emphasizes the connections between a city and other cities, as well as between a city and its hinterlands (Hall and Hay 1980; Ramaswami et al. 2017b; Xu et al. 2018c). An important point is that growth in one city affects growth in other cities in the global, national or regional system of cities (Gabaix 1999; Scholvin et al. 2019; Knoll 2021).

Moreover, there is a hierarchy of cities (Taylor 1997; Liu et al. 2014), with very large cities at the top of the hierarchy concentrating political power and financial resources, but of which there are very few. Rather, the urban system is dominated by small- and medium-sized cities and towns. With globalization and increased interconnectedness of financial flows, labour, and supply chains, cities across the world today have long-distance relationships on multiple dimensions but are also connected to their hinterlands for resources.

The second key component of the urban systems lens identifies the activities and sectors within a city as being inter-connected—that cities are ecosystems (Rees 1997; Grimm et al. 2000; Newman and Jennings 2008; Acuto et al. 2019; Abdullah and Garcia-Chueca 2020; Acuto and Leffel 2021). This urban systems perspective emphasizes linkages and interrelations within cities. The most evident example of this is urban form and infrastructure, which refer to the patterns and spatial arrangements of land use, transportation systems, and urban design. Changes in urban form and infrastructure can simultaneously affect multiple sectors, such as buildings, energy, and transport.

This chapter assesses urban systems beyond simply jurisdictional boundaries. Using an urban systems lens has the potential to accelerate mitigation beyond a single sector or purely jurisdictional approach (see Section 8.4). An urban systems perspective presents both challenges and opportunities for urban mitigation strategies. It shows that any mitigation option potentially has positive or negative consequences in other sectors, other settlements, cities, or other parts of the world, and requires more careful and comprehensive considerations on the broader impacts, including equity and social justice (see Glossary for a comprehensive definition of 'equity' in the context of mitigation and adaption). This chapter focuses on cities, city regions, metropolitan regions, megalopitans, mega-urban regions, towns, and other types of urban configurations because they are the primary sources of urban GHG emissions and tend to be where mitigation action can be most impactful.

There is no internationally agreed upon definition of urban, urban population, or urban area. Countries develop their own definitions of urban, often based on a combination of population size or density, and other criteria including the percentage of population not employed in agriculture, the availability of electricity, piped water, or other infrastructures, and characteristics of the built environment, such as dwellings and built structures. This chapter assesses urban systems, which includes cities and towns. It uses a similar framework as Chapter 6 of AR6 IPCC WGII, referring to cities and urban settlements as 'concentrated human habitation centres that exist along a continuum' (Dodman et al. 2022) (for further definitions of 'urban,' 'cities,' 'settlements,' and related terms, see Glossary, and WGII Chapter 6).

8.1.4 The urban century

The 21st century will be the urban century, defined by a massive increase in global urban populations and a significant building up of new urban infrastructure stock to accommodate the growing urban population. Six trends in urbanization are especially important in the context of climate change mitigation.

First, the size and relative proportion of the urban population is unprecedented and continues to increase. As of 2018, approximately 55% of the global population lives in urban areas (about 4.3 billion people) (UN DESA 2019). It is predicted that 68% of the world population will live in urban areas by 2050. This will mean adding 2.5 billion people to urban areas between 2018 and 2050, with 90% of this increase taking place in Africa and Asia. There is a strong correlation between the level of urbanization and the level of national income, with considerable variation and complexity in the relationship between the two (UN DESA 2019). In general, countries with levels of urbanization of 75% or greater all have high national incomes, whereas countries with low levels of urbanization under 35% have low national incomes (UN DESA 2019). In general, there is a clear positive correlation between the level of urbanization and income levels (see Figure 8.1, also Box 8.1).

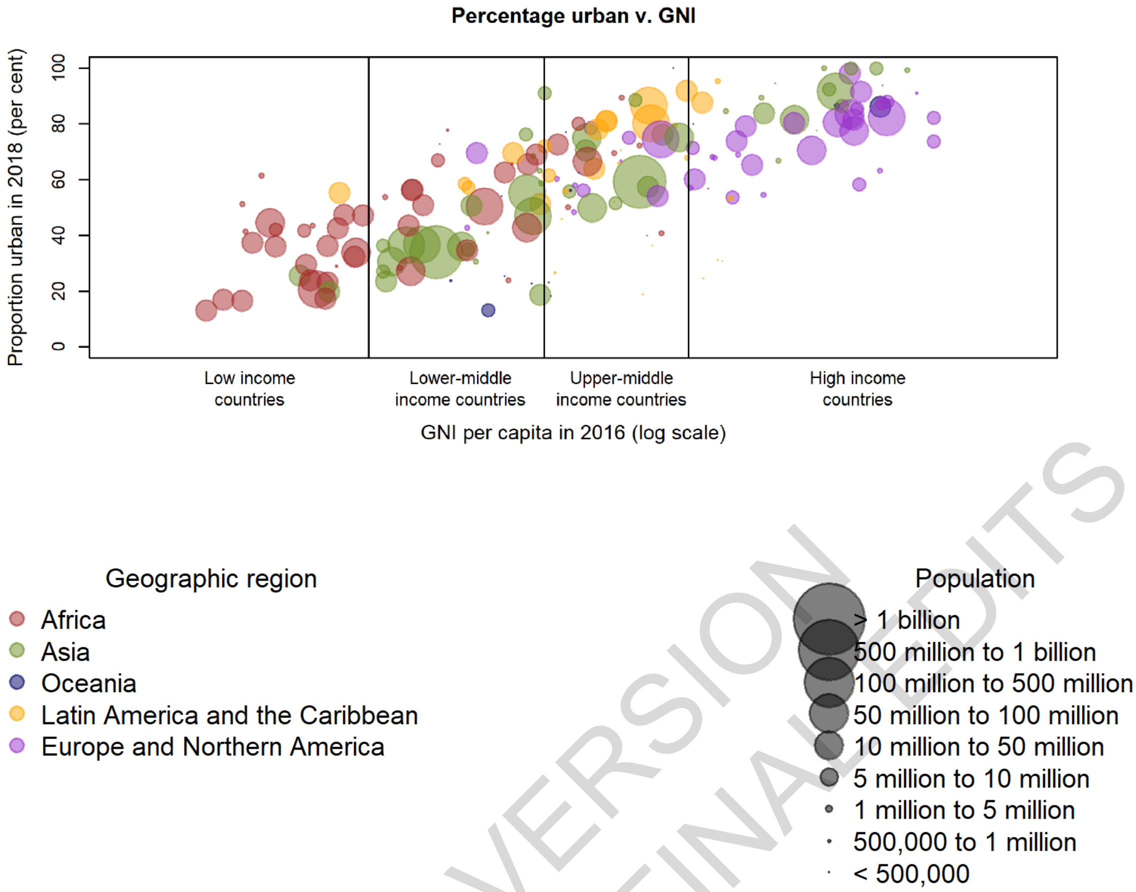

Figure 8.1[1] Relationship between urbanization level and Gross National Income

There is a positive and strong correlation between the urbanization level and gross national income. High income countries have high levels of urbanization, on average 80%. Low-income countries have low levels of urbanization, on average 30%.

Source: UN DESA 2019, p. 42

Second, the geographic concentration of the world's current urban population is in emerging economies, and the majority of future urban population growth will take place in developing countries and Least-Developed Countries (LDCs). About half of the world's urban population in 2018 lived in just seven countries, and about half of the increase in urban population through 2050 is projected to be concentrated in eight countries (UN DESA 2019) (see Figure 8.2). Of these eight, seven are emerging economies where there will be a need for significant financing to construct housing, roads, and other urban infrastructure to accommodate the growth of the urban population. How these new cities of tomorrow will be designed and constructed will lock-in patterns of urban energy behaviour for decades if not generations (see Section 8.3.4 and 8.4). Thus, it is essential that urban climate change mitigation strategies include solutions appropriate for cities of varying sizes and typologies (see Section 8.6 and Figure 8.21).

FOOTNOTE[1] The countries and areas classification in the underlying report for this figure deviates from the standard classification scheme adopted by WGIII as set out in Annex II, section 1.

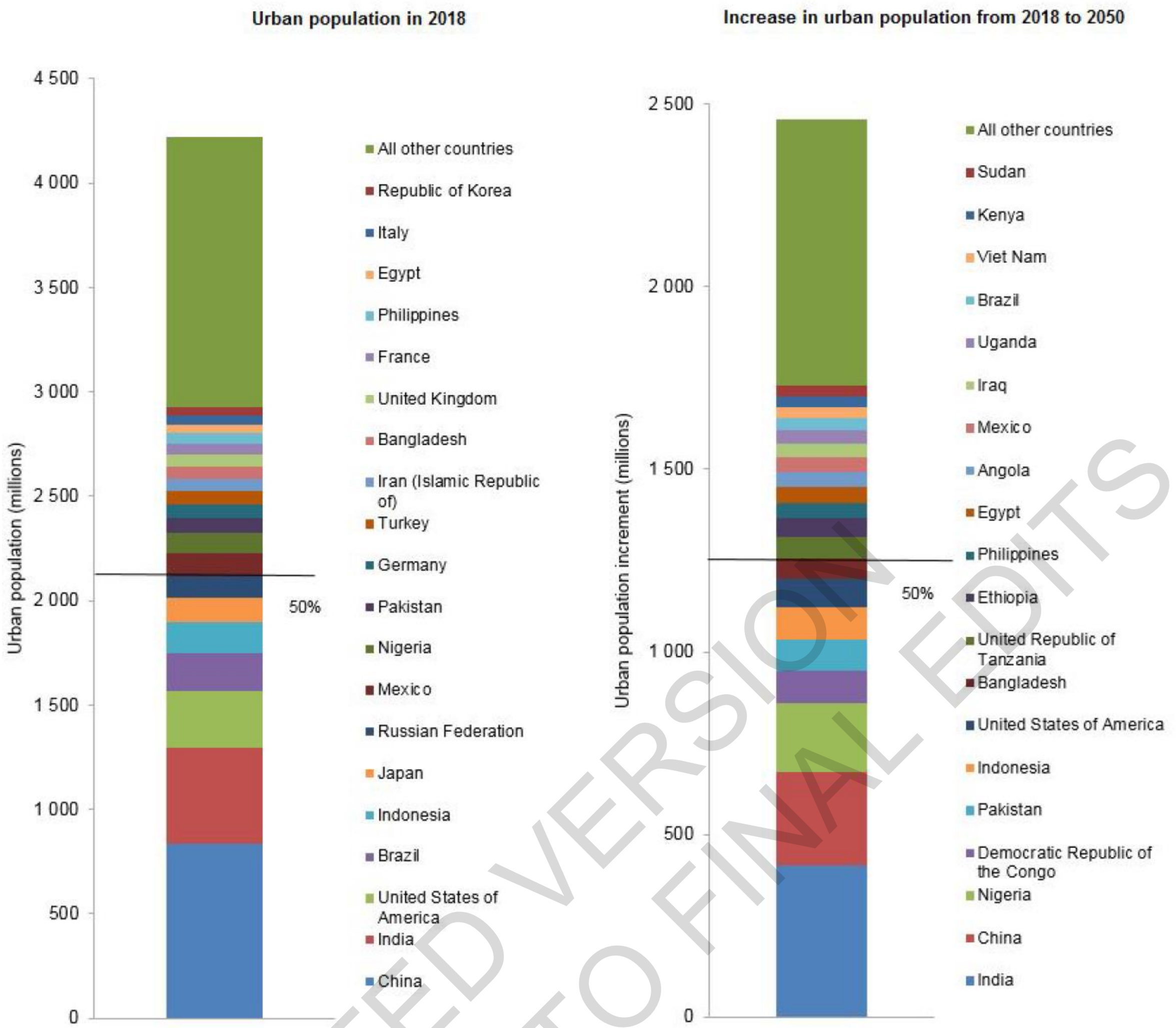

Figure 8.2 Urban population size in 2018 and increase in the projected urban population.

In 2018, about half of the world's urban population lived in seven countries, and about half of the increase in urban population through 2050 is forecasted to concentrate in eight countries.

Source: UN DESA 2019, p. 44

Third, small and medium-sized cities and towns are a dominant type of urban settlement. In 2018, more than half (58%) of the urban population lived in cities and towns with fewer than 1 million inhabitants and almost half of the world's urban population (48%) lived in settlements with fewer than 500,000 inhabitants (see Figure 8.3). Although megacities receive a lot of attention, only about 13% of the urban population worldwide lived in a megacity—an urban area with at least 10 million inhabitants (UN DESA 2019). Thus, there is a need for a wide range of strategies for urban mitigation of climate change that are appropriate for cities of varying levels of development, sizes, especially smaller cities which often have lower levels of financial capacities than large cities.

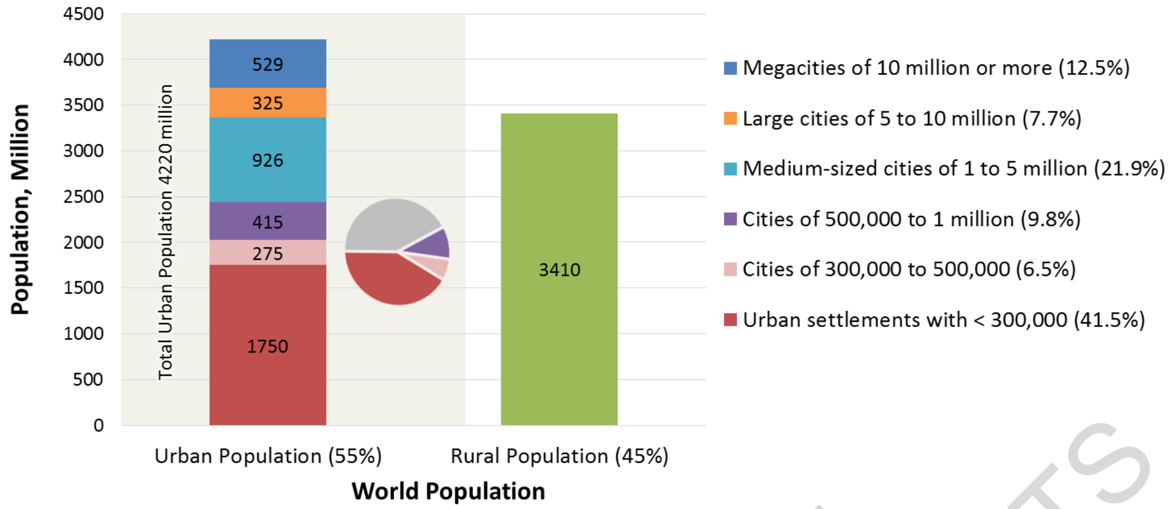

Figure 8.3 Population of the world, by area of residence and size class of urban settlement for 2018

As of 2018, 4.2 billion people or 55% of the world population reside in urban settlements while 45% reside in rural areas. The coloured stacked bars for the urban population represent the total number of inhabitants for a given size class of urban settlements. Megacities of 10 million or more inhabitants have a total of only 529 million inhabitants that corresponded to 12.5% of the urban population. In contrast, about 1.8 billion inhabitants reside in urban settlements with fewer than 300,000 inhabitants that corresponded to 41.5% of the urban population. The pie chart represents the respective shares for 2018, with 42% of the urban population residing in settlements with more than 1 million inhabitants, and 58% of the urban population residing in settlements with fewer than 1 million inhabitants. Almost half of the world's urban population (48%) live in settlements with fewer than 500,000 inhabitants.

Source: adapted from UN DESA 2019, p. 56.

Fourth, another trend is the rise of megacities and extended metropolitan regions. The largest cities around the world are becoming even larger, and there is a growing divergence in economic power between megacities and other large cities (Kourtit et al. 2015; Hoornweg and Pope 2017; Zhao et al. 2017b). Moreover, there is evidence that the largest city in each country has an increasing share of the national population and economy.

Fifth, population declines have been observed for cities and towns across the world, including in Poland, Republic of Korea, Japan, United States, Germany, and Ukraine. The majority of cities that have experienced population declines are concentrated in Europe. Multiple factors contribute to the decline in cities, including declining industries and the economy, declining fertility, and outmigration to larger cities. Shrinking urban populations could offer retrofitting opportunities (UNEP 2019) and increasing greenspaces (Jarzebski et al. 2021), but the challenges for these cities differ in scope and magnitude from rapidly expanding cities.

Sixth, urbanization in many emerging economies is characterized by informality and an informal economy (Brown and McGranahan 2016). The urban informal economy includes a wide array of activities, including but not limited to street vending, home-based enterprises, unreported income from self-employment, informal commerce, domestic service, waste-picking, and urban agriculture. The urban informal economy is large and growing. Globally, about 44% of the urban economy is informal, although there is much variation between countries and regions (ILO 2018). Emerging and developing economies have the highest percentage of the urban informal economy, with Africa (76%) and the Arab States (64%) with the largest proportion (ILO 2018). Urban informality also extends to planning, governance and institutions (Roy 2009; EU 2016; Lamson-Hall et al. 2019). Given its prevalence, it is important for urban climate change mitigation strategies to account for informality, especially in emerging and developing countries (see Section 8.3.2).

8.1.5 Urbanization in developing countries

Urbanization in the 21st century will be dominated by population and infrastructure growth in developing countries, and as such it is important to highlight three aspects that are unique and especially relevant for climate change mitigation. First, urbanization will increase in speed and magnitude. Given their significant impact on emissions, mitigation action in Asian cities, especially the large and rapidly growing cities, will have significant implications on global ambitions (see Section 8.3.4).

Second, a number of cities in developing countries lack institutional, financial and technical capacities to enable local climate change action (Sharifi et al. 2017; Fuhr et al. 2018). While these capacities differ across contexts (Hickmann et al. 2017), several governance challenges are similar across cities (Gouldson et al. 2015). These factors also influence the ability of cities to innovate and effectively implement mitigation action (Nagendra et al. 2018) (see Chapter 17).

Third, there are sizable economic benefits in developing country cities that can provide an opportunity to enhance political momentum and institutions (Colenbrander et al. 2016). The co-benefits approach (see Section 8.2), which frames climate objectives alongside other development benefits, is increasingly seen as an important concept justifying and driving climate change action in developing countries (Sethi and Puppim de Oliveira 2018).

Large-scale system transformations are also deeply influenced by factors outside governance and institutions such as private interests and power dynamics (Jaglin 2014; Tyfield 2014). In some cases, these private interests are tied up with international flows of capital. In India, adaptation plans involving networks of private actors and related mitigation actions have resulted in the dominance of private interests. This has led to trade-offs and adverse impacts on the poor (Chu 2016; Mehta et al. 2019).

When planning and implementing low-carbon transitions, it is important to consider the socio-economic context. An inclusive approach emphasizes the need to engage non-state actors, including businesses, research organizations, non-profit organizations and citizens (Lee and Painter 2015; Hale et al. 2020). For example, engaging people in defining locally relevant mitigation targets and actions has enabled successful transformations in China (Engels 2018), Africa (Göpfert et al. 2019) and Malaysia (Ho et al. 2015). An active research and government collaboration through multiple stakeholder interactions in a large economic corridor in Malaysia led to the development and implementation of a low-carbon blueprint for the region (Ho et al. 2013). Many cities in LDCs and developing countries lack adequate urban infrastructure and housing. An equitable transformation in these cities entails prioritizing energy access and basic services including safe drinking water and sanitation, to meet basic needs of their populations.

8.1.6 Urban carbon footprint

Urban areas concentrate GHG fluxes because of the size of the urban population, the size and nature of the urban economy, the energy and GHGs embodied in the infrastructure (see Glossary for a definition of 'embodied emissions'), and the goods and services imported and exported to and from cities (USGCRP 2018).

8.1.6.1 Urban carbon cycle

In cities, carbon cycles through natural (e.g., vegetation and soils) and managed (e.g., reservoirs and anthropogenic—buildings, transportation) pools. The accumulation of carbon in urban pools, such as buildings or landfills, results from the local or global transfer of carbon-containing energy and raw materials used in the city (Churkina 2008; Pichler et al. 2017; Chen et al. 2020b). Quantitative understanding of these transfers and the resulting emissions and uptake with an urban area is essential for accurate urban carbon accounting (USGCRP 2018). Currently, urban areas are a net source of carbon because they emit more carbon than they uptake. Thus, urban mitigation strategies require a twofold strategy: reducing urban emissions of carbon into the atmosphere, and enhancing uptake of carbon in urban pools (Churkina 2012) (for a broader definition of 'carbon cycle' and related terms such as 'carbon sink,' carbon stock,' 'carbon neutrality,' 'GHG neutrality,' and others, see Glossary).

Burning fossil fuels to generate energy for buildings, transportation, industry, and other sectors is a major source of urban GHG emissions (Gurney et al. 2015). At the same time, most cities do not generate within their boundaries all of the resources they use, such as electricity, gasoline, cement, water, and food needed for local homes and businesses to function (Jacobs 1969), requiring consideration of GHG emissions embodied in supply chains serving cities. Furthermore, urban vegetation, soils, and aquatic systems can both emit or remove carbon from the urban atmosphere and are often heavily managed. For example, urban parks, forests, and street trees actively remove carbon from the atmosphere through growing season photosynthesis. They can become a net source of carbon most often during the dormant season or heat waves. Some of the sequestered carbon can be stored in the biomass of urban trees, soils, and aquatic systems. Urban infrastructures containing cement also uptake carbon through the process of carbonation. The uptake of carbon by urban trees is at least two orders of magnitude faster than by cement-containing infrastructures (Churkina 2012) (see Section 8.4.4, and Figures 8.17 and 8.18).

8.1.6.2 Urban emissions accounting

Urban GHG emissions accounting can determine critical conceptual and quantitative aspects of urban GHG emissions. The accounting framework chosen can therefore predetermine the emissions responsibility, the mitigation options available, and the level of effort required to correctly account for emissions (Afionis et al. 2017).

Two main urban carbon accounting advances have occurred since AR5. The first includes efforts to better understand and clarify how the different urban GHG accounting frameworks that have emerged over the past 15 years are inter-related, require different methodological tools, and reflect differing perspectives on emissions responsibility and quantification effort. The second main advance lies in a series of methodological innovations facilitating practical implementation, emissions verification, and scaling-up of the different GHG accounting approaches. This section provides an overview of the most used GHG urban accounting frameworks followed by a review of the advances since AR5.

Numerous studies have reviewed urban GHG accounting frameworks and methods with somewhat different nomenclatures and categorical divisions (Lin et al. 2015; Lombardi et al. 2017; Chen et al. 2019b; Arioli et al. 2020; Heinonen et al. 2020; Hachaichi and Baouni 2021; Ramaswami et al. 2021). Furthermore, accounting frameworks are reflected in multiple protocols used by urban practitioners (BSI 2013; Fong et al. 2014; ICLEI 2019b). Synthesis of these reviews and protocols, as well as the many individual methodological studies available, point to four general frameworks of urban GHG accounting: (1) territorial accounting (TA); (2) communitywide infrastructure supply chain foot-printing (CIF); and (3 and 4) consumption-based carbon footprint accounting (CBCF) (Wiedmann and Minx 2008). The last, CBCF, can be further divided into accounting with a focus on household or personal consumption—(3) the personal carbon footprint (PCF)—and an approach in which one includes final consumption in an area by all consumers—(4) the areal carbon footprint (ACF) (Heinonen et al. 2020). A number of small variations to these general categories are found in the literature (Lin et al. 2015; Chen et al. 2020a), but these four general frameworks capture the important distinctive (i.e., policy-relevant) features of urban GHG accounting.

All these approaches are foundationally rooted in the concept of urban metabolism that is, the tracking of material and energy flows into, within, and out of cities (Wolman 1965). These frameworks all aim to quantify urban GHG emissions but reflect different perspectives on where the emission responsibility is allocated in addition to how much and which components of the GHG emissions associated with the import and export of good and services to and from a city ('transboundary embedded/embodied GHG emissions') are included in a given urban emissions account. The four frameworks share some common, overlapping GHG emission quantities and their inter-relationships have been defined mathematically (Chavez and Ramaswami 2013).

A key advance since AR5 lies in understanding the different GHG accounting frameworks in terms of what they imply for responsibility—shared or otherwise—and what they imply for the depth and breadth of GHG emission reductions. TA focuses on in-city direct emission of GHGs to the atmosphere (e.g., combustion, net ecosystem exchange, methane – CH_4 – leakage) within a chosen geographic area (Sovacool and Brown 2010; Gurney et al. 2019). CIF connects essential infrastructure use and demand activities in cities with their production, by combining TA emissions with the transboundary supply chain emissions associated with imported electricity, fuels, food, water, building materials, and waste management services used in cities (Ramaswami et al. 2008; Kennedy et al. 2009; Chavez and Ramaswami 2013).

CBCF considers not only the supply-chain-related GHG emissions of key infrastructure, but also emissions associated with all goods and services across a city, often removing emissions associated with goods and services exported from a city (Wiedmann et al. 2016, 2021). The distinction between the PCF and ACF variants of the CBCF are primarily associated with whether the agents responsible for the final demand are confined to only city residents (PCF) or all consumers in a city (ACF), which can include government consumers, capital formation, and other final demand categories (Heinonen et al. 2020).

A recent synthesis of these frameworks in the context of a net zero GHG emissions target suggests that the four frameworks contribute to different aspects of decarbonization policy and can work together to inform the overall process of decarbonization (Ramaswami et al. 2021). Furthermore, the relative magnitude of GHG emissions for a given city resulting from the different frameworks is often a reflection of the city's economic structure as a 'consumer-' or producer city' (Chavez and Ramaswami 2013; Sudmant et al. 2018).

The TA framework is unique in that it can be independently verified through direct measurement of GHGs in the atmosphere, offering a check on the integrity of emission estimates (Lauvaux et al. 2020; Mueller et al. 2021). It is traditionally simpler to estimate by urban practitioners given the lower data requirements, and it can be relevant to policies aimed specifically at energy consumption and mobility activities within city boundaries. However, it will not reflect electricity imported for use in cities or lifecycle emissions associated with in-city consumption of goods and services.

The CIF framework adds to the TA framework by including GHG emissions associated with electricity imports and the lifecycle GHG emissions associated with key infrastructure provisioning activities in cities, serving all homes, businesses, and industries. This widens both the number of emitting categories and the responsibility for those emissions by including infrastructure-related supply chain emissions. The CIF framework enables individual cities to connect communitywide demand for infrastructure and food with their transboundary production, strategically aligning their net zero emissions plans with larger-scale net zero efforts (Ramaswami and Chavez 2013; Ramaswami et al. 2021; Seto et al. 2021).

The PCF version of the CBCF shifts the focus of the consumption and associated supply chain emissions to only household consumption of goods and services (Jones and Kammen 2014). This both reduces the TA emissions considered and the supply chain emissions, excluding all emissions associated with government, capital formation, and exports. The ACF, by contrast, widens the perspective considerably, including the TA and supply chain emissions of all consumers in a city, but often removing emissions associated with exports.

An additional distinction is the ability to sum up accounts from individual cities in a region or country, for example, directly to arrive at a regional or national total. This can only be done for the TA and PCF frameworks. The ACF and CIF frameworks would require adjustment to avoid double-counting emissions (Chen et al. 2020a).

A second major area of advance since AR5 has been in methods to implement, verify and scale up the different GHG foot-printing approaches. Advances have been made in six key areas: (1) advancing urban metabolism accounts integrating stocks and flows, and considering biogenic and fossil-fuel-based emissions (Chen et al. 2020b); (2) improving fine-scale and near-real-time urban use-activity data through new urban data science (Gately et al. 2017; Gurney et al. 2019; Turner et al. 2020; Yadav et al. 2021); (3) using atmospheric monitoring from the ground, aircraft, and satellites combined with inverse modelling to independently quantify TA emissions (Lamb et al. 2016; Lauvaux et al. 2016, 2020; Davis et al. 2017; Mitchell et al. 2018; Sargent et al. 2018; Turnbull et al. 2019; Wu et al. 2020a); (4) improving supply chain and input-output modelling, including the use of physically based input-output models (Wachs and Singh 2018); (5) establishing the global multi-region input-output models (Lenzen et al. 2017; Wiedmann et al. 2021); and (6) generating multi-sector use and supply activity data across all cities in a nation, in a manner where data aggregate consistently across city, province, and national scales (Tong et al. 2021) (see Section 8.3).

8.2 Co-Benefits and trade-offs of urban mitigation strategies

Co-benefits are 'the positive effects that a policy or measure aimed at one objective might have on other objectives, thereby increasing the total benefits to the society or environment' (Matthews et al. 2018). AR5 WGIII Chapter 12 reported a range of co-benefits associated with urban climate change mitigation strategies, including public savings, air quality and associated health benefits, and productivity increases in urban centres (Seto et al. 2014). Since AR5, evidence continues to mount on the co-benefits of urban mitigation. Highlighting co-benefits could make a strong case for driving impactful mitigation action (Bain et al. 2016), especially in developing countries, where development benefits can be the argument for faster implementation (Sethi and Puppim de Oliveira 2018). Through co-benefits, urban areas can couple mitigation, adaptation, and sustainable development while closing infrastructure gaps (Thacker et al. 2019; Kamiya et al. 2020).

The urgency of coupling mitigation and adaptation is emphasized through a special Cross-Working Group Box on 'Cities and Climate Change' (see Section 8.2.3 and Cross-Working Group Box 2). This section further addresses synergies and trade-offs for sustainable development with a focus on linkages with the SDGs and perspectives for economic development, competitiveness, and equity.

8.2.1 Sustainable development

Sustainable development is a wide concept, encompassing socioeconomic and environmental dimensions, envisaging long-term permanence and improvement. Whilst long-term effects are more related to resilience—and hence carry co-benefits and synergies with the mitigation of GHG emissions—some short-term milestones were defined by the post-2015 UN Sustainable Development Agenda SDGs, including a specific goal on climate change (SDG 13) and one on making cities inclusive, safe, resilient and sustainable (SDG 11) (United Nations 2015). The SDGs and related indicators can be an opportunity to improve cities by using science-based decision-making and engaging a diverse set of stakeholders (Simon et al. 2016; Klopp and Petretta 2017; Kutty et al. 2020).

There are multiple ways that development pathways can be shifted towards sustainability (see Section 4.3.3, Cross-Chapter Box 5 in Chapter 4, Chapter 17, and Figure 17.1). Urban areas can work to redirect development pathways towards sustainability while increasing co-benefits for urban inhabitants. Figure 8.4 indicates that mitigation options for urban systems can provide synergistic linkages across a wide range of SDGs, and some cases where linkages can produce both synergies and trade-offs. While linkages are based on context and the scale of implementation, synergies can be most significant when urban areas pursue integrated approaches where one mitigation option supports the other (see also Sections 8.4 and 8.6).

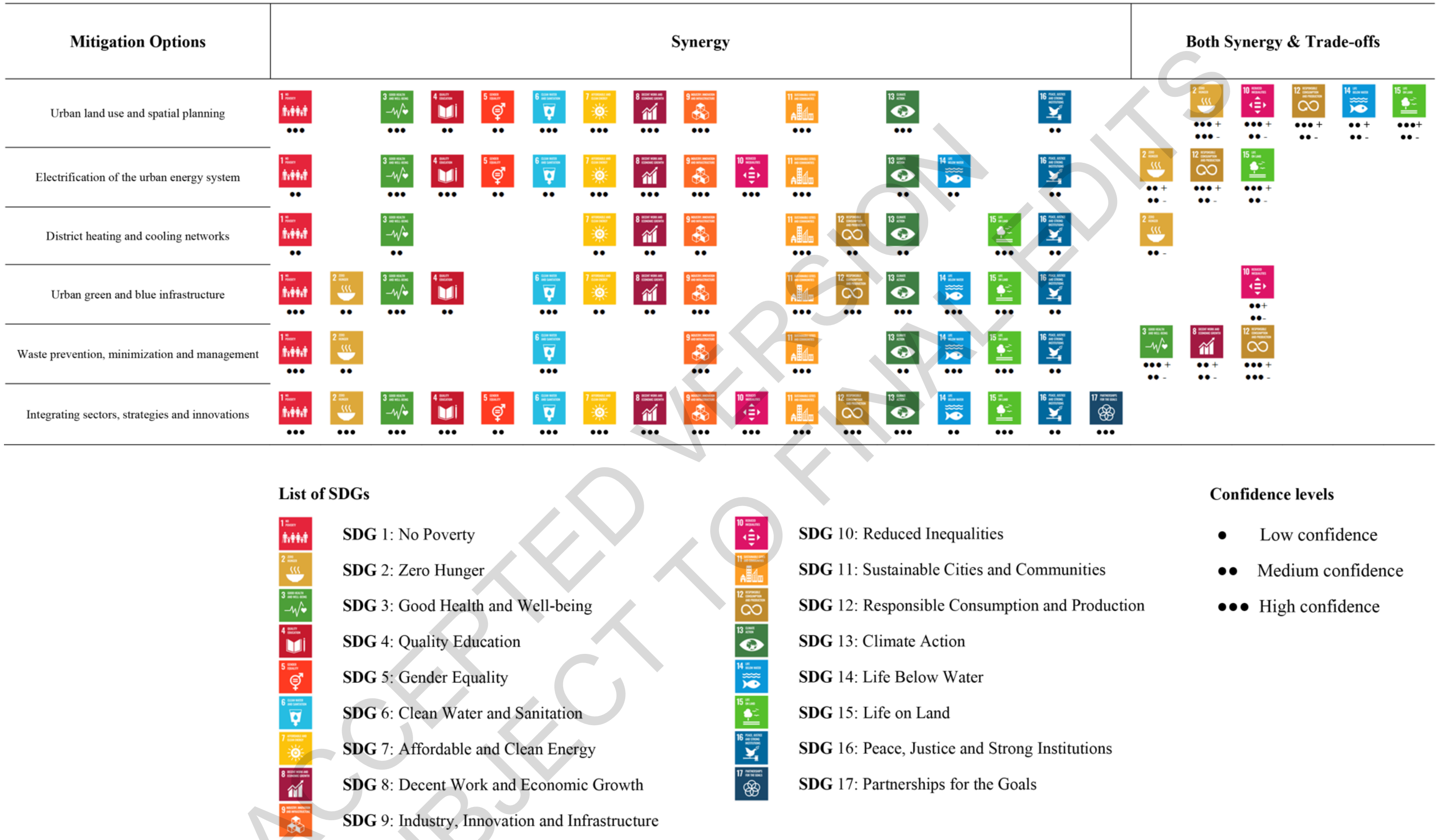

Figure 8.4 Co-benefits of urban mitigation actions.

The first column lists urban mitigation options. The second column indicates synergies with the SDGs. The third column indicates both synergies and/or trade-offs. The dots represent confidence levels with the number of dots representing levels from low to high. In the last column, confidence levels for synergies and/or trade-offs are provided separately. A plus sign (+) represents synergy and a minus sign (-) represents a trade-off. Supplementary Material SM8.1 provides 64 references and extends the SDG mappings that are provided in Thacker et al. (2019) and Fuso Nerini et al. (2018). Please see Supplementary Material Table 17.1 for details and Annex II for the methodology of the SDG assessment.

Figure 8.4 summarizes an evaluation of the synergies and/or trade-offs with the SDGs for the mitigation options for urban systems based on Supplementary Material (SM) 8.1 (SM8.1). The evaluations depend on the specific urban context with synergies and/or trade-offs being more significant in certain contexts than others. Urban mitigation with a view of the SDGs can support shifting pathways of urbanization towards greater sustainability. The feasibility of urban mitigation options is also malleable and can increase with more 'enabling conditions' (see Glossary), provided, perhaps, though institutional (i.e., financial or governmental) support (see Section 8.5). Strengthened institutional capacity that supports the coordination of mitigation options can increase linkages with the SDGs and their synergies. For example, urban land use and spatial planning for walkable and co-located densities together with electrification of the urban energy system can hold more benefits for the SDGs than any one of the mitigation options alone (see Sections 8.4.2.2, 8.4.3.1, and 8.6).

Evidence on the co-benefits of urban mitigation measures for human health has increased significantly since AR5, especially through the use of health impact assessments, where energy savings and cleaner energy supply structures based on measures for urban planning, heating, and transport have reduced CO_2, nitrogen oxides (NO_x), and coarse particulate matter (PM_{10}) emissions (Diallo et al. 2016). Some measures, especially those related to land-use planning and transportation, have also increased opportunities for physical activity for improved health (Diallo et al. 2016). In developing countries, the co-benefits approach has been effective in justifying climate change mitigation actions at the local level (Puppim de Oliveira and Doll 2016). Mixed-use compact development with sufficient land use diversity can have a positive influence on urban productivity (see Section 8.4.2). Conversely, urban spatial structures that increase walking distances and produce car dependency have negative impacts on urban productivity considering congestion as well as energy costs (Salat et al. 2017).

There is increasing evidence that climate mitigation measures can lower health risks that are related to energy poverty, especially among vulnerable groups such as the elderly and in informal settlements (Monforti-Ferrario et al. 2018). Measures such as renewable energy-based electrification of the energy system not only reduce outdoor air pollution, but also enhance indoor air quality by promoting smoke-free heating and cooking in buildings (Kjellstrom and McMichael 2013). The environmental and ecological benefits of electrification of the urban energy system include improved air quality based on a shift to non-polluting energy sources (Jacobson et al. 2018; Ajanovic and Haas 2019; Bagheri et al. 2019; Gai et al. 2020). Across 74 metropolitan areas around the world, an estimated 408,270 lives per year are saved due to air quality improvements that stem from a move to 100% renewable energy (Jacobson et al. 2020). Other studies indicate that there is potential to reduce premature mortality by up to 7,000 people in 53 towns and cities, to create 93,000 new jobs, and to lower global climate costs and personal energy costs, through renewable energy transformations (Jacobson et al. 2018).

Across 146 signatories of a city climate network, local energy-savings measures led to 6,596 avoided premature deaths and 68,476 years of life saved due to improved air quality (Monforti-Ferrario et al. 2018). Better air quality further reinforces the health co-benefits of climate mitigation measures based on walking and bicycling since evidence suggests that increased physical activity in urban outdoor settings with low levels of black carbon improves lung function (Laeremans et al. 2018). Physical activity can also be fostered through urban design measures and policies that promote the development of ample and well-connected parks and open spaces, and can lead to physical and mental health benefits (Kabisch et al. 2016) (see Section 8.4.4 and Figure 8.18).

Cities in India, Indonesia, Vietnam, and Thailand show that reducing emissions from major sources (e.g., transport, residential burning, biomass open burning and industry) could bring substantial co-benefits of avoided deaths from reduced $PM_{2.5}$ (fine inhalable particulates) emissions and radiative forcing from black carbon (Pathak and Shukla 2016; Dhar et al. 2017; Permadi et al. 2017; Karlsson et al. 2020), reduced noise, and reduced traffic injuries (Kwan and Hashim 2016). Compact city policies and interventions that support a modal shift away from private motor vehicles towards walking, cycling, and low-emission public transport delivers significant public health benefits (Creutzig 2016; Ürge-Vorsatz et al. 2018). Trade-offs associated with compact development include the marginal health costs of transport air pollution (Lohrey and Creutzig 2016) and stress from traffic noise (Gruebner et al. 2017) (Section 8.4.2.2).

Urban green and blue infrastructure—a subset of nature-based solutions (NBS)—acts as both climate mitigation and adaptation measures by reducing heat stress (Kim and Coseo 2018; Privitera and La Rosa 2018; Herath et al. 2021) improving air quality, reducing noise (Scholz et al. 2018; De la Sota et al. 2019), improving urban biodiversity (Hall et al. 2017b), and enhancing well-being, including contributions to local development (Lwasa et al. 2015). Health benefits from urban forestry and green infrastructure include reduced cardiovascular morbidity, improved mental health (van den Bosch and Ode Sang 2017; Vujcic et al. 2017; Al-Kindi et al. 2020; Sharifi et al. 2021), raised birth weight (Dzhambov et al. 2014), and increased life expectancy (Jonker et al. 2014). Urban agriculture, including urban orchards, roof-top gardens, and vertical farming contribute to enhancing food security and fostering healthier diets (Cole et al. 2018; Petit-Boix and Apul 2018; De la Sota et al. 2019) (see Section 8.4.4, Figure 8.18, and Box 8.2).

8.2.2 Economic development, competitiveness, and equity

Sustainable management of urban ecosystems entails addressing economic growth, equity, and good governance. In total, 102 SDG targets (99 synergies and 51 trade-offs) are identified with published evidence of relationships with urban ecosystems—out of the 169 in the 2030 Agenda (Maes et al. 2019). The targets require action in relation to urban ecosystem management, environmental improvements, equality related to basic services, long-term economic growth, economic savings, stronger governance, and policy development at multiple scales.

Mitigation measures related to different sectors can provide co-benefits and reduce social inequities. Transport-related measures, such as transportation demand management, transit-oriented development (TOD), and promotion of active transport modes provide economic co-benefits through, for example, reducing healthcare costs linked with pollution and cardiovascular diseases, improving labour productivity, and decreasing congestion costs (including waste of time and money) (Sharifi et al. 2021). As a case-in-point, data from cities such as Bangkok, Kuala Lumpur, Jakarta, Manila, Beijing, Mexico City, Dakar, and Buenos Aires indicate that economic costs of congestion account for a considerable share of their gross domestic product (GDP) (ranging from 0.7% to 15.0%) (Dulal 2017) (see Section 8.4.2).

Since policy interventions can result in negative impacts or trade-offs with other objectives, fostering accessibility, equity, and inclusivity for disadvantaged groups is essential (Viguié and Hallegatte 2012; Sharifi 2020; Pörtner et al. 2021). Anti-sprawl policies that aim to increase density or introduction of large green areas in cities could increase property prices, resulting in trade-offs with affordable housing and pushing urban poor further away from cities (Reckien et al. 2017; Alves et al. 2019). Deliberate strategies can improve access of low income populations to jobs, and gender-responsive transport systems that can enhance women's mobility and financial independence (Viguié and Hallegatte 2012; Lecompte and Juan Pablo 2017; Reckien et al. 2017; Priya Uteng and Turner 2019).

Low-carbon urban development that triggers economic decoupling and involves capacity building measures could have a positive impact on employment and local competitiveness (Dodman 2009; Kalmykova et al. 2015; Chen et al. 2018b; García-Gusano et al. 2018; Hu et al. 2018; Shen et al. 2018). Sustainable and low-carbon urban development that integrates issues of equity, inclusivity, and affordability while safeguarding urban livelihoods, providing access to basic services, lowering energy bills, addressing energy poverty, and improving public health, can also improve the distributional effects of existing and future urbanization (Friend et al. 2016; Claude et al. 2017; Colenbrander et al. 2017; Ma et al. 2018; Mrówczyńska et al. 2018; Pukšec et al. 2018; Wiktorowicz et al. 2018; Ramaswami 2020).

Depending on the context, green and blue infrastructure can also offer considerable economic co-benefits. For example, green roofs and facades and other urban greening efforts such as urban agriculture and greening streets can improve microclimatic conditions and enhance thermal comfort, thereby reducing utility and healthcare costs. The presence of green and blue infrastructure may also increase the economic values of nearby properties (Votsis 2017; Alves et al. 2019) (see Section 8.4.4 and Figure 8.18).

Studies in the UK show that beneficiaries are willing to pay (WTP) an additional fee (up to 2% more in monthly rent) for proximity to green and blue infrastructure, with the WTP varying depending on the size and nature of the green space (Mell et al. 2013, 2016). Urban agriculture can not only reduce household food expenditure, but also provide additional sources of revenue for the city (Ayerakwa 2017; Alves et al. 2019). Based on the assessed literature, there is *high agreement* on the economic co-benefits of green and blue infrastructure, but supporting evidence is still limited (see Section 8.7).

Implementing waste management and wastewater recycling measures can provide additional sources of income for citizens and local authorities. Wastewater recycling can minimize the costs associated with the renewal of centralized wastewater treatment plants (Bernstad Saraiva Schott and Cánovas 2015; Gharfalkar et al. 2015; Gonzalez-Valencia et al. 2016; Herrero and Vilella 2018; Matsuda et al. 2018; Nisbet et al. 2019). Waste management and wastewater recycling is also a pathway for inclusion of the informal sector into the urban economy with *high agreement* and *medium evidence* (Sharifi 2021). Additionally, authorities can sell energy generated from wastewater recycling to compensate for the wastewater management costs (Colenbrander et al. 2017; Gondhalekar and Ramsauer 2017). Another measure that contributes to reducing household costs is the promotion of behavioural measures such as dietary changes that can decrease the demand for costly food sources and reduce healthcare costs through promoting healthy diets (Hoppe et al. 2016) (see Sections 8.4.5 and 8.4.6).

In addition to cost savings, various measures such as stormwater management and urban greening can enhance social equity and environmental justice. For example, the thermal comfort benefits provided by green and blue infrastructure and passive design measures can address issues related to energy poverty and unaffordability of expensive air conditioning systems for some social groups (Sharma et al. 2018; He et al. 2019). To achieve such benefits, however, the costs of integrating green and blue infrastructure and passive design measures into building design would need to be minimized. Another example is the flood mitigation benefits of stormwater management measures that can reduce impacts on urban poor who often reside in flood-prone and low-lying areas of cities (Adegun 2017; He et al. 2019). Generally, the urban poor are expected to be disproportionately affected by climate change impacts. Carefully designed measures that reduce such disproportionate impacts by involving experts, authorities and citizens would enhance social equity (Pandey et al. 2018; He et al. 2019; Mulligan et al. 2020).

8.2.3 Coupling mitigation and adaptation

There are numerous synergies that come from coupling urban adaptation and mitigation. A number of studies have developed methods to assess the synergies between mitigation and adaptation strategies, as well as their co-benefits (Solecki et al. 2015; Buonocore et al. 2016; Chang et al. 2017; Helgenberger and Jänicke 2017). Co-benefits occur when implementing mitigation (or adaptation) measures that have positive effects on adaptation (or mitigation) (Sharifi 2021). In contrast, the trade-offs emerge when measures aimed at improving mitigation (adaptation) undermine the ability to pursue adaptation (mitigation) targets (Sharifi 2020). The magnitude of such co-benefits and trade-offs may vary depending on various factors. A systematic review of over 50 climate change articles provides evidence that mitigation can contribute to resilience—especially to temperature changes and flooding—with varying magnitudes depending on factors, such as the type of mitigation measure and the scale of implementation (Sharifi 2019).

Measures from different sectors that can provide both mitigation and adaptation benefits involve urban planning (see Section 8.4.2), buildings (Sections 8.4.3.2 and 8.4.4), energy (Section 8.4.3), green and blue infrastructure (Section 8.4.4), transportation (Section 8.4.2), socio-behavioural aspects (Section 8.4.5), urban governance (Section 8.5), waste (Section 8.4.5.2), and water (Section 8.4.6). In addition to their energy-saving and carbon-sequestration benefits, many measures can also enhance adaptation to climate threats, such as extreme heat, energy shocks, floods, and droughts (Sharifi 2021). Existing evidence is mainly related to urban green infrastructure, urban planning, transportation, and buildings. There has been more emphasis on the potential co-benefits of measures, such as proper levels of density, building energy efficiency, distributed and decentralized energy infrastructure, green roofs and facades, and public/active transport modes. Renewable-based distributed and decentralized energy systems improve resilience to energy shocks and can enhance adaptation to water stress considering the water-energy nexus. By further investment on these measures, planners and decision makers can ensure enhancing achievement of mitigation/adaptation co-benefits at the urban level (Sharifi 2021).

As for trade-offs, some mitigation efforts may increase exposure to stressors such as flooding and the urban heat island (UHI) effect (see Glossary), thereby reducing the adaptive capacity of citizens. For instance, in some contexts, high-density areas that lack adequate provision of green and open spaces may intensify the UHI effect (Pierer and Creutzig 2019; Xu et al. 2019). There are also concerns that some mitigation efforts may diminish adaptive capacity of urban poor and marginalized groups through increasing costs of urban services and/or eroding livelihood options. Environmental policies designed to meet mitigation targets through phasing out old vehicles may erode livelihood options of poor households, thereby decreasing their adaptive capacity (Colenbrander et al. 2017). Ambitious mitigation and adaptation plans could benefit private corporate interests resulting in adverse effects on the urban poor (Chu et al. 2018; Mehta et al. 2019).

Urban green and blue infrastructure such as urban trees, greenspaces, and urban waterways can sequester carbon and reduce energy demand, and provide adaptation co-benefits by mitigating the UHI effect (Berry et al. 2015; Wamsler and Pauleit 2016; WCRP 2019) (see Section 8.4.4, Figure 8.18, and Box 8.2).

START CROSS-WORKING GROUP BOX 2 HERE

Cross-Working Group Box in Working Group II, Chapter 6

Cross-Working Group Box 2: Cities and Climate Change

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Introduction

This Cross-Working Group Box on Cities and Climate Change responds to the critical role of urbanization as a mega-trend impacting climate adaptation and mitigation. Issues associated with cities and urbanization are covered in substantial depth within all three Working Groups (including WGI Box TS.14, WGII Chapter 6 'Cities, settlements and key infrastructure,' WGII regional chapters, WGII Cross-Chapter Paper 'Cities and settlements by the sea', and WGIII Chapter 8 'Urban systems and other settlements'). This Box highlights key findings from WGII and III and substantial gaps in literature where more research is urgently needed relating to policy action in cities. It describes methods of addressing mitigation and adaptation in an integrated way across sectors and cities to advance sustainable development and equity outcomes and assesses the governance and finance solutions required to support climate resilient responses.

Urbanization: A megatrend driving global climate risk and potential for low-carbon and resilient futures

Severe weather events, exacerbated by anthropogenic emissions, are already having devastating impacts on people who live in urban areas, on the infrastructure that supports these communities, as well as people living in distant places (*high confidence*) (Cai et al. 2019; Folke et al. 2021). Between 2000 and 2015, the global population in locations that were affected by floods grew by 58–86 million (Tellman et al. 2021). The direct economic costs of all extreme events reached USD 210-268 billion in 2020 (Aon 2021; Munich RE 2021; WMO 2021) or about USD 0.7 billion per day; this figure does not include knock-on costs in supply chains (Kii 2020) or lost days of work, implying that the actual economic costs could be far higher. Depending on RCP, between half (RCP2.6) and three-quarters (RCP8.5) of the global population could be exposed to periods of life-threatening climatic conditions arising from coupled impacts of extreme heat and humidity by 2100 (Mora et al. 2017; Huang et al. 2019) (see WGII Section 6.2.2.1, WGII Figure 6.3, and WGIII Sections 8.2 and 8.3.4).

Urban systems are now global, as evidenced by the interdependencies between infrastructure, services, and networks driven by urban production and consumption; remittance flows and investments reach into rural places shaping natural resource use far from the city and bring risk to the city when these places are impacted by climate change (see WGIII Sections 8.4 and WGIII Figure 8.15). This megatrend (Kourtit et al. 2015) amplifies as well as shapes the potential impacts of climate events and integrates the aims and approaches for delivering mitigation, adaptation, and sustainable development (*medium evidence, high agreement*) (Dawson et al. 2018; Tsavdaroglou et al. 2018; Zscheischler et al. 2018). For cities facing flood damage, wide-ranging impacts have been recorded on other urban areas near and far (Carter et al. 2021; Simpson et al. 2021) as production and trade is disrupted (Shughrue et al. 2020). In the absence of integrated mitigation and adaptation across and between infrastructure systems and local places, impacts that bring urban economies to a standstill can extend into supply chains and across energy networks causing power outages.

Urban settlements contribute to climate change, generating about 70% of global CO_2-eq emissions (*high confidence*) (see WGI Box TS.14, WGII Sections 6.1 and 6.2, and WGIII Section 8.3). This global impact feeds back to cities through the exposure of infrastructure, people, and business to the impacts of climate-related hazards. Particularly in larger cities, this climate feedback is exacerbated by local choices in urban design, land use, building design, and human behaviour (Viguié et al. 2020) that shape local environmental conditions. Both the local and global combine to increase hazardousness. Certain configurations of urban form and their elements can add up to 2°C to warming; concretisation of open space can increase run-off, and building height and orientation influences wind direction and strength (see WGII Section 6.3 and WGIII Section 8.4.2).

Designing for resilient and low-carbon cities today is far easier than retrofitting for risk reduction tomorrow. As urbanization unfolds, its legacy continues to be the locking-in of emissions and vulnerabilities (*high confidence*) (Seto et al. 2016; Ürge-Vorsatz et al. 2018) (see WGIII Section 8.4 and Figure 8.15). Retrofitting, disaster reconstruction, and urban regeneration programmes offer scope for strategic direction changes to low-carbon and high-resilience urban form and function, so long as they are inclusive in design and implementation. Rapid urban growth means new investment, new buildings and infrastructure, new demands for energy and transport and new questions about what a healthy and fulfilling urban life can be. The USD 90 trillion expected to be invested in new urban development by 2030 (NCE 2018) is a global opportunity to place adaptation and mitigation directly into urban infrastructure and planning, as well as to consider social policy including education, healthcare, and environmental management (Ürge-Vorsatz et al. 2018). If this opportunity is missed, and business-as-usual urbanization persists, social and physical vulnerability will become much more challenging to address.

The benefits of actions taken to reduce GHG emissions and climate stressors diminish with delayed action, indicating the necessity for rapid responses. Delaying the same actions for increasing the resilience of infrastructure from 2020 to 2030 is estimated to have a median cost of at least USD 1 trillion (Hallegatte et al. 2019) while also missing the carbon emissions reductions required in the narrowing window of opportunity to limit global warming to 1.5°C (WGI). In contrast, taking integrated actions towards mitigation, adaptation, and sustainable development will provide multiple benefits for the health and well-being of urban inhabitants and avoid stranded assets (see WGII Section 6.3, WGII Chapter 17, Cross-Chapter Box FEASIBILITY in WGII Chapter 18, WGIII Chapter 5, and WGIII Section 8.2).

The policy-action gap: urban low-carbon and climate resilient development

Cities are critical places to realize both adaptation and mitigation actions simultaneously with potential co-benefits that extend far beyond cities (*medium evidence high agreement*) (Göpfert et al. 2019; Grafakos et al. 2020). Given rapid changes in the built environment, transforming the use of materials and the land intensiveness of urban development, including in many parts of the Global South, will be critical in the next decades, as well as mainstreaming low-carbon development principles in new urban development in all regions. Much of this development will be self-built and 'informal'—and new modes of governance and planning will be required to engage with this. Integrating mitigation and adaptation now rather than later, through reshaping patterns of urban development and associated decision-making processes, is a prerequisite for attaining resilient and zero-carbon cities (see WGIII Sections 8.4 and 8.6, and WGIII Figure 8.21).

While more cities have developed plans for climate adaptation and mitigation since AR5, many remain to be implemented (*limited evidence*, *high agreement*) (Araos et al. 2017; Aguiar et al. 2018; Olazabal and Ruiz De Gopegui 2021). A review of local climate mitigation and adaptation plans across 885 urban areas of the European Union suggests mitigation plans are more common than adaptation plans—and that city size, national legislation, and international networks can influence the development of local climate and adaptation plans with an estimated 80% of those cities with above 500,000 inhabitants having a mitigation and/or an adaptation plan (Reckien et al. 2018).

Integrated approaches to tackle common drivers of emissions and cascading risks provide the basis for strengthening synergies across mitigation and adaptation, and help manage possible trade-offs with sustainable development (*limited evidence, medium agreement*) (Grafakos et al. 2019; Landauer et al. 2019; Pierer and Creutzig 2019). An analysis of 315 local authority emission reduction plans reveals that the most common policies cover municipal assets and structures (Palermo et al. 2020a). Estimates of emission reductions by non-state and sub-state actors in ten high-emitting economies projected GHG emissions in 2030 would be 1.2–2.0 $GtCO_2$-eq per year or 3.8–5.5% lower compared to scenario projections for current national policies (31.6–36.8 $GtCO_2$-eq per year) if the policies are fully implemented and do not change the pace of action elsewhere (Kuramochi et al. 2020). The value of integrating mitigation and adaptation is underscored in the opportunities for decarbonizing existing urban areas, and investing in social, ecological, and technological infrastructure resilience (WGII Section 6.4). Integrating mitigation and adaption is challenging (Landauer et al. 2019) but can provide multiple benefits for the health and well-being of urban inhabitants (Sharifi 2021) (See WGIII Section 8.2.3).

Effective climate strategies combine mitigation and adaptation responses, including through linking adaptive urban land use with GHG emission reductions (*medium evidence*, *high agreement*) (Xu et al. 2019; Patterson 2021). For example, urban green and blue infrastructure can provide co-benefits for mitigation and adaptation (Ürge-Vorsatz et al. 2018) and is an important entry point for integrating adaptation and mitigation at the urban level (Frantzeskaki et al. 2019) (see WGIII Section 8.4.4 and WGIII Figure 8.18). Grey and physical infrastructure, such as sea defences can immediately reduce risk, but also transfer risk and limit future options. Social policy interventions including social safety nets provide financial security for the most at-risk and can manage vulnerability determined by specific hazards or independently.

Hazard-independent mechanisms for vulnerability reduction—such as population-wide social security—provide resilience in the face of unanticipated cascading impacts or surprise and novel climate-related hazard exposure. Social interventions can also support or be led by ambitions to reach the SDGs (Archer 2016). Climate-resilient development invites planners to develop interventions and monitor the effectiveness of outcomes beyond individual projects and across wider remits that consider sustainable development. Curbing the emission impacts of urban activities to reach net zero emissions in the next decades, while improving the resilience of urban areas, necessitates an integrated response now.

Key gaps in knowledge include: urban-enabling environments; the role of smaller settlements, low-income communities, and informal settlements, as well as those in rental housing spread across the city; and the ways in which actions to reduce supply chain risk can be supported to accelerate equitable and sustainable adaptation in the face of financial and governance constraints (Birkmann et al. 2016; Shi et al. 2016; Rosenzweig et al. 2018; Dulal 2019).

Enabling action

Innovative governance and finance solutions are required to manage complex and interconnected risks across essential key infrastructures, networks, and services, as well as to meet basic human needs in urban areas (*medium confidence*) (Colenbrander et al. 2018a; Moser et al. 2019). There are many examples of ‘ready-to-use’ policy tools, technologies, and practical interventions for policymakers seeking to act on adaptation and mitigation (Bisaro and Hinkel 2018; Keenan et al. 2019; Chirambo 2021) (see WGIII Section 8.5.4). Tax and fiscal incentives for businesses and individuals can help support city-wide behaviour change towards low-carbon and risk reducing choices. Change can start where governments have most control—often in public sector institutions and investment—but the challenge ahead requires partnership with private sector and community actors acting at scale and with accountability. Urban climate governance and finance needs to address urban inequalities at the forefront if the urban opportunity is to realize the ambition of the SDGs.

Increasing the pace of investments will put pressure on governance capability, transparency, and accountability of decision-making (*medium confidence*) (see WGII Section 6.4.5). Urban climate action that actively includes local actors is more likely to avoid unintended, negative maladaptive impacts and mobilize a wide range of local capacities. In the long run, this is also more likely to carry public support, even if some experiments and investments do not deliver the intended social benefits. Legislation, technical capacity, and governance capability is required to be able to absorb additional finance.

In recent years, about USD 384 billion of climate finance has been invested in urban areas per year. This remains at about 10% of the annual climate finance that would be necessary for low-carbon and resilient urban development at a global scale (Negreiros et al. 2021). Rapid deployment of funds to stimulate economies in the recovery from COVID-19 has highlighted the pitfalls of funding expansion ahead of policy innovation and capacity building. The result can be an intensification of existing carbon-intensive urban forms—exactly the kinds of ‘carbon lock-in’ (see WGIII Glossary and WGIII Section

8.4.1) that have contributed to risk creation and its concentration amongst those with little public voice or economic power.

Iterative and experimental approaches to climate adaptation and mitigation decision-making grounded in data and co-generated in partnership with communities can advance low-carbon climate resilience (*medium evidence, high confidence*) (Culwick et al. 2019; Caldarice et al. 2021; van der Heijden and Hong 2021). Conditions of complexity, uncertainty, and constrained resources require innovative solutions that are both adaptive and anticipatory. Complex interactions among multiple agents in times of uncertainty makes decision-making about social, economic, governance, and infrastructure choices challenging and can lead decision-makers to postpone action. This is the case for those balancing household budgets, residential investment portfolios, and city-wide policy responsibilities. Living with climate change requires changes to business-as-usual design-making. Co-design and collaboration with communities through iterative policy experimentation can point the way towards climate resilient development pathways (Ataöv and Peker 2021). Key to successful learning is transparency in policymaking, inclusive policy processes, and robust local modelling, monitoring, and evaluation, which are not yet widely undertaken (Sanchez Rodriguez et al. 2018; Ford et al. 2019).

The diversity of cities' experiences of climate mitigation and adaptation strategies brings an advantage for those city governments and other actors willing to 'learn together' (*limited evidence, high confidence*) (Bellinson and Chu 2019; Haupt and Coppola 2019). While contexts are varied, policy options are often similar enough for the sharing of experiments and policy champions. Sharing expertise can build on existing regional and global networks, many of which have already placed knowledge, learning, and capacity-building at the centre of their agendas. Learning from innovative forms of governance and financial investment, as well as strengthening coproduction of policy through inclusive access to knowledge and resources, can help address mismatches in local capacities and strengthen wider SDGs and COVID-19 recovery agendas (*limited evidence, medium agreement*). Perceptions of risk can greatly influence the reallocation of capital and shift financial resources (Battiston et al. 2021). Coupling mitigation and adaptation in an integrated approach offers opportunities to enhance efficiency, increases the coherence of urban climate action, generates cost savings, and provides opportunities to reinvest the savings into new climate action projects to make all urban areas and regions more resilient.

Local governments play an important role in driving climate action across mitigation and adaptation as managers of assets, regulators, mobilizers, and catalysts of action, but few cities are undertaking transformative climate adaptation or mitigation actions (*limited evidence, medium confidence*) (Heikkinen et al. 2019). Local actors are providers of infrastructure and services, regulators of zoning, and can be conveners and champions of an integrated approach for mitigation and adaptation at multiple levels (*limited evidence high confidence*). New opportunities in governance and finance can enable cities to pool resources together and aggregate interventions to innovate ways of mobilizing urban climate finance at scale (Colenbrander et al. 2019; Simpson et al. 2019; White and Wahba 2019). However, research increasingly points towards the difficulties faced during the implementation of climate financing in situ, such as the fragmentation of structures of governance capable of managing large investments effectively (Mohammed et al. 2019) (see WGIII Section 8.5 and WGIII Chapter 13).

Scaling up transformative place-based action for both adaptation and mitigation requires enabling conditions, including land-based financing, intermediaries, and local partnerships (*medium evidence, high agreement*) (Chu et al. 2019; Chaudhuri, 2020) supported by a new generation of big data approaches. Governance structures that combine actors working at different levels with a different mix of tools are effective in addressing challenges related to implementation of integrated action while cross-sectoral coordination is necessary (Singh et al. 2020). Joint institutionalization of mitigation and adaptation in local governance structures can also enable integrated action (Göpfert et al. 2020; Hurlimann et al. 2021). However, the proportion of international finance that reaches local recipients remains low, despite the repeated focus of climate policy on place-based adaptation and mitigation

(Manuamorn et al. 2020). Green financing instruments that enable local climate action without exacerbating current forms of inequality can jointly address mitigation, adaptation, and sustainable development. Climate finance that also reaches beyond larger non-state enterprises (e.g., small and medium-sized enterprises, local communities, non-governmental organizations—NGOs, etc.), and is inclusive in responding to the needs of all urban inhabitants (e.g., disabled individuals, citizens of different races or ethnicities, etc.) is essential for inclusive and resilient urban development (Colenbrander et al. 2019; Gabaldón-Estevan et al. 2019; Frenova 2021). Developing networks that can exert climate action at scale is another priority for climate finance.

The urban megatrend is an opportunity to transition global society. Enabling urban governance to avert cascading risk and achieve low-carbon, resilient development will involve the coproduction of policy and planning, rapid implementation and greater cross sector coordination, and monitoring and evaluation (*limited evidence, medium agreement*) (Di Giulio et al. 2018; Grafakos et al. 2019). New constellations of responsible actors are required to manage hybrid local-city or cross-city risk management and decarbonization initiatives (*limited evidence, medium agreement*). These may increasingly benefit from linkages across more urban and more rural space as recognition of cascading and systemic risk brings recognition of supply chains, remittance flows, and migration trends as vectors of risk and resilience. Urban governance will be better prepared in planning, prioritizing, and financing the kind of measures that can reduce GHG emissions and improve resilience at scale when they consider a view of cascading risks and carbon lock-ins globally, while also acting locally to address local limitations and capacities, including the needs and priorities of urban citizens (Colenbrander et al. 2018a; Rodrigues 2019).

END CROSS-WORKING GROUP BOX 2 HERE

8.3 Urban systems and GHG emissions

This section assesses trends in urban land use, the built environment, and urban GHG emissions, as well as forecasts for urban land use and emissions under certain scenarios to 2050 or 2100. These trends and scenarios hold implications for optimizing the approaches to urban climate change mitigation discussed in Section 8.4 and 8.6.

8.3.1 Trends in urban land use and the built environment

Urban land use is one of the most intensive human impacts on the planet (Pouyat et al. 2007; Grimm et al. 2008). Urban land expansion to accommodate a growing urban population has resulted in the conversion of agricultural land (Pandey et al. 2018; Liu et al. 2019), deforestation (van Vliet 2019), habitat fragmentation (Liu et al. 2016b), biodiversity loss (McDonald et al. 2018, 2020), and the modification of urban temperatures and regional precipitation patterns (Li et al. 2017; Krayenhoff et al. 2018; Liu and Niyogi 2019; Zhang et al. 2019).

Urban land use and the associated built environment and infrastructure shape urban GHG emissions through the demand for materials and the ensuing energy-consuming behaviours. In particular, the structure of the built environment (i.e., its density, form, and extent) have long-lasting influence on urban GHG emissions, especially those from transport and building energy use, as well as the embodied emissions of the urban infrastructure (Butler et al. 2014; Salat et al. 2014; Ramaswami et al. 2016; Seto et al. 2016; d'Amour et al. 2017). Thus, understanding trends in urban land use is essential for assessing energy behaviour in cities as well as long-term mitigation potential (see Sections 8.4 and 8.6, and Figure 8.21).

This section draws on the literature to discuss three key trends in urban land expansion, and how those relate to GHG emissions.

First, urban land areas are growing rapidly all around the world. From 1975 to 2015, urban settlements expanded in size approximately 2.5 times, accounting for 7.6% of the global land area (Pesaresi et al. 2016). Nearly 70% of the total urban expansion between 1992 and 2015 occurred in Asia and North America (Liu et al. 2020a). By 2015, the extent of urban and built-up lands was between 0.5–0.6% of the total 130 Mkm^2 global ice-free land use, taking up other uses such as fertile cropland and natural ecosystems.

Second, as Figure 8.5 shows, urban population densities are declining, with significant implications for GHG emissions. From 1970 to 2010, while the global urban settlement extent doubled in size (Pesaresi et al. 2016), most regions (grouped by the WGIII AR6 10-region aggregation) exhibited a trend of decreasing urban population densities suggesting expansive urban growth patterns. Urban population densities have consistently declined in the Asia-Pacific Developed, Europe, North America, and Southern Asia regions, across all city sizes. North America consistently had the lowest urban population densities. Notably, the Middle East region appears to be the only region exhibiting an overall increasing trend across all city-size groups, while Latin America and Caribbean appears to be relatively stable for all city sizes. While the larger cities in Africa and South-East Asia and Developing Pacific exhibit slightly stable urban population densities, the small- and medium-sized cities in those regions trend toward lower urban population densities. In large urban centres of Eastern Asia and North America, rapid decreases in earlier decades seem to have tapered. Compared to larger cities, small-medium urban areas with populations of less than 2 million have more declines in urban population densities and higher rates of urban land expansion (Güneralp et al. 2020).

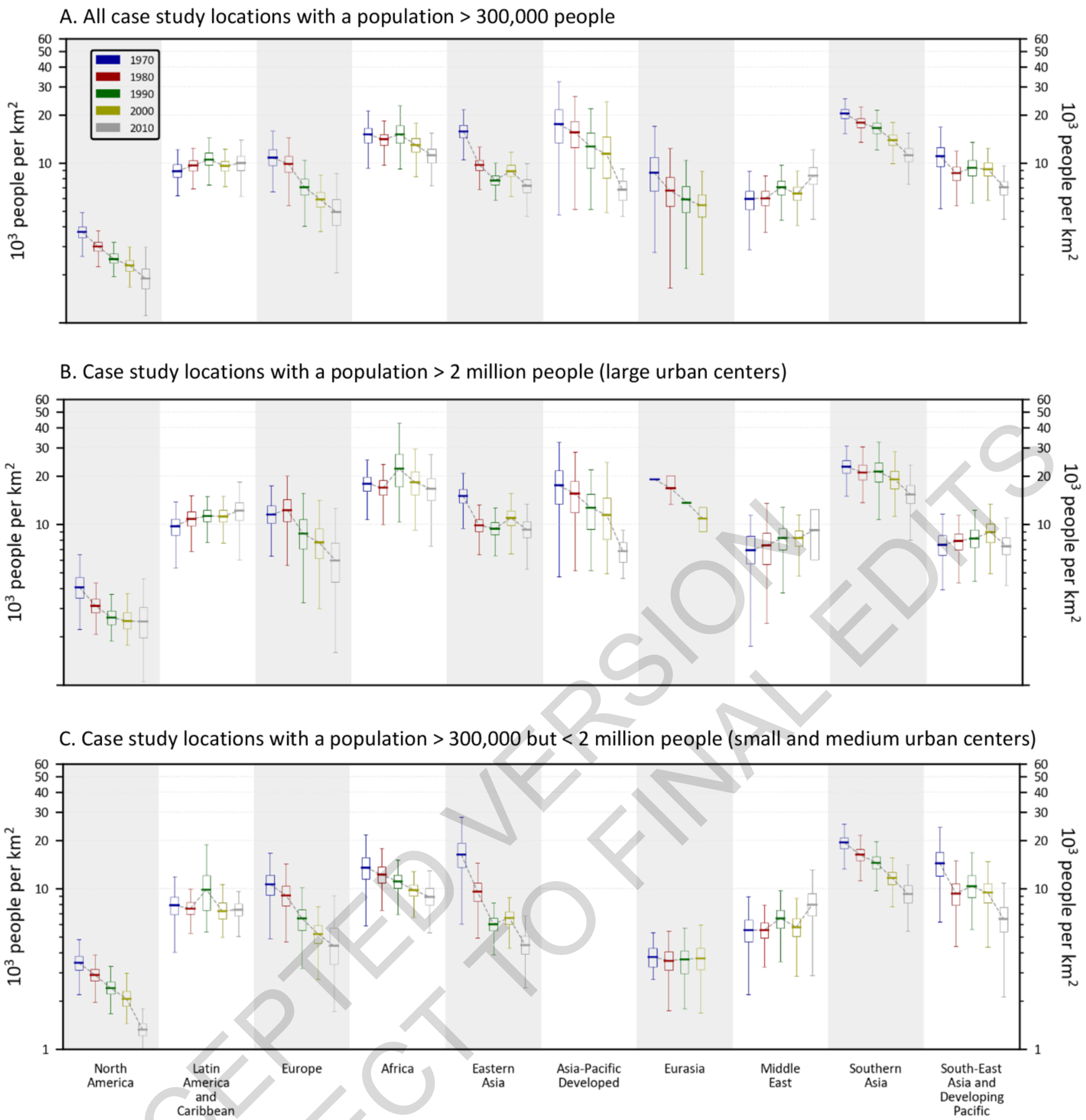


Figure 8.5 Urban population density by decade (1970-2010) grouped by the WGIII AR6 10-region aggregation.

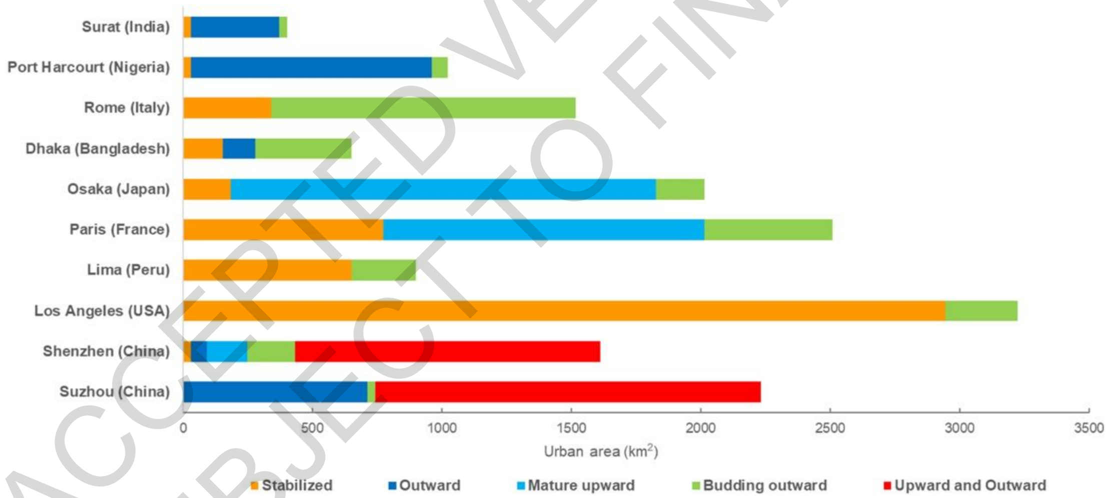
The first panel (a) displays the results from all case study locations with a population >300,000. Panels (b) and (c) show results grouped by city size: (b) cities with a population >2 million (large urban centres), and (c) those with a population >300,000 but <2 million (small and medium urban centres). Box plots show the median, first and third quartiles, and lower and upper mild outlier thresholds of bootstrapped average urban population densities at the turn of each decade. The estimates are shown on a logarithmic scale. The data shows an overall trend of declining urban population densities among all but one region in the last four decades, at varying rates—although the Latin America and Caribbean region indicates relatively constant urban population density over time. The Middle East region is the only region to present with an increase in urban population density across all city sizes.

Source: Adapted from Güneralp et al. (2020, p. 7)

This decline in urban densities is paralleled by an increase in 'sprawl', or 'outward' urban development. Urban expansion occurs in either one of three dimensions: (1) outward in a horizontal manner; (2) upward, by way of vertical growth; or (3) infill development, where unused, abandoned, or underutilized lands within existing urban areas are developed or rehabilitated (see, also, Figure 8.20). Outward expansion results in more urban land area and occurs at the expense of other land uses (i.e., the conversion and loss of cropland, forests, etc.). Vertical expansion results in more multi-story buildings and taller buildings, more floor space per area, and an increase in urban built-up density. Every city has some combination of outward and upward growth in varying degrees (Mahtta et al. 2019) (see Figure 8.6). That each city is comprised of different and multiple urban growth typologies suggests the need for differentiated mitigation strategies for different parts of a single city (see Section 8.6 and Figure 8.21). Recent research shows that the relative combination of outward versus upward growth is a reflection of its economic and urban development (Lall et al. 2021). That is, how a city grows—whether upward or outward—is a function of its economic development level. Upward growth, or more tall buildings, is a reflection of higher land prices (Ahlfeldt and McMillen 2018; Ahlfeldt and Barr 2020).

An analysis of 478 cities with populations of more than 1 million people found that the predominant urban growth pattern worldwide is outward expansion, suggesting that cities are becoming more expansive than dense (Mahtta et al. 2019) (see Figure 8.6). The study also found that cities within a geographic region exhibit remarkably similar patterns of urban growth. Some studies have found a mix of urban forms emerging around the world; an analysis of 194 cities identified an overall trend (from 1990 to 2015) toward urban forms that are a mixture of fragmented and compact (Lemoine-Rodriguez et al. 2020). The exception to this trend is a group of large cities in Australia, New Zealand, and the United States that are still predominantly fragmented. The same study also identified small- to medium-sized cities as the most dynamic in terms of their expansion and change in their forms.

a)



b)

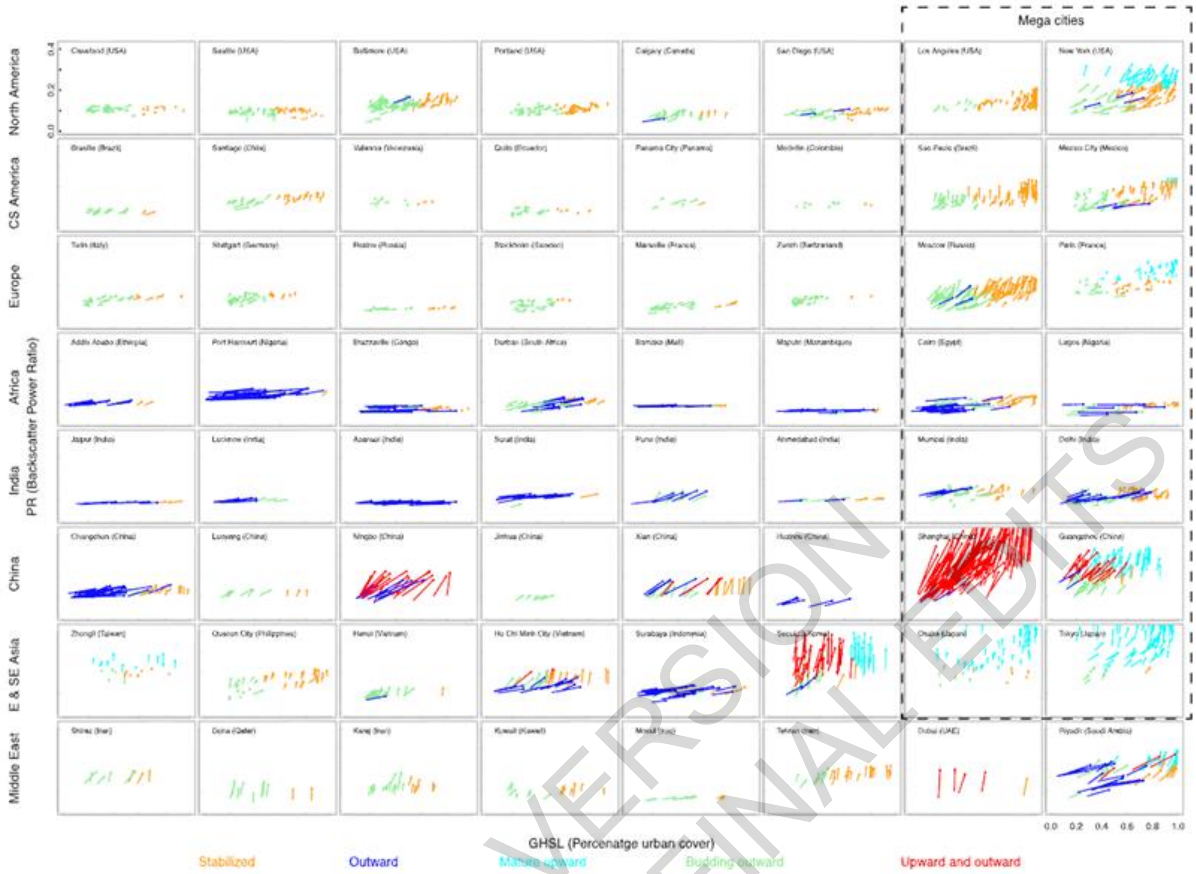


Figure 8.6 (a) Distribution of growth typologies across 10 cities, and (b) sample of 64 cities by region with different patterns of urban growth

The empirical data is based on the Global Human Settlement Layer and backscatter power ratio for different patterns of urban growth across the sample of cities. In (b), the blue arrows indicate outward urban growth. Other urban patterns indicate stabilized (orange), mature upward (light blue), budding outward (green), and upward and outward (red). Note that with few exceptions, each city is comprised of multiple typologies of urban growth.

Source: Mahtta et al., 2019

A third trend in is urban land growth taking place on agricultural land, carbon stocks, and other land uses (see ‘carbon stocks’ and ‘AFOLU’—agriculture, forestry, and other land uses—in Glossary). As Figure 8.7 shows, over 60% of the reported urban expansion (nearly 40,000 km^2) from 1970 to 2010 was formerly agricultural land (Güneralp et al. 2020). This percentage increased to about 70% for global urban expansion that occurred between 1992 and 2015, followed by grasslands (about 12%) and forests (about 9%) (Liu et al. 2020a). In terms of percent of total urban land expansion, the largest conversion of agricultural lands to urban land uses from 1970 to 2010 took place in the Eastern Asia, and South-East Asia and Developing Pacific regions; the largest proportional losses of natural land cover were reported for the North America and Asia-Pacific Developed regions (Güneralp et al. 2020). At a sub-regional level, agricultural land constituted the largest proportion of land converted to urban areas in China, India, Europe, Southeast Asian countries and the central United States between 1995 and 2015; in the eastern United States, most of new urban land was converted from forests (Liu et al. 2020a). Urban expansion through 2040 may lead to the loss of almost 65 Mtonnes of crop production—a scenario that underscores the ongoing relationship between urbanization and AFOLU (van Vliet et al. 2017) (see, also, Chapter 7).

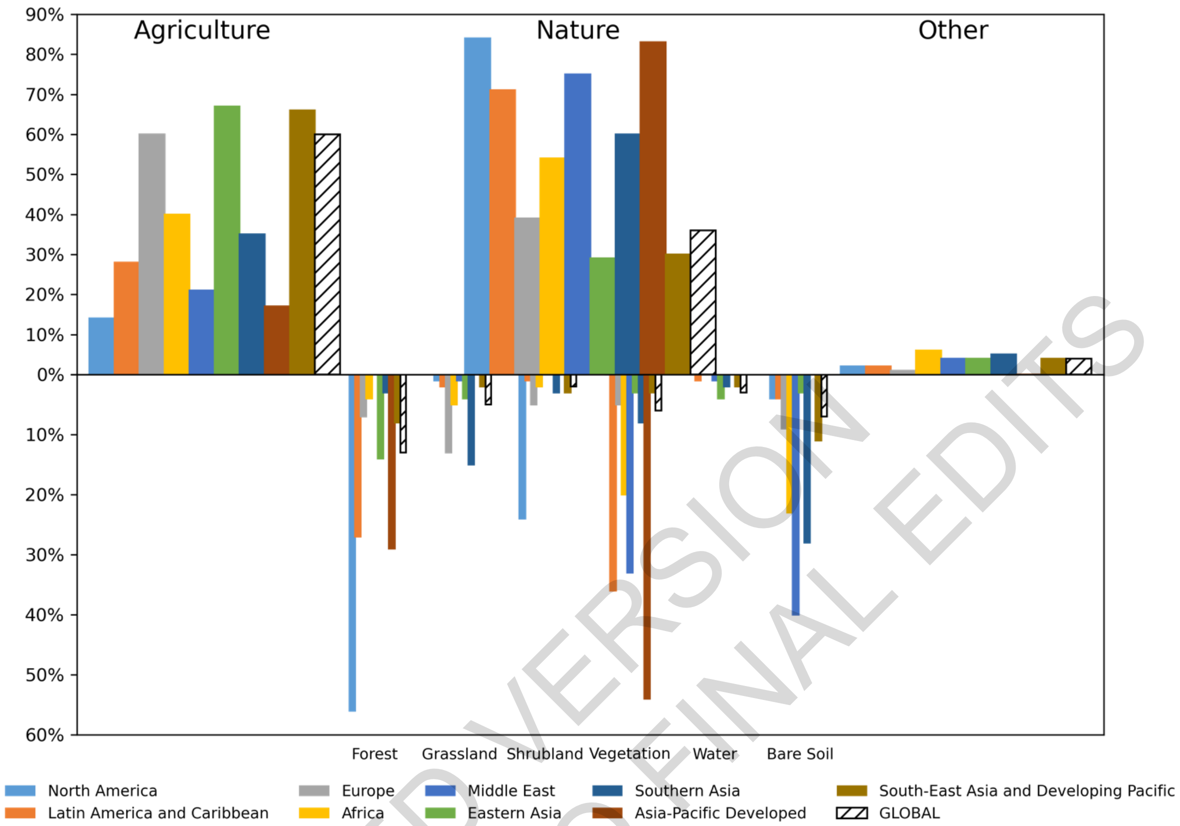


Figure 8.7 Percent of total urban land expansion from other land covers, sorted by the WGIII AR6 10-region aggregation (1970–2010)

As urban land has expanded outward, other forms of land cover, including agriculture, 'nature' (e.g., forest, grassland, shrubland, water, and bare soil, all of which are disaggregated to the bottom half of the plot), and other land covers, have been displaced. Globally, agriculture comprises the majority (about 60%) of the land displaced by urban expansion since 1970. Forests and shrubland vegetation—important carbon stocks—also make up a significant proportion of displacement. The loss of carbon-sequestering land like forests and shrubland independently impacts climate change by reducing global carbon stocks. Eurasia is omitted because there are no case studies from that region that report land conversion data.

Source: Adapted from Güneralp et al. (2020, p. 9)

8.3.2 Informal urban settlements

About 880 million people currently live in informal settlements—defined as unplanned areas operating outside of legal and regulatory systems, where residents have no legal claim over their property and have inadequate basic services and infrastructure (United Nations 2018). Furthermore, upgrading informal settlements and inadequate housing is essential for improving resilience to climate change and well-being. Given the ubiquity of informal settlements in developing countries and LDCs, there is potential to harness informality to accelerate transitions to low-carbon urban development. There are several key reasons for their potential to mitigate GHG emissions. First, informal urban areas may not require large investments in retrofitting as they have developed with minimal investment in large-scale infrastructure. Second, these areas exhibit flexibility of development and can potentially be transformed into an urban form that supports low- or carbon-neutral infrastructure for transportation, energy use in residential buildings, and other sectors (Baurzhan and Jenkins 2016; Henneman et al. 2016; Byrne et al. 2017; Oyewo et al. 2019).

Informal urban areas can avoid the conventional trajectory of urban development by utilizing large-scale strategies, such as micro-scale technologies, modal shifts towards compact, walkable urban form, as well as decentralized or meso-scale utilities of water, sanitation, and service centres,—thereby mitigating emissions associated with transport and treating wastes (Tongwane et al. 2015; Yang et al. 2018). Some specific mitigation options include spatial adjustments for walkability of neighbourhoods, low-energy-intensive mobility, low-energy-intensive residential areas, low-carbon energy sources at city-scale, off-grid utilities, and electrification and enhancement of the urban ecology—all of which have multiple potential benefits (Colenbrander et al. 2017; Fang et al. 2017; Laramee et al. 2018; van der Zwaan et al. 2018; Wu et al. 2018; Silveti and Andersson 2019). Some of the co-benefits of the various mitigation options include more job opportunities and business start-ups, increased incomes, air quality improvement, and enhanced health and well-being (Gebreegziabher et al. 2014; Dagnachew et al. 2018; Keramidas et al. 2018; Adams et al. 2019; Ambole et al. 2019; Boltz et al. 2019; Moncada et al. 2019; Weimann and Oni 2019; Manga et al. 2020) (see Section 8.2).

Non-networked and non-centralized urban services and infrastructure in informal settlements, including sanitation, waste, water, and electricity, serve over 60% of the urban population in developing country cities (Lawhon et al. 2018). The alternatives of disruptive, hybrid, largely non-networked multiplicity of technologies applicable at micro- to meso-scales have potential for low-emissions development in urban areas of developing countries (Narayana 2009; Dávila and Daste 2012; Radomes Jr and Arango 2015; Potdar et al. 2016; Grové et al. 2018). These technologies can be applied in the short-term as responses with long-term influence on emissions reduction. The cumulative impact of the disruptive technologies can reduce emissions by 15–25% through enhanced emissions sinks in small- and medium-sized cities (Tongwane et al. 2015; du Toit et al. 2018; Nero et al. 2018, 2019; Frantzeskaki et al. 2019; Mantey and Sakyi 2019; Singh and G. 2019).

8.3.3 Trends in urban GHG emissions

One major innovation presented in AR6—particularly in this chapter—is the inclusion of trend data on urban GHG emissions. Using multiple datasets in conjunction with the SSP and RCP scenarios, this chapter provides an estimate of urban GHG emissions from 1990 through 2100, based on a consumption-based approach. This innovation provides, for the first time, a temporal dimension to urban footprints considering different climate scenarios with implications for urban mitigation. The new analysis presents a comparison of ways urban emissions can evolve given different scenario contexts (see Section 8.3.4.2). Additionally, new research has quantified trends in urban CO_2 emissions and their key drivers across 91 global cities from 2000 to 2018 (Luqman et al. 2021).

Figures 8.8 and 8.9 present key urban emission metrics and trends for six regions (based on the WGIII AR6 regional breakdown)—the first for the year 2015, and the latter for both 2000 and 2015.

The key trends are as follows. First, the urban share of global GHG emissions (including CO_2 and CH_4) is substantive and continues to increase (see Figure 8.9). Total urban CO_2-eq emissions based on consumption-based accounting were estimated to be 24.5 $GtCO_2$-eq, or 62% of the global total in 2015, and increased to an estimated 28.5 ± 0.1 $GtCO_2$-eq in 2020, representing about 67-72% of global emissions, excluding aviation, shipping, and biogenic sources. About 100 of the highest-emitting urban areas account for approximately 18% of the global carbon footprint (Moran et al. 2018). Globally, the urban share of national CO_2-eq emissions increased 6 percentage points, from 56% in 2000 to 62% in 2015.

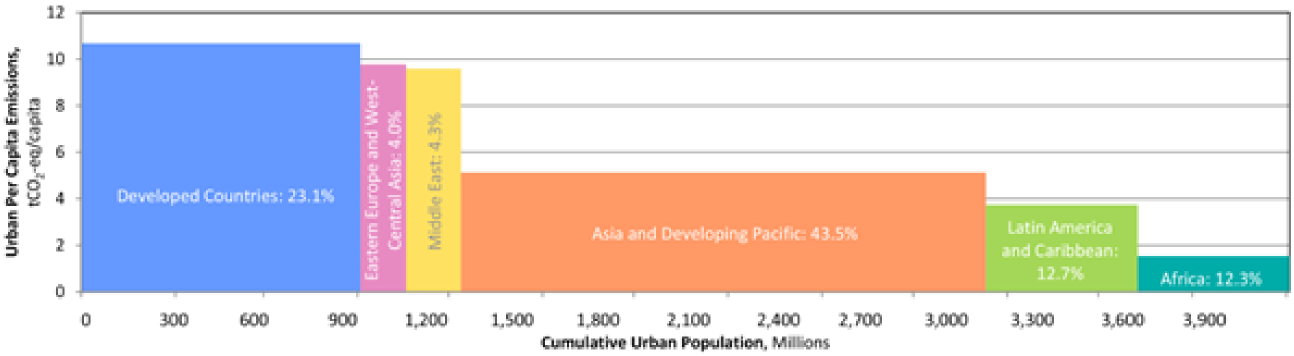


Figure 8.8 2015 average urban GHG emissions per capita considering CO_2 and CH_4 emissions from a consumption based perspective, alongside urban population, for regions represented in the WGIII AR6 6-region aggregation.

The average urban per capita emissions are given by the height of the bars while the width represents the urban population for a given region, based on 2015 values for both axes. Provided within the bars are the percentage shares of the urban population by region as a share of the total urban population.

Source: Adapted from UN DESA (2019) and Gurney et al. (2021a)

Second, while urban CO_2 emissions were increasing in all urban areas, the dominant drivers were dependent upon development level. Emissions growth in urban areas other than in Developed Countries was driven by increases in area and per capita emissions. Across all cities, higher population densities are correlated with lower per capita GHG emissions (Luqman et al. 2021). Third, the urban share of regional GHG emissions increased between 2000 and 2015, with much inter-region variation in the magnitude of the increase (*high confidence)* (see Figure 8.9). Between 2000 to 2015, the urban emissions share across WGIII AR6 regions (6-region aggregation) increased from 28% to 38% in Africa, from 46% to 54% in Asia and Developing Pacific, from 62% to 72% in Developed Countries, from 57% to 62% in Eastern Europe and West-Central Asia, from 55% to 66% in Latin America and Caribbean, and from 68% to 69% in the Middle East.

Between 2000 and 2015, urban population, urban CO_2-eq emissions, and national CO_2-eq emissions increased as a share of the global total in the Asia and Developing Pacific region while the share declined for Developed Countries. The urban share of total regional CO_2-eq emissions decreased in Developed Countries from 58.2% (2000) to 40.0% (2015). Urban per capita CO_2-eq and national per capita CO_2-eq also increased in all regions except for the urban per capita CO_2-eq value in the Developed Countries region which declined slightly.

Fourth, the global average per capita urban GHG emissions increased between 2000 and 2015, with cities in the Developed Countries region producing nearly seven times more per capita than the lowest emitting region (*medium confidence).* From 2000 to 2015, the global urban GHG emissions per capita increased from 5.5 to 6.2 tCO_2-eq per person (an increase of 11.8%), with increases across five of the six regions: Africa increased from 1.3 to 1.5 tCO_2-eq per person (22.6%); Asia and Developing Pacific increased from 3.0 to 5.1 tCO_2-eq per person (71.7%); Eastern Europe and West-Central Asia increased from 6.9 to 9.8 tCO_2-eq per person (40.9%); Latin America and the Caribbean increased from 2.7 to 3.7 tCO_2-eq per person (40.4%); and the Middle East increased from 7.4 to 9.6 tCO_2-eq per person (30.1%). Albeit starting from the highest level, Developed Countries had a decline of 11.4 to 10.7 tCO_2-eq per person (-6.5%).

In 2015, regional urban per capita consumption-based CO_2-eq emissions were lower than regional consumption-based national per capita CO_2-eq emissions in five of the six regions. These regions in order of the difference are Developed Countries (lower by 1.0 tCO_2-eq per capita), Latin America and

Caribbean (lower by 0.8 tCO_2-eq per capita), Eastern Europe and West-Central Asia (lower by 0.7 tCO_2-eq per capita), Middle East (lower by 0.4 tCO_2-eq per capita), and Africa (lower by 0.2 tCO_2-eq per capita), while higher only in the Asia and Developing Pacific region (higher by 0.9 tCO_2-eq per capita). All regions show convergence of the urban and national per capita CO_2-eq, as the urban share of national emissions increases and dominates the regional total.

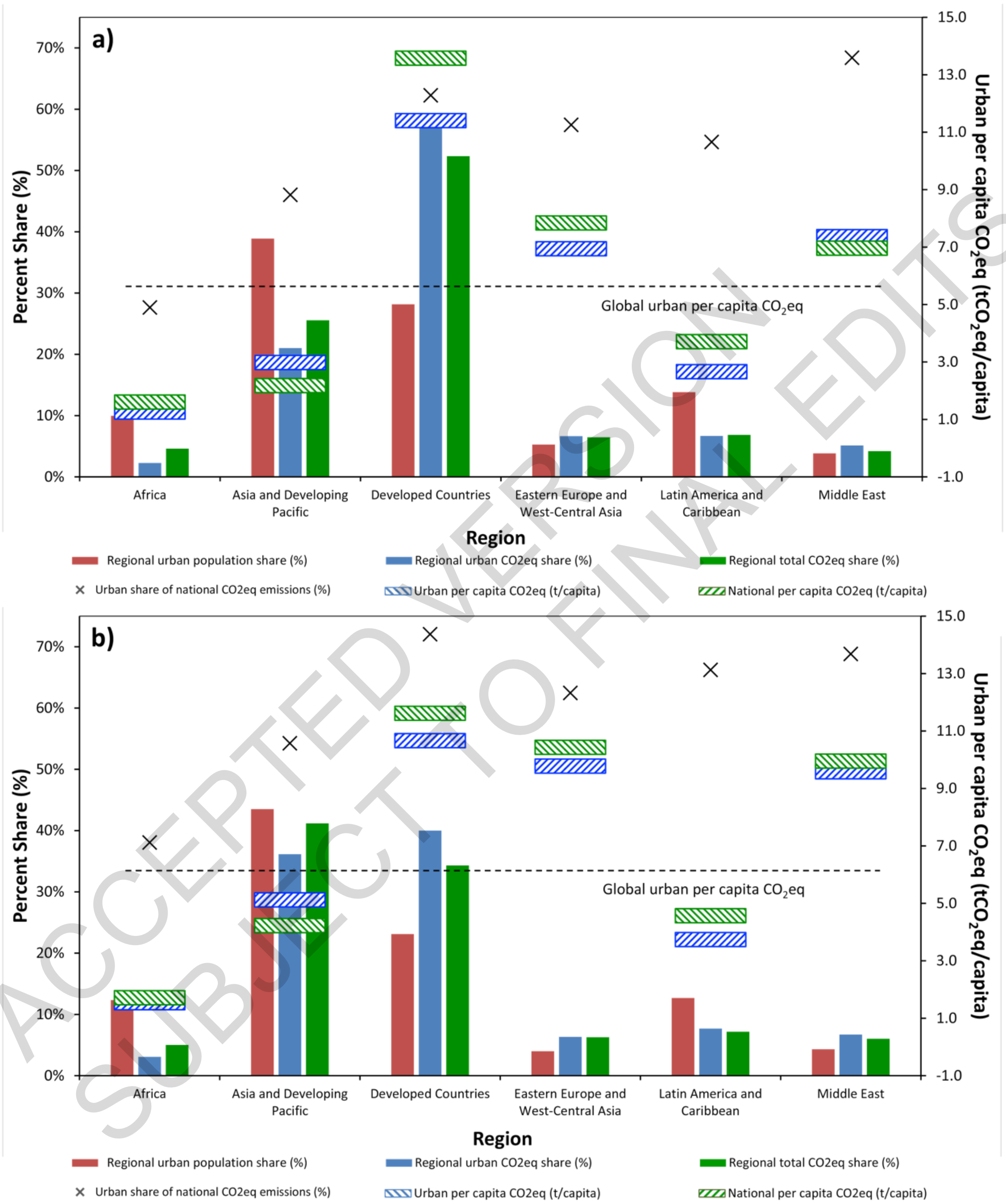


Figure 8.9 Changes in six metrics associated with urban and national-scale CO_2 and CH_4 emissions represented in the WGIII AR6 6-region aggregation, with (a) 2000 and (b) 2015

The trends in Luqman et al. (2021) were combined with the work of Moran et al. (2018) to estimate the regional urban CO_2-eq share of global urban emissions, the urban share of national CO_2-eq emissions, and the urban per capita CO_2-eq emissions by region. The total values exclude aviation, shipping, and biogenic sources. The dashed grey line represents the global average urban per capita CO_2-eq emissions.

The regional urban population share, regional CO_2-eq share in total emissions, and national per capita CO_2-eq emissions by region are given for comparison.

Source: Adapted from Gurney et al. (2021)

START BOX 8.1 HERE

Box 8.1 Does urbanization drive emissions?

Urbanization can drive emissions if the process is accompanied by an income increase and higher levels of consumption (Sudmant et al. 2018). This is typically observed in countries with a large urban-rural disparity in income and basic services, and where urbanization is accompanied by economic growth that is coupled to emissions. In addition, the outward expansion of urban land areas often results in the conversion and loss of agricultural land (Pandey et al. 2018; Liu et al. 2019), forests (Austin et al. 2019), and other vegetated areas, thereby reducing carbon uptake and storage (Quesada et al. 2018) (see Section 8.3.1). Furthermore, the build-up and use of urban infrastructure (e.g., buildings, power, sanitation) requires large amounts of embodied energy and carbon (see Figures 8.17 and 8.22). Building new and upgrading existing urban infrastructure could produce a cumulative emissions of 226 $GtCO_2$ by 2050 (Bai et al. 2018).

However, for the same level of consumption and basic services, an average urban dweller often requires less energy than their rural counterparts, due to higher population densities that enable sharing of infrastructure and services, and economies of scale. Whether and to what extent such emission reduction potentials can be realized depends on how cities are designed and laid out (i.e., urban form – see Section 8.4.2) as well as how urban infrastructure is built and powered, such as the energy intensity of the city's transportation system, type and level of urban services, the share of renewable energy, as well as the broader national and international economic and energy structure that supports the function of the cities (see Sections 8.4.3 and 8.6).

Although population-dense cities can be more efficient than rural areas in terms of per capita energy use, and cities contribute less GHG emissions per person than low-density suburbs (Jones and Kammen 2014), there is some, albeit *limited*, evidence that larger cities are not more efficient than smaller ones (Fragkias et al. 2013; Ribeiro et al. 2019). A number of studies comparing urban and rural residents in the same country have shown that urban residents have higher per capita energy consumption and CO_2 emissions (Chen et al. 2019a; Hachaichi and Baouni 2021). There is some evidence that the benefits of higher urban densities on reducing per capita urban GHG emissions may be offset by higher incomes, smaller household sizes, and, most importantly, higher consumption levels, thus creating a counter-effect that could increase GHG emissions with urbanization (Gill and Moeller 2018).

Many studies have shown that the relationship between urbanization and GHG emissions is dependent on the level and stage of urban development, and follows an inverted U-shaped relationship of the environmental Kuznets curve (Wang et al. 2016, 2022; Zhang et al. 2017; Xu et al. 2018a; Zhou et al. 2019) (see Sections 8.3.1 and 8.6, and Figure 8.20). Considering existing trends, earlier phases of urbanization accompanied by rapid industrialization, development of secondary industries, and high levels of economic growth, are correlated with higher levels of energy consumption and GHG emissions. However, more mature phases of urbanization, with higher levels of economic development and establishment of the service sector, are correlated with lower levels of energy consumption and GHG emissions (Khan and Su 2021).

END BOX 8.1 HERE

8.3.4 Scenarios of future urbanization and GHG emissions

This section assesses scenarios of future urban land expansion and urban GHG emissions. These scenarios have implications for the urban climate change mitigation strategies discussed in Sections 8.4 and 8.6—in particular, in the context of the potential mitigation and development pathways for urban areas under certain scenarios.

8.3.4.1 Urban land expansion and GHG emissions

The uncertainties across urban land expansion forecasts, and associated SSPs, highlight an opportunity to pursue compact, low- or net zero GHG emissions development that minimizes land-use competition, avoids carbon lock-in, and preserves carbon-sequestering areas like forests and grasslands (see Sections 8.4. and 8.6, and Figure 8.21). Among the forecasts available are six global-scale spatially explicit studies of urban land expansion that have been published since AR5; four of the six, which present forecasts for each of the five SSPs, are considered in Table 8.1 and Figure 8.10 (Huang et al. 2019; Li et al. 2019b; Chen et al. 2020a; Gao and O'Neill 2020). All four have forecasts to 2050 but only three to 2100. One of the two not included here (van Vliet et al. 2017) also forecasts land displacement due to urban land expansion.

Four overarching findings can be gleaned from these studies.

First, urban land areas will expand significantly by 2050—by as much as 211% (see SSP5 forecast in Huang et al. 2019), but likely within a large potential range of about 43–106% over the 2015 extent by 2050—to accommodate the growing urban population (see Table 8.1). Globally, there are large uncertainties and variations among the studies—and between the SSPs—about the rates and extent of future urban expansion, owing to uncertainties about economic development and population growth (ranges of estimates are provided in Table 8.1). Overall, the largest urban extents are forecasted under SSP5 (fossil fuel-intensive development) for both 2050 and 2100, whereas the smallest forecasted urban extents are under SSP3 ('regional rivalry'). Forecasted global urban extents could reach between 1 and 2.2 million km^2 (median of 1.4 million km^2, a 106% increase) in 2050 under SSP5, and between 0.85 and 1.5 million km^2 (median of 1 million km^2, a 43% increase) in 2050 under SSP3. Under SSP1, which is characterized by a focus on sustainability with more compact, low-emissions development, urban extents could reach 1 million km^2 (range of 0.9 to 2 million km^2), a 49% increase, in 2050. By 2100, the forecasted urban extents reach between 1.4 and 3.6 million km^2 (median 2.5 million km^2) under SSP5 and between 1 and 1.5 million km^2 (median 1.3 million km^2) under SSP3. Across the studies, substantially larger amounts of urban land expansion are expected after 2050 under SSP5 compared to other SSPs.

Second, there is a wide variation in estimates of urban land expansion across regions (using the WGIII AR6 6-region aggregation). Across all four sets of forecasts, current urban land (circa 2015) is the largest in Developed Countries and in the Asia and Developing Pacific region, with approximately two-thirds of the current urban extent occurring in those two regions (see Table 8.1 and Figure 8.10). The largest increases in urban land by 2050 are expected in the Asia and Developing Pacific and Developed Countries regions, across all the SSPs. However, the rate of increase in urban land in Eastern Europe and West-Central Asia, Latin America and the Caribbean, and the Middle East is significant and urban land could more than double by 2050. One-third of the studies conclude that the United States, China, and India will experience continued urban land expansion at least until 2050 (Huang et al. 2019; Li et al. 2019b). However, Li et al. (2019) report that, after 2050, China could experience a decrease in the rate of urban land expansion, while growth will continue for India. This is not surprising since India's urban demographic transition will only get underway after the middle of the century, when the urban population is expected to exceed the rural population. In contrast, China's urban demographic transition could be nearly complete by 2050.

Third, in spite of these general trends, there are differences in forecasted urban expansion in each region across the SSPs and studies, with Huang et al. (2019) forecasting the most future urban land expansion between 2015 and 2050. The range across studies is significant. Under SSP1, urban land areas could increase by between 69,000 and 459,000 km^2 in Developed Countries, 77,000–417,000 km^2 in Asia and Developing Pacific, and 28,000–216,000 km^2 in Africa. Under SSP3, where urban land expansion is forecasted to be the lowest, urban land areas could increase by between 23,000 and 291,000 km^2 in Developed Countries, 57,000–168,000 km^2 in Asia and Developing Pacific, and 16,000–149,000 km^2 in Africa. Under SSP5, where urban land expansion is forecasted to be the highest, urban land area could increase by 129,000 to 573,000 km^2 in Developed Countries, 83,000–472,000 km^2 in Asia and Developing Pacific, and 40,000–222,000 km^2 in Africa (Huang et al. 2019; Li et al. 2019b; Chen et al. 2020a; Gao and O'Neill 2020). By 2100, however, the Developed Countries region is expected to have the most urban expansion only in SSP5. In SSP2 and SSP4, the Developed Countries and Asia and Developing Pacific regions have about equal amounts of new urban land; in SSP3, Asia and Developing Pacific has more new urban land forecasted.

Fourth, both the range of estimates and their implications on land-use competition and urban life point to an opportunity for urban areas to consider their urban form when developing. Under the current urbanization trajectory, 50–63% of newly expanded urban areas are expected to occur on current croplands (Chen et al. 2020a). However, there is significant regional variation; between 2000 and 2040, 12.5% of cropland in China and 7.5% of cropland in the Middle East and North Africa could be displaced due to urban expansion, compared to the world average of 3.7% (van Vliet et al. 2017). As urban clusters increase in size and green space is converted, future urban land expansion is expected to intensify UHIs and exacerbate night-time extreme temperatures. An urban footprint increase of 78–171% by 2050 over the urban footprint in 2015 is expected to result in average summer daytime and night-time warming in air temperature of 0.5°C–0.7°C, even up to about 3°C in certain locations (Huang et al. 2019). Furthermore, this urban expansion-induced warming is on average about half—and in certain locations nearly twice—as strong as warming that will be caused by GHG emissions based on the multi-model ensemble average forecasts in RCP4.5. In short, future urban expansion will amplify the background warming caused by GHG emissions, with extreme warming most pronounced during night-time (*very high confidence)* (Huang et al. 2019). These findings corroborate those in the Technical Summary of AR6 WGI (Arias et al. 2021).

The forecasted amounts and patterns of urban expansion presented here bear significant uncertainty due to underlying factors beyond mere methodological differences between the studies. These factors include potential changes in the social, economic, and institutional dynamics that drive urban land development across the world (Güneralp and Seto 2013). Some of these changes may come in the form of sudden shocks such as another global economic crisis or pandemic. The forecasts presented here do not take such factors into account.

Table 8.1. Forecasts of total urban land per WGIII AR6 region (6-region aggregation) in 2050 for each SSP, with the median and range of estimates from four studies: Huang et al. 2019, Li et al. 2019, Chen et al. 2020, and Gao and O'Neill 2020. Median estimates for the 2015 urban extent are based on the mean/median of estimates in Huang et al. 2019 and Chen et al. 2020. Median and range of estimates for each SSP in 2050 are based on values derived from the four studies: Huang et al. 2019; Li et al. 2019; Chen et al. 2020; and Gao and O'Neill 2020. While each study and SSP forecast increases in urban land in each region, the range and magnitude vary.

Source: Data compiled from Huang et al. 2019, Li et al. 2019, Chen et al. 2020, and Gao and O'Neill 2020.

	2015 Median (range)	**SSP1 Median** (range)	**SSP2 Median** (range)	**SSP3 Median** (range)	**SSP4 Median** (range)	**SSP5 Median** (range)
Africa	**64,423**	**97,718**	**116,486**	**96,571**	**119,971**	**138,604**
	(41,472–87,373)	(67,488–303,457)	(59,638–274,683)	(56,071–235,922)	(54,633–344,645)	(79,612–309,532)
Asia and Developing Pacific	**241,430**	**293,647**	**355,445**	**296,431**	**329,485**	**419,781**
	(167,548–315,312)	(244,575–732,303)	(236,677–624,659)	(224,520–483,335)	(240,639–632,678)	(250,670–787,257)
Developed Countries	**260,167**	**459,624**	**506,301**	**414,661**	**496,526**	**616,847**
	(188,660–331,674)	(407,483–648,023)	(431,592–614,592)	(362,063–479,584)	(411,320–586,058)	(510,468–761,275)
Eastern Europe and West-Central Asia	**35,970**	**63,625**	**65,251**	**59,779**	**64,434**	**76,994**
	(27,121–44,819)	(42,990–91,612)	(52,397–91,108)	(44,129–90,794)	(50,806–86,546)	(54,039–93,008)
Latin America and Caribbean	**62,613**	**86,236**	**88,793**	**93,804**	**85,369**	**102,343**
	(60,511–64,716)	(63,507–163,329)	(86,411–162,526)	(65,286–162,669)	(82,148–144,940)	(82,961–167,102)
Middle East	**21,192**	**51,351**	**51,221**	**48,032**	**49,331**	**55,032**
	(19,017–23,366)	(187,68–69,266)	(25,486–69,716)	(19,412–63,236)	(25,415–71,720)	(33,033–75,757)
World	**685,795**	**1,023,220**	**1,174,742**	**980,719**	**1,123,900**	**1,412,390**
	(669,246–702,343)	(919,185–1,991,579)	(927,820–1,819,174)	(850,681–1,493,454)	(922,539–1,851,438)	(1,018,321–2,180,816)

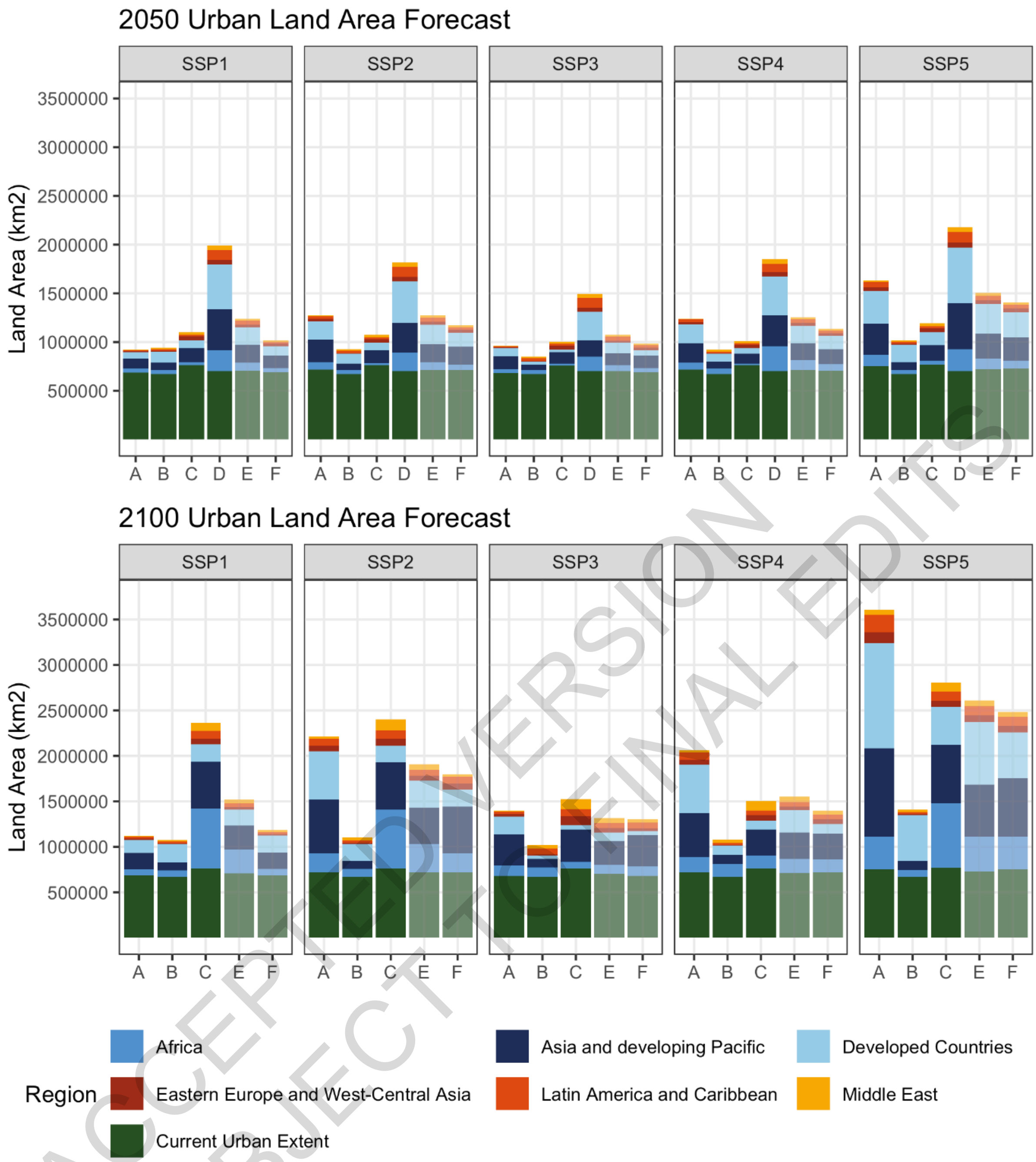


Figure 8.10 Forecasts of urban land expansion in 2050 and 2100 according to each SSP and WGIII AR6 6-region aggregation, by study, where A: Gao and O'Neill (2020), B: Chen et al. (2020a), C: Li et al. (2019), D: Huang et al. (2019), E: Mean across studies, and F: Median across all studies.

Three studies (Li et al. 2019b; Chen et al. 2020a; Gao and O'Neill 2020) report forecasts of urban land expansion to both 2050 and 2100. One study (Huang et al. 2019) reports the forecast only to 2050. Global current urban extents and the respective initial years vary slightly among the four studies. Years for values of current urban extent range from 2010 to 2020. See Table 8.1 for the range of data across the four studies and across SSPs.

Source: Data compiled form Huang et al. 2019, Li et al. 2019, Chen et al. 2020, and Gao and O'Neill 2020.

8.3.4.2 Scenarios of future urban GHG emissions

There remains little globally comprehensive literature on projections of future baseline GHG emissions from urban areas or scenarios deploying urban mitigation actions on the part of city or regional governments. This dearth of research rests on limited urban emissions data that are consistent and comparable across the globe, making review and synthesis challenging (Creutzig et al. 2016b). Some research has presented urban emissions forecasts and related projections, including estimated urban energy use in 2050 (Creutzig et al. 2015), energy savings for low-carbon development (Creutzig et al. 2016b), emission savings from existing and new infrastructure (Creutzig et al. 2016a) (see Figure 8.12), and urban emissions from buildings, transport, industry, and agriculture (IEA 2016a).

In its study of about 700 urban areas with a population of at least 750,000, the Coalition for Urban Transitions (2019), attempts to quantify the urban portion of global GHG emissions, including the residential and commercial building, transport, waste, and material production (focusing on cement, aluminium, and steel) sectors, along with mitigation wedges aimed at staying below a 2°C level of atmospheric warming (Figure 8.11). Starting in 2015 with a global urban emissions total of almost 14 $GtCO_2$-eq, the study projects an increase to 17.3 $GtCO_2$-eq by 2050—but this reduces to 1.8 $GtCO_2$-eq by 2050 with the inclusion of mitigation wedges: 58% from buildings, 21% from transport, 15% materials efficiency, and 5% waste, with decarbonization of electricity supply as a cross-cutting strategy across the wedges.

Similar analysis by the urban networks C40 and GCoM examine current and future GHG emissions on smaller subsets of global cities, offering further insight on the potential emissions impacts of urban mitigation options. However, this analysis is limited to just a sample of the global urban landscape and primarily focused on cities in the Global North (GCoM 2018, 2019; C40 Cities et al. 2019) with methods to project avoided emissions in development (Kovac et al. 2020). Different scopes of analysis between sectors, as well as limited knowledge of the impact of existing and new urban infrastructure, limit the possibility of direct comparisons in emissions. Still, the shares of urban mitigation potential ranges between 77.7% and 78.9% for combined strategies that involve decarbonized buildings and transport in urban infrastructure, and the wedges approach the remaining emissions reductions also considering construction materials and waste. This data supports urban areas pursuing a package of multiple, integrated mitigation strategies in planning for decarbonization (see Sections 8.4 and 8.6, and Figure 8.21).

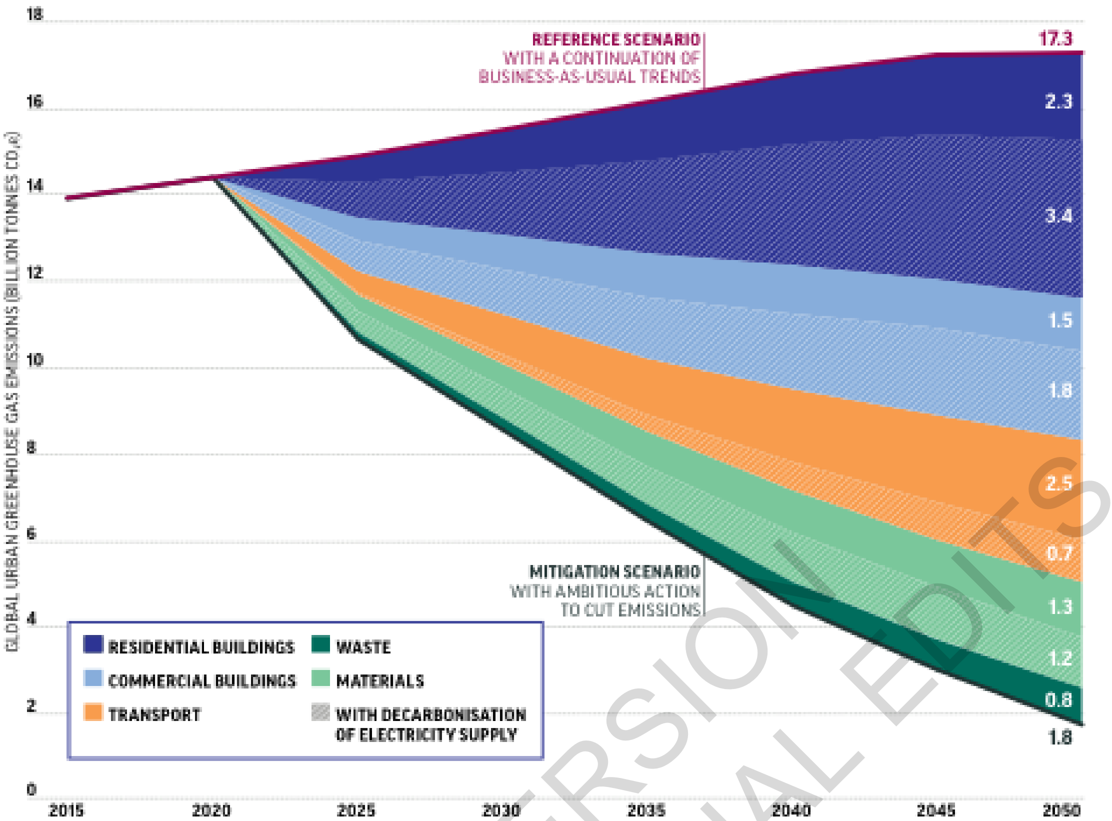


Figure 8.11 Reference scenario and mitigation potential for global urban areas in the residential and commercial building, transport, waste, and material production sectors

The top red line indicates the reference scenario where no further emissions reduction efforts are taken, while the bottom dark line indicates the combined potential of reducing emissions across the sectors displayed. Wedges are provided for potential emissions savings associated with decarbonizing residential buildings, commercial buildings, transport, waste, and materials as indicated in the legend. The shaded areas that take place among the wedges with lines indicate contributions from decarbonization of electricity supply.

Source: Coalition for Urban Transitions (2019, p. 13)

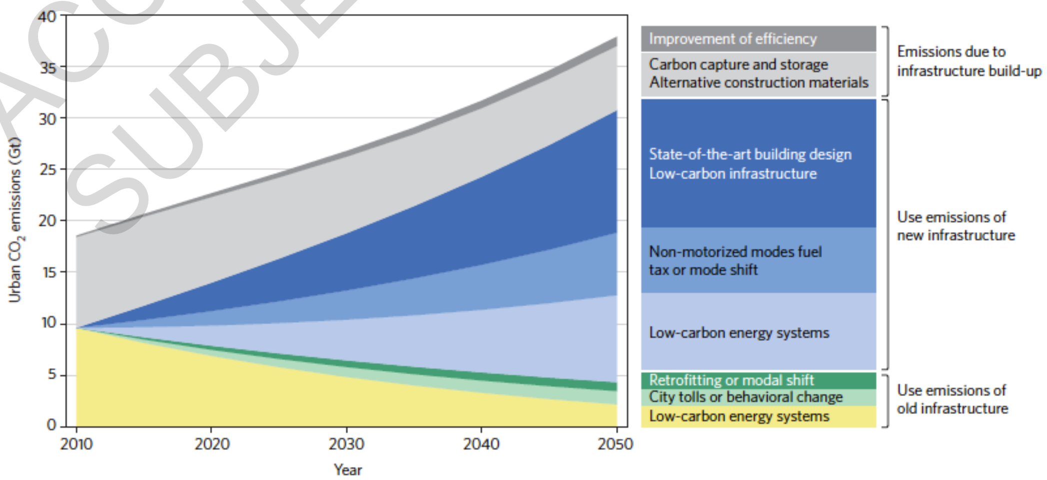


Figure 8.12 Urban infrastructure-based CO_2-eq emission mitigation wedges

Urban infrastructure-based CO_2-eq emission mitigation wedges across categories of existing (yellow/green), new (blue), and construction (grey) of urban infrastructure. The wedges include low-carbon energy systems and infrastructure, modal shift, tolls/tax, or behavioural change, and reductions from construction materials.

Source: Creutzig et al. (2016a, p. 1056)

The most comprehensive approach to-date for quantifying urban emissions within the global context (Gurney et al. 2021a) combines the per capita carbon footprint estimates for 13,000 cities from Moran et al. (2018) with projections of the share of urban population (Jiang and O'Neill 2017) within the IPCCs SSP-RCP framework (van Vuuren et al. 2014, 2017a; Riahi et al. 2017). Urban emissions in seven SSP-RCP scenarios are shown in Figure 8.13 along with an estimate of the global total CO_2-eq for context.

In 2020, total urban emissions (including CO_2 and CH_4) derived from consumption-based accounting were estimated to be 28.5 ± 0.1 $GtCO_2$-eq, representing between 67% and 72% of global CO_2 and CH_4 emissions, excluding aviation, shipping, and biogenic sources of emissions. By 2050, with no or moderate urban mitigation efforts, urban emissions are projected to rise to 34–65 $GtCO_2$-eq—driven by growing urban population, infrastructure, and service demands. However, scenarios that involve rapid urbanization can have different outcomes as seen in SSP1-RCP1.9 based on green growth, versus SSP5-RCP8.5 with the strongest carbon lock-in lacking any decarbonization. Other scenarios involve mixed and/or low urbanization, along with other differences, including the implementation of electrification, energy, and material efficiency, technology development and innovation, renewable energy preferences, and behavioural, lifestyle, and dietary responses (see Table 8.2). With aggressive and immediate mitigation policies to limit global warming below 1.5°C by the end of the century, urban GHG emissions could approach net zero and reach a maximum of 3.3 $GtCO_2$-eq in 2050, compared to 28.6 $GtCO_2$-eq in 2020 (SSP1-RCP1.9). Under aggressive but not immediate urban mitigation policies to limit global warming to 2°C, urban emissions could reach 17.2 $GtCO_2$-eq in 2050 (SSP1-RCP2.6).

When 2020 levels are compared to the values for the year 2030, urban areas that utilize multiple opportunities towards resource-efficient and walkable urbanization are estimated to represent a savings potential of 9.8 $GtCO_2$-eq of urban emissions, under SSP1-RCP1.9 scenario conditions, on the path towards net zero CO_2 and CH_4 emissions. In contrast, urban emissions would increase by 3.4 $GtCO_2$-eq from 2020 levels in 2030 under SSP2-RCP4.5 scenario conditions with moderate changes lacking ambitious mitigation action (see Figure 8.14).

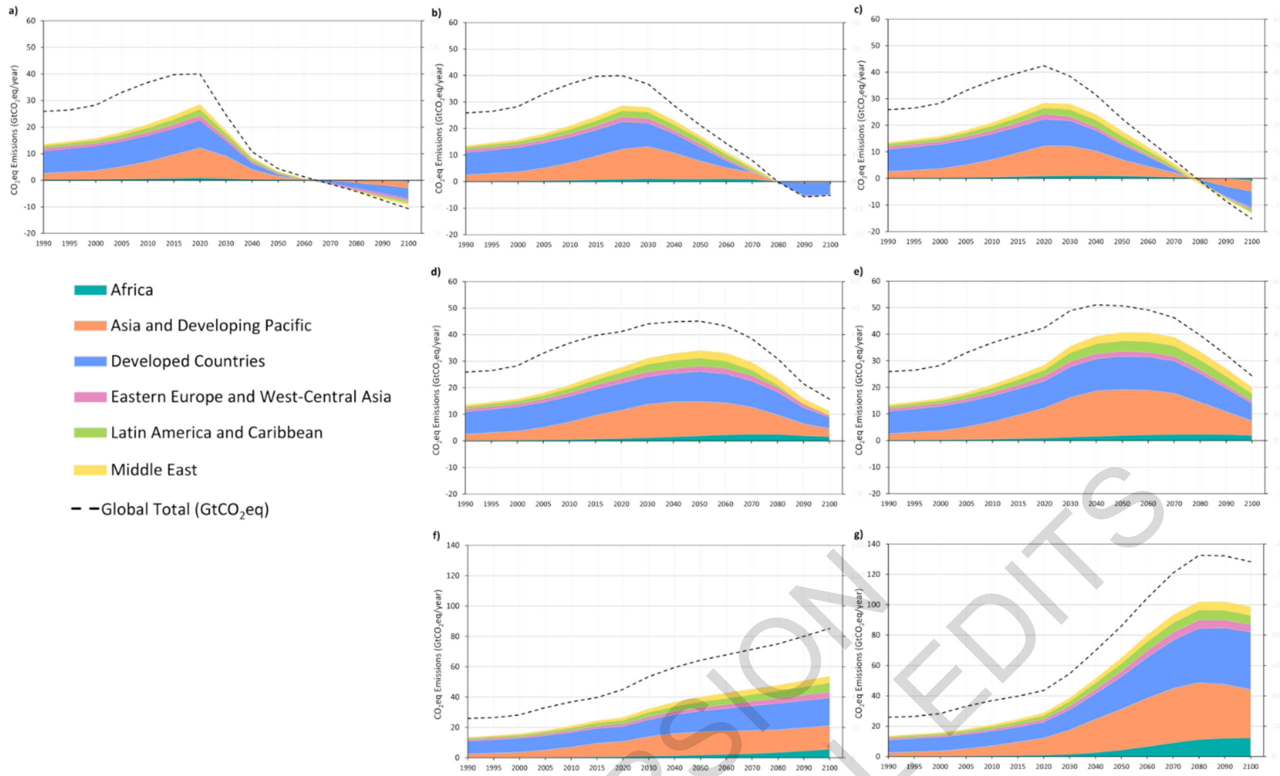


Figure 8.13 CO_2-eq emissions from global urban areas in seven SSP-RCP variations spanning the 1990 to 2100 time period

Urban areas are aggregated to six regional domains based on the WGIII AR6 6-region aggregation. Global total CO_2-eq emissions (CO_2 and CH_4) are also shown as marked by the dashed line. Future urban emissions in the context of SSP-RCP-SPA variations correspond to (a) SSP1-RCP1.9-SPA1, (b) SSP1-RCP2.6-SPA1, (c) SSP4-RCP3.4-SPA4, (d) SSP2-RCP4.5-SPA2, (e) SSP4-RCP6.0-SPA4, (f) SSP3-RCP7.0-SPA0 and (g) SSP5-RCP8.5 based on the marker scenario implementations. The first three scenarios (a-c) with more stringent reduction pathways represent contexts where urban per capita emissions decline rapidly against various increases in urban population and are oriented to reach net zero emissions within this century at different radiative forcing levels. SSP1 scenarios (a-b) represent contexts where urbanization takes place rapidly while providing resource efficiency based on compact urban form (Jiang and O'Neill 2017), with high levels of electrification (van Vuuren et al. 2017b; Rogelj et al. 2018). The scenario context of SSP1-RCP1.9 represents a pathway in which there can be a transformative shift towards sustainability. Note that the scale of the panels (f) and (g) are different from the other panels. [2] See Table 8.2 detailing the SSP-RCPs.

Source: Adapted from Gurney et al. (2021)

[2]FOOTNOTE: The SSP1-RCP1.9 scenario is aligned with the same SSP-RCP context as the Illustrative Mitigation Pathways (IMP) for IMP-LD, IMP-Ren and IMP-SP. Implications are provided in Table 8.3.

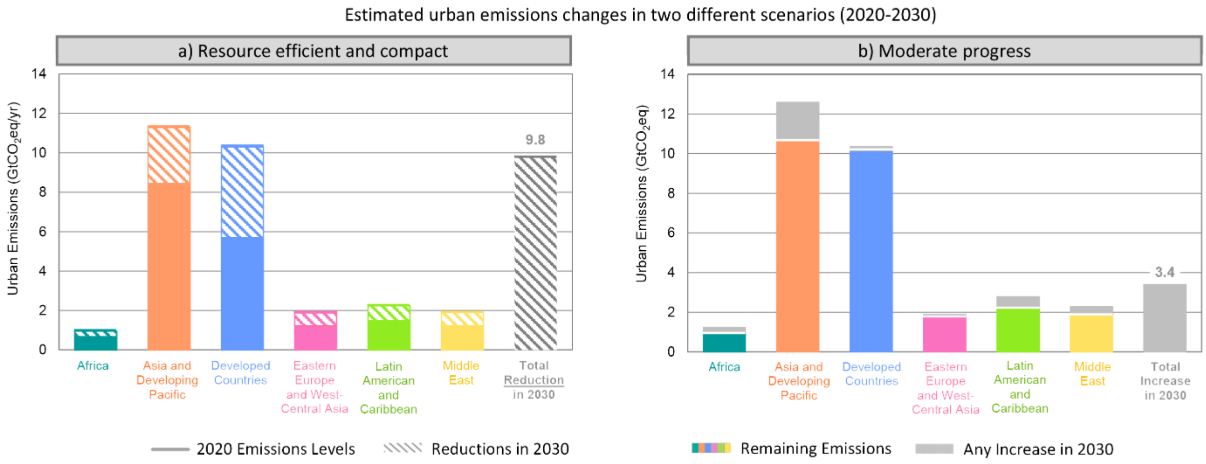


Figure 8.14 Comparison of urban emissions under different urbanization scenarios (GtCO$_2$-eq yr^{-1}) for the WGIII AR6 6-region aggregation

The panels represent the estimated urban emissions change in two different scenarios for the time period 2020-2030. Panel (a) represents resource efficient and compact urbanization while panel (b) represents urbanization with moderate progress. The two scenarios are consistent with estimated urban emissions under the SSP1-RCP1.9-SPA1 and SSP2-RCP4.5-SPA2 scenarios, respectively (see Figure 8.13). In both panels, urban emissions estimates for the year 2020 are marked by the lines for each region. In the resource efficient and compact scenario, various reductions in urban emissions that take place by 2030 are represented by the dashed areas within the bars. The remaining solid shaded areas represent the remaining urban emissions in 2030 for each region on the path towards net zero emissions. The total reductions in urban emissions worldwide that are given by the last dashed grey bar in panel (a) is estimated to be 9.8 GtCO$_2$-eq yr^{-1} between 2020 and 2030 in this scenario. In the scenario with moderate progress, there are no regions with reductions in urban emissions. Above the white lines that represent urban emissions in 2020, the grey shaded areas are the estimated increases for each region so that the total urban emissions would increase by 3.4 GtCO$_2$-eq yr^{-1} from 2020 levels in 2030 under this scenario. The values are based on urban scenario analyses as given in Gurney et al. (2021).

Source: Adapted from Gurney et al. (2021)

Table 8.2 Synthesis of the urbanization and scenario contexts of the urban emissions scenarios. Descriptions for urbanization are adapted based on Jiang and O'Neill (2017) while high-, medium-, low-, or mixed-levels in the scenario context are drawn from the marker model implementations of SSP1-SSP5 for IMAGE (van Vuuren et al. 2017b; Rogelj et al. 2018), MESSAGE-GLOBIOM (Fricko et al. 2017), AIM/CGE (Fujimori et al. 2017), GCAM (Calvin et al. 2017), and REMIND-MAgPIE (Kriegler et al. 2017). The letters in parentheses refer to the panels in Figure 8.13. Energy and material efficiency relate to energy efficiency improvement and decrease in the intermediate input of materials, including steel, and cement. Dietary responses include less meat-intensive diets. Implications for urban areas relate to the mitigation options in Section 8.4.

Source: Adapted from Gurney et al. (2021).

SSP/RCP Frame-work	**Urbanization Context**	**Scenario Context**					
		Electrification	Energy and material efficiency	Technology development/ innovation	Renewable energy preferences	Behavioural, lifestyle and dietary responses	Afforestation and re-forestation
	Resource efficient,	High	High	High	High	High	High

SSP1 RCP1.9 (a) RCP2.6 (b)	walkable and sustainable rapid urbanization	**Implications for urban climate mitigation include:** → Electrification across the urban energy system while supporting flexibility in end-use → Resource efficiency from a consumption-based perspective with cross-sector integration → Knowledge and financial resources to promote urban experimentation and innovation → Empowerment of urban inhabitants for reinforcing positive lock-in for decarbonisation → Integration of sectors, strategies and innovations across different typologies and regions					
SSP2 RCP4.5 (d)	Moderate progress	Medium	Medium	Medium	Medium	Medium	Medium
SSP3 RCP7.0 (f)	Slow urbanization, inadequate urban planning	Medium	Low	Low	Medium	Low	Low
SSP4 RCP 3.4 (c) RCP6.0 (e)	Pace of urbanization differs with inequalities	Mixed	Mixed	Mixed	Mixed	Mixed	Mixed
SSP5 RCP8.5 (g)	Rapid urbanization with carbon lock-in	High	Low	High	Low	Low	-

Among the 500 urban areas with the highest consumption-based urban emissions footprint in 2015 (Moran et al. 2018), urban level emission scenarios under SSP1 conditions are constructed for 420 urban areas located across all regions of the world (Kılkış 2021a). These scenarios are based on urban level population projections by SSP (Kii 2021), trends in relevant CMIP6 scenarios (Gidden et al. 2019), and a 100% renewable energy scenario (Bogdanov et al. 2021). In the year 2020, the 420 urban areas are responsible for about 10.7 ± 0.32 $GtCO_2$-eq, or 27% of the global total CO_2 and CH_4 emissions of about 40 $GtCO_2$-eq, excluding aviation, shipping, and biogenic sources. Under three SSP1-based scenarios, the urban emissions of the 420 urban areas in 2030 is projected to be about 7.0 $GtCO_2$-eq in SSP1-RCP1.9, 10.5 $GtCO_2$-eq in SSP1-RCP2.6, and 5.2 $GtCO_2$-eq in the SSP1 renewable energy scenario.

The Illustrative Mitigation Pathways (IMPs) represent different strategies for maintaining temperature goals that are compliant with the Paris Agreement, as well as their comparison with the continuation of current policies (see Table 8.3 and Sections 1.5 and 3.2.5). The key characteristics that define the IMPs involve aspects of energy, land use, lifestyle, policy, and innovation. Urban areas provide cross-cutting contexts where each of these key characteristics can be enabled and have a particularly important role in the transformation pathways for renewable energy (IMP-Ren), low demand (IMP-LD), and shifting to sustainability (IMP-SP). Pathways that are compliant with the Paris Agreement include such urban implications as a reversal of decreasing land-use efficiency in urban areas to lower energy demand based on spatial planning for compact urban form (see Section 8.4.2), changes in urban infrastructure for supporting demand flexibility to handle variable energy supply (see Section 8.4.3), as well as policies and governance that are conducive to innovation in urban areas (see Section 8.5). Spatial planning for compact urban form can enable reduced energy demand and changes in service provisioning, including through walkable neighbourhoods and mixed land use, providing venues for socio-behavioural change towards active transport (see Section 8.4.5). Electrification and sector coupling in urban infrastructure can, for instance, be an important enabler of supporting higher penetrations of renewable energy in the energy system.

Table 8.3 Cross-cutting implications of the reference scenarios and Illustrative Mitigation Pathways (IMPs) for urban areas. The IMPs illustrate key themes of mitigation strategies throughout the WGIII report (Section 3.2.5). The implications of the key themes of the 6 IMPs (in addition to 2 Pathways illustrative of higher emissions) for mitigation in urban areas are represented based on the main storyline elements that involve energy, land use, food biodiversity and lifestyle, as well as policy and innovation. The cross-cutting implications of these elements for urban areas where multiple elements interact are summarized for each reference scenario and the IMPs. IMP-Ren, IMP-LD and IMP-SP represent pathways in the context of SSP1-1.9.

Source: Adapted from the key themes of the IMPs for urban areas.

Reference Scenarios and IMPs	Cross-Cutting Implications for Urban Areas
Current Policies (CurPol scenario)	→ Urban mitigation is challenged by overcoming lock-in to fossil fuel consumption also with car-based and low-density urban growth prevailing → Consumption patterns has land impacts, supply chains remain the same, urban inhabitants have limited participation in mitigation options → Progress in low-carbon urban development takes place at a relatively slower pace and there is limited policy learning within climate networks
Moderate Action (ModAct scenarios)	→ Renewable energy continues to increase its share that is supported by urban areas to a more limited extent with ongoing lock-in effects → Changes in land use, consumption patterns, and lifestyles mostly continue as before with negligible changes taking place—if any → The fragmented policy landscape also prevails at the urban level with different levels of ambitions and without integration across the urban system
Gradual Strengthening (IMP-GS)	→ Urban areas depend upon energy supply from distant power plants or those in rural areas without rapid progress in urban electrification → Afforestation/reforestation is supported with some delay while lower incentives for limiting growth in urban extent provide inconsistencies → The mobilization of urban actors for GHG emission reductions is strengthened more gradually with stronger coordination taking place after 2030
Net Negative Emissions (IMP-Neg)	→ Urban areas depend upon energy supply from distant power plants or those in rural areas with more limited electrification in urban energy systems → Afforestation/reforestation is supported to a certain extent while lower incentives for limiting growth in urban extent provide inconsistencies → Urban areas are less prominent in policy and innovation given emphasis on CCS options. Rural areas are more prominent considering BECCS
Renewable Electricity (IMP-Ren)	→ Urban areas support renewable energy penetration with electrification of urban infrastructure and sector coupling for increasing system flexibility → Consumption patterns and urban planning are able to reduce pressures on land use, demand response is increased to support renewables → Urban climate governance is enabling rapid deployment of renewable energy while fostering innovation for sustainable urban planning
Low Demand (IMP-LD)	→ Walkable urban form is increased, active and public transport modes are encouraged, low energy buildings and green-blue infrastructure is integrated → Changes in consumption patterns and urban planning reduce pressures on land use to lower levels while service provisioning is improved → Urban policy making is used to accelerate solutions that foster innovation and increased efficiencies across all sectors, including material use
Shifting Pathways (IMP-SP)	→ Urban areas are transformed to be resource efficient, low demand, and renewable energy supportive with an integrated approach in urban planning → Reinforcing measures enable GHG emission reductions from consumption patterns while also avoiding resource impacts across systems → Urban climate mitigation is best aligned with the SDGs to accelerate GHG emission reductions, increasing both scalability and acceptance

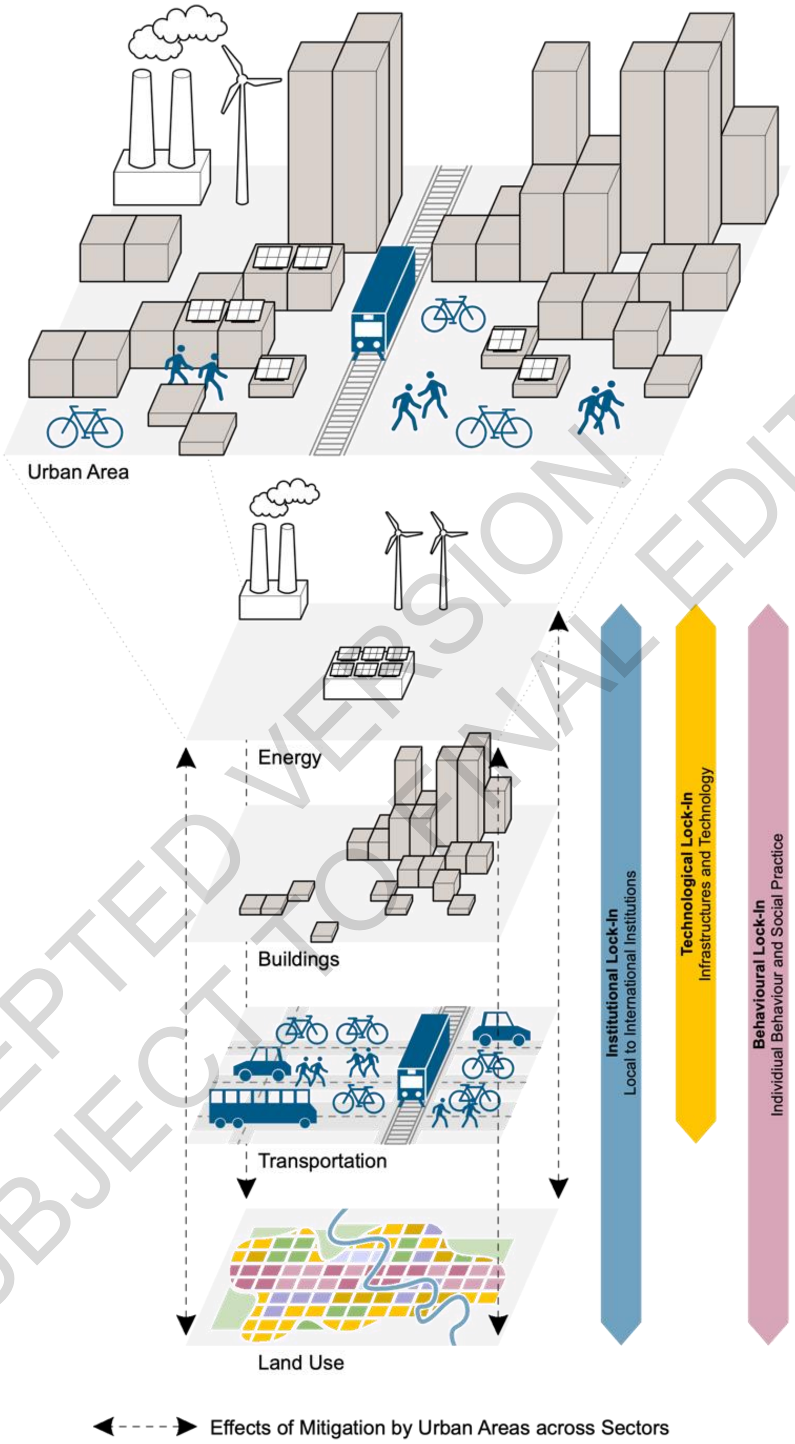
8.4 Urban mitigation options

Urban mitigation options can be categorized into three broad strategies: (1) reducing urban energy consumption across all sectors, including through spatial planning and infrastructure; (2) electrification and switching to net zero emissions resources; and (3) enhancing carbon stocks and uptake through urban green and blue infrastructure, which can also offer multiple co-benefits. A fourth, socio-behavioural aspects, can shift energy demand and emerge as the result of implementing the strategies. Urban mitigation options covered in this section are organized around these three strategies and can facilitate deep decarbonization through systemic transformation (see Section 8.6 and Figure 8.21 for prioritizing mitigation options based on urban form and urban growth typologies).

Urban areas are systems where multiple mitigation options—especially when integrated—have cascading effects across transport, energy, buildings, land use, and behaviour. These cascading effects take place both within and across urban systems (see Figure 8.15). Mitigation actions also occur at multiple urban scales, from households and blocks to districts and city regions, and can be implemented as standalone sectoral strategies, such as increasing energy efficiency for appliances, and also as system-wide actions. In reducing emissions locally, urban areas can help lower emissions outside of their administrative boundaries through their use of materials and resources, and by increasing the efficiency of infrastructure and energy use beyond what is possible with individual sectoral strategies. Urban mitigation policies that implement multiple integrated interventions will provide more emissions savings than the sum of individual interventions (Sethi et al. 2020).

Integrated action also has a key role in providing benefits for human well-being. Urban mitigation options and strategies that are effective, efficient, and fair can also support broader sustainability goals (Güneralp et al. 2017; Kona et al. 2018; Pasimeni et al. 2019). Due to the complex and intensive interactions in urban systems and the interlinked nature among the SDGs, cities can be important intervention points to harness synergies and co-benefits for achieving emissions reductions along with other SDGs (Nilsson et al. 2016; Corbett and Mellouli 2017) (see Section 8.2 and Figure 8.4).

Panel a)


Urban Area
Energy
Buildings
Transportation
Land Use
Institutional Lock-In
Local to International Institutions
Technological Lock-In
Infrastructures and Technology
Behavioural Lock-In
Individiual Behaviour and Social Practice
Effects of Mitigation by Urban Areas across Sectors

Panel b)

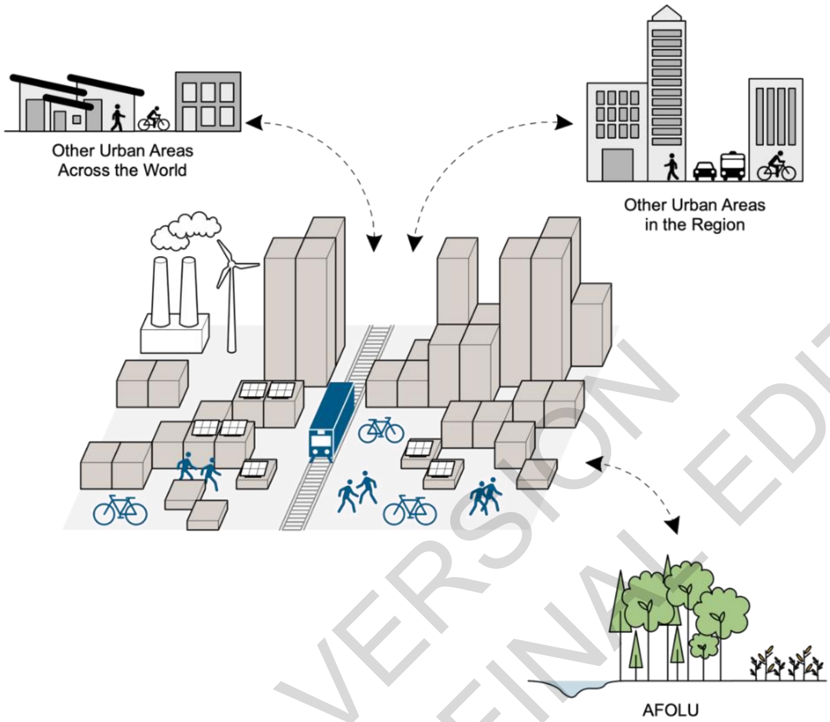


Figure 8.15 Urban systems, lock-in, and cascading effects of mitigation strategies.

Cities are systems of inter-connected sectors, activities, and governance structures. Urban-scale mitigation action can have cascading effects across multiple sectors, as shown in panel (a), as well as regional, national, and global impacts through supply chains, resource flows, and institutions, as show in panel (b). Mitigation efforts implemented at larger scales of governance or in sectors that transcend urban boundaries, like energy and transportation, can also facilitate and amplify mitigation at the urban scale, as shown by the arrows extending in both directions across layers (a). Because urban areas are connected locally and globally, urban mitigation efforts can also impact other cities and surrounding areas (AFOLU). Cities are prone to carbon lock-in due to the numerous reinforcing interactions among urban infrastructures and technologies, institutions, and individual and collective behaviours; see the side arrows extending across the layers in panel (a): the yellow arrow represents the infrastructure and technological lock-in involving user technologies and supporting infrastructure, the blue arrow indicates lock-in of local to international institutions, and the pink arrow represents behavioural lock-in for individuals and society. Urban carbon lock-is strongly determined by urban form, in particular the layout of streets and land-use mix. The different coloured spatial patterns represent varying levels of co-location of housing and jobs, and mobility options (also see Figure 8.16). Efforts to break urban carbon lock-in require meta-transformations to break inertia in and among infrastructures, institutions, and behaviours.

Source: Adapted in part from Seto et al. (2016)

8.4.1 Avoiding carbon lock-in

Carbon lock-in occurs as the result of interactions between different geographic and administrative scales (institutional lock-in) and across sectors (infrastructural and technological lock-in), which create the conditions for behavioural lock-in covering both individual and social structural behaviours (Seto et al. 2016) (see Glossary for a broader definition of 'lock-in'). The way that urban areas are designed, laid out, and built affects and is affected by the interactions across the different forms of carbon lock-in (see Figures 8.15 and 8.16). Cities are especially prone to carbon lock-in because of the multiple interactions of technological, institutional, and behavioural systems, which create inertia and path dependency that are difficult to break. For example, the lock-in of gasoline cars is reinforced by highway and energy infrastructures that are further locked-in by social and cultural preferences for individual mobility options. The dominance of cars and their supporting infrastructures in auto-centric urban forms is further reinforced by zoning and urban development patterns, such as dispersed and low-density housing distantly located from jobs, that create obstacles to create alternative mobility options (Seto et al. 2016) (see Figure 8.16 on urban form). (Linton et al. 2021)

Urban infrastructures and the built environment are long-lived assets, embodying triple carbon lock-ins in terms of their construction, operations, and demolition (Creutzig et al. 2016b; Seto et al. 2016; Ürge-Vorsatz et al. 2018). There is much focus in the climate change literature on the operational lifetimes of the energy sector, especially power plants and the electricity grid, which are between 30 and 60 years (Rode et al. 2017). Yet, in reality, the lifespans of urban infrastructures, especially the basic layout of roadways, are often much longer (Reyna and Chester 2015). A number of detailed case studies on the evolution of urban road networks for cities around the world reveal that the current layout of streets grew out of street networks that were established hundreds of years ago (Strano et al. 2012; Masucci et al. 2013; Mohajeri and Gudmundsson 2014). Furthermore, there is evidence that urban street layout, population growth, urban development, and automobile ownership co-evolve (Li et al. 2019a).

For cities to break out of mutually reinforcing carbon lock-in, it will require systematic transformation and systems-based planning that integrates mitigation strategies across sectors and geo-political scales. Urban energy demand patterns are locked-in whenever incremental urban design and planning decisions, coupled with investments in long-lasting infrastructure, such as roads and buildings, take place (Seto et al. 2016). The fundamental building blocks of cities are based on the layout of the street network, the size of city blocks, and the density of street intersections. If not significantly altered, these three factors will continue to shape and lock-in energy demand for decades after their initial construction, influencing the mitigation potential of urban areas (see Section 8.4.2 and Figure 8.22).

Avoiding carbon lock-in inherently involves decisions that extend beyond the administrative boundaries of cities. This includes pricing of low-emissions technology or materials, such as electric battery or hydrogen vehicles and buses, although cities can support their development and deployment (see Cross-Chapter Box 12 in Chapter 16 on Transition Dynamics). In contrast, urban governments in most parts of the world do have powers to set building codes that regulate materials and construction standards for buildings, including heating and cooling technologies, and major appliances. Other examples include zoning that determines the location of buildings, land uses, standards for densities, and the inclusion of energy planning in their building standards and public works, including streets, parks, and open spaces (Blanco et al. 2011; Raven et al. 2018).

8.4.2 Spatial planning, urban form, and infrastructure

Urban form is the resultant pattern and spatial layout of land use, transportation networks, and urban design elements, including the physical urban extent, configuration of streets and building orientation, and the spatial figuration within and throughout cities and towns (Lynch 1981; Handy 1996). Infrastructure describes the physical structures, social and ecological systems, and corresponding institutional arrangements that provide services and enable urban activity (Dawson et al. 2018; Chester 2019) and comprises services and built-up structures that support urban functioning, including transportation infrastructure, water and wastewater systems, solid waste systems, telecommunications, and power generation and distribution (Seto et al. 2014).

Urban Form

AR5 concluded that infrastructure and four dimensions of urban form are especially important for driving urban energy use: density, land use mix, connectivity, and accessibility. Specifically, low-carbon cities have the following characteristics: (1) co-located medium to high densities of housing, jobs, and commerce; (2) high mix of land uses; (3) high connectivity of streets; and (4) high levels of accessibility, distinguished by relatively low travel distances and travel times that are enabled by multiple modes of transportation. Urban areas with these features tend to have smaller dwelling units, smaller parcel sizes, walking opportunities, high density of intersections, and are highly accessible to shopping. For brevity, we will refer to these characteristics collectively as 'compact and walkable urban form' (see Figure 8.16). Compact and walkable urban form has many co-benefits, including mental and physical health, lower resource demand, and saving land for AFOLU. In contrast, dispersed and auto-centric urban form is correlated with higher GHG emissions, and characterized by separated land uses, low population and job densities, large block size, and low intersection density.

Figure 8.16 Urban form and implications for GHG emissions

Compact and walkable urban form is strongly correlated with low GHG emissions and characterized by co-located medium to high densities of housing and jobs, high street density, small block size, and mixed land use (Seto et al. 2014). Higher population densities at places of origin (e. g., home) and destination (e. g., employment, shopping) concentrate demand and are necessary for achieving the ASI approach for sustainable mobility (see Chapters 5 and 10). Dispersed and auto-centric urban form is strongly correlated with high GHG emissions, and characterized by separated land uses, especially of housing and jobs, low street density, large block sizes, and low urban densities. Separated and low densities of employment, retail, and housing increase average travel distances for both work and leisure, and make active transport and modal shift a challenge. Since cities are systems, urban form has interacting implications across energy, buildings, transport, land use, and individual behaviour. Compact and walkable urban form enables effective mitigation while dispersed and auto-centric urban form locks-in higher levels of energy use. The colours represent different land uses and indicate varying levels of co-location and mobility options.

Since AR5, a range of studies have been published on the relationships between urban spatial structures, urban form, and GHG emissions. Multiple lines of evidence reaffirm the key findings from AR5, especially regarding the mitigation benefits associated with reducing vehicle miles or kilometres travelled (VMT/VKT) through spatial planning. There are important cascading effects not only for transport but also other key sectors and consumption patterns, such as in buildings, households, and energy. However, these benefits can be attained only when the existing spatial structure of an urban area does not limit locational and mobility options, thereby avoiding carbon lock-in through the interaction of infrastructure and the resulting socio-behavioural aspects.

Modifying the layout of emerging urbanization to be more compact, walkable, and co-located can reduce future urban energy use by 20–25% in 2050 while providing a corresponding mitigation potential of 23–26% (Creutzig et al. 2015, 2016b; Sethi et al. 2020), forming the basis for other urban mitigation options. Cross-Chapter Box 7 in Chapter 10 provides perspectives on simultaneously reducing urban transport emissions, avoiding infrastructure lock-in, and providing accessible services (see Chapter 10). The systemic nature of compact urban form and integrated spatial planning influences 'Avoid-Shift-Improve' (ASI, see Glossary) options across several sectors simultaneously, including for mobility and shelter (for an in-depth discussion on the integration of service provision solutions within the ASI framework, see Section 5.3).

8.4.2.1 Co-located housing and jobs, mixed land use, and high street connectivity

Integrated spatial planning, co-location of higher residential and job densities, and systemic approaches are widely identified with development that is characterized by the 5Ds of TOD based on density, diversity (mixed land uses), design (street connectivity), destination accessibility, and distance to transit. Spatial strategies that integrate the 5Ds are shown to reduce VMT/VKT, and thereby transport-related GHG emissions through energy savings. The effect of urban form and built environment strategies on VMT per capita varies by a number of factors (Ewing and Cervero 2010; Stevens 2017; Blanco and Wikstrom 2018). Density and destination accessibility have the highest elasticities, followed by design (Stevens 2017). Population-weighted densities for 121 metropolitan areas have further found that the concentration of population and jobs along mass transit corridors decreases VMT/VKT significantly when compared to more dispersed metropolitan areas. In this sample, elasticity rates were twice as high for dense metropolitan areas located along mass transit lines (Lee and Lee 2020).

Meta-analyses of the reduction in VMT and the resulting GHG emissions consider the existing and still dominant use of emitting transportation technology, transportation fleets, and urban form characteristics. Varied historical legacies of transportation and the built environment, which can be utilized to develop more sustainable cities (Newman et al. 2016, 2017), are often not taken into account directly. Metropolitan policies and spatial planning, as evident in Copenhagen's Finger Plan, as well as strategic spatial planning in Stockholm and Seoul, have been major tools to restructure urban regions and energy patterns (Sung and Choi 2017). Road prices and congestion charges can provide the conditions for urban inhabitants to shift mobility demands and reduce vehicle use (see Section 5.6.2). Surprisingly, even cities with higher population densities and a greater range of land uses can show declines in these important attributes, which can lead to emissions increases, such as found in a study of 323 East and South East Asian cities (Chen et al. 2020c). Conversely, the annual CO_2 emissions reduction of passenger cars in compact versus dispersed urban form scenarios can include at least a 10% reduction by 2030 (Matsuhashi and Ariga 2016). When combined with advances in transport technology, this share increases to 64–70% in 2050 based on compact urban form scenarios for 1,727 municipalities (Kii 2020).

As a reaffirmation of AR5, population density reduces emissions per capita in the transport, building, and energy sectors (Baur et al. 2015; Gudipudi et al. 2016; Wang et al. 2017; Yi et al. 2017) (see also Sections 8.3.1 and 8.3.4 on past trends and forecasts of urban population density and land expansion). Urban compactness tends to reduce emissions per capita in the transport sector, especially for commuting (Matsuhashi and Ariga 2016; Lee and Lim 2018; Lee and Lee 2020). The relative accessibility of neighbourhoods to the rest of the region, in addition to the density of individual neighbourhoods, is important (Ewing et al. 2018). Creating higher residential and employment densities, developing smaller block sizes, and increasing housing opportunities in an employment area can significantly reduce household car ownership and car driving, and increase the share of transit, walk, and bicycle commuting (Ding et al. 2018). In addition to population density, land-use mix, rail transit accessibility, and street design reduce emissions from transport (Dou et al. 2016; Cao and Yang 2017; Choi 2018). The impact of population density and urban compactness on emissions per capita in the household or energy sector is also associated with socioeconomic characteristics or lifestyle preferences (Baiocchi et al. 2015; Miao 2017). Changes in the attributes of urban form and spatial structure have influences on overall energy demand across spatial scales, particularly street, block, neighbourhood, and city scales, as well as across the building (housing) and transport (mobility) sectors (Silva et al. 2017). Understanding the existing trade-offs (or synergetic links) between urban form variables across major emissions source sectors, and how they impact the size of energy flows within the urban system, is key to prioritizing action for energy-efficient spatial planning strategies, which are likely to vary across urban areas.

8.4.2.2 Urban form, growth, and sustainable development

Spatial planning for compact urban form is a system-wide intervention (Sethi et al. 2020) and has potential to be combined with sustainable development objectives while pursuing climate mitigation for urban systems (Große et al. 2016; Cheshmehzangi and Butters 2017; Facchini et al. 2017; Lwasa 2017; Stokes and Seto 2019). Compact urban form can enable positive impacts on employment and green growth given that the local economy is decoupled from GHG emissions and related parameters while the concentration of people and activity can increase productivity based on both proximity and efficiency (Lee and Erickson 2017; Salat et al. 2017; Gao and Newman 2018; Han et al. 2018; Li and Liu 2018; Lall et al. 2021)

Public acceptance can have a positive impact on integrated spatial planning especially when there is a process of co-design (Grandin et al. 2018; Webb et al. 2018). The quality of spatial planning can also increase co-benefits for health and well-being, including decisions to balance urban green areas with density (Li et al. 2016; Sorkin 2018; Pierer and Creutzig 2019). The distributional effects of spatial planning can depend on the policy tools that shape the influence of urban densification on affordable housing while evidence for transit-induced gentrification is found to be partial and inconclusive (Chava and Newman 2016; Jagarnath and Thambiran 2018; Padeiro et al. 2019; Debrunner and Hartmann 2020) (see Sections 8.2 and 8.4.4).

Reducing GHG emissions across different urban growth typologies (see Figure 8.20) depends in part on the ability to integrate opportunities for climate mitigation with co-benefits for health and well-being (Grandin et al. 2018). At the same time, requirements for institutional capacity and governance for cross-sector coordination for integrated urban planning is high given the complex relations between urban mobility, buildings, energy systems, water systems, ecosystem services, other urban sectors, and climate adaptation (Große et al. 2016; Castán Broto 2017a; Endo et al. 2017; Geneletti et al. 2017). The capacity for implementing land-use zoning and regulations in a way that is consistent with supporting spatial planning for compact urban form is not equal across urban areas and depends on different contexts as well as institutional capacities (Bakır et al. 2018; Deng et al. 2018; Shen et al. 2019).

Currently, integrating spatial planning, urban form, and infrastructure in urban mitigation strategies remains limited in mainstream practices, including in urban areas targeting an emissions reduction of 36–80% in the next decades (Asarpota and Nadin 2020). Capacity building for integrated spatial planning for urban mitigation includes increasing collaboration among city departments and with civil society to develop robust mitigation strategies, bringing together civil engineers, architects, urban designers, public policy and spatial planners, and enhancing the education of urban professionals (Asarpota and Nadin 2020) (see Section 8.5).

Spatial planning for compact urban form is a prerequisite for efficient urban infrastructure, including district heating and/or cooling networks (Swilling et al. 2018; Möller et al. 2019; Persson et al. 2019; UNEP and IRP 2020). District heating and cooling networks benefit from urban design parameters, including density, block area, and elongation that represent the influence of urban density on energy density (Fonseca and Schlueter 2015; Shi et al. 2020). Heat-demand density is a function of both population density and heat demand per capita and can be equally present in urban areas with high population density or high heat demand per capita (Möller et al. 2019; Persson et al. 2019). Low-temperature networks that utilize waste heat or renewable energy can provide an option to avoid carbon lock-in to fossil fuels while layout and eco-design principles can further optimize such networks (Gang et al. 2016; Buffa et al. 2019; Dominković and Krajačić 2019). Replacing gas-based heating and cooling with electrified district heating and cooling networks, for instance, provide 65% emissions reductions also involving carbon-aware scheduling for grid power (De Chalendar et al. 2019). The environmental and ecological benefits increase through the interaction of urban energy and spatial planning (Tuomisto et al. 2015; Bartolozzi et al. 2017; Dénarié et al. 2018; Zhai et al. 2020). These interactions include support for demand-side flexibility, spatial planning using geographic information systems, and access to renewable and urban waste heat sources (Möller et al. 2018; REN21 2020; Sorknæs et al. 2020; Dorotić et al. 2019) (see Table SM8.2 for other references).

8.4.3 Electrification and switching to net zero emissions resources

Pursuing the electrification mobility, heating, and cooling systems, while decarbonizing electricity and energy carriers, and switching to net zero materials and supply chains, represent important strategies for urban mitigation. Electrification of energy end uses in cities and efficient energy demand for heating, transport, and cooking through multiple options and urban infrastructure, has an estimated mitigation potential of at least 6.9 $GtCO_2$-eq by 2030 and 15.3 $GtCO_2$-eq by 2050 (Coalition for Urban Transitions 2019). Energy efficiency measures in urban areas can be enabled by urban form, building codes, retrofitting and renovation, modal shifts, and other options. Decarbonizing electricity supply raises the mitigation potential of efficient buildings and transport in urban areas to about 75% of the total estimate (Coalition for Urban Transitions 2019). In addition, relatively higher-density urban areas enable more cost-effective infrastructure investments, including electric public transport and large-scale heat pumps in districts that support electrification. Urban policymakers can play a key role in supporting carbon-neutral energy systems by acting as target setters and planners, demand aggregators, regulators, operators, conveners, and facilitators for coordinated planning and implementation across sectors, urban form, and demand (IEA 2021a; IRENA 2021).

8.4.3.1 Electrification and decarbonization of the urban energy system

Urban energy infrastructures often operate as part of larger energy systems that can be electrified, decarbonized, and become enablers of urban system flexibility through demand-side options. With multiple end-use sectors (e.g., transport, buildings) and their interactions with land use drawing on the same urban energy system(s), increasing electrification is essential for rapid decarbonization, renewable energy penetration, and demand flexibility (Kammen and Sunter 2016) (see IMPs in Sections 3.2.5 and 8.3.4). The mitigation potential of electrification is ultimately dependent on the carbon intensity of the electricity grid (Kennedy 2015; Hofmann et al. 2016; Peng et al. 2018; Zhang and Fujimori 2020) and starts providing lifecycle emission savings for carbon intensities below a threshold of 600 tCO_2-eq GWh^{-1} (Kennedy et al. 2019). Integrated systems of roof-top photovoltaics (PVs) and all-electric vehicles (EVs) alone could supply affordable carbon-free electricity to cities and reduce CO_2 emissions by 54%–95% (Brenna et al. 2014; Kobashi et al. 2021). Furthermore, electrification and decarbonization of the urban energy system holds widespread importance for climate change mitigation across different urban growth typologies and urban form (see Section 8.6 and Figure 8.21) and leads to a multitude of public health co-benefits (see Section 8.2).

Strategies that can bring together electrification with reduced energy demand based on walkable and compact urban form can accelerate and amplify decarbonization. Taking these considerations—across the energy system, sectors, and land use—contributes to avoiding, or breaking out of, carbon lock-in and allows continued emission savings as the energy supply is decarbonized (Kennedy et al. 2018; Teske et al. 2018; Seto et al. 2021). Indeed, electrification is already transforming urban areas and settlements and has the potential to continue transforming urban areas into net-negative electric cities that may sequester more carbon than emitted (Kennedy et al. 2018; Seto et al. 2021).

In its simplest form, electrification involves the process of replacing fossil fuel-based technologies with electrified innovations such as electric vehicles, buses, streetcars, and trains (see Sections 10.4.1 and 10.4.2), heat pumps, PVs (see Section 6.4.2.1), electric cook-stoves (see Section 9.8.2.1), and other technologies (Stewart et al. 2018). Cost-effective decarbonisation of energy use can be supported by electrification in urban areas if there is also demand-side flexibility for power, heat, mobility, and water with sector coupling (Guelpa et al. 2019; Pfeifer et al. 2021). Overall, demand-side flexibility across sectors in urban areas is supported by smart charging, electric mobility, electrified urban rail, power-to-heat, demand side response, and water desalination (Lund et al. 2015; Calvillo et al. 2016; Salpakari et al. 2016; Newman 2017; Meschede 2019).

As an enabler, electrification supports integrating net zero energy sources in urban infrastructure across sectors, especially when there is more flexible energy demand in mobility, heating, and cooling to absorb greater shares of variable renewable energy. In the transport sector, smart charging can reduce electric vehicle impacts on peak demand by 60% (IEA 2021a). Urban areas that connect efficient building clusters with the operation of smart thermal grids in district heating and cooling networks with large-scale heat pumps can support higher penetrations of variable renewable energy in smart energy systems (Lund et al. 2014, 2017). Higher urban densities provide the advantage of increasing the penetration of renewable power for deep decarbonization, including mixed-use neighbourhoods for grid balancing and electric public transport (Hsieh et al. 2017; Tong et al. 2017; Fichera et al. 2018; Kobashi et al. 2020). Based on these opportunities, urban areas that provide low-cost options to energy storage for integrating the power sector with multiple demands reduce investment needs in grid electricity storage capacities (Mathiesen et al. 2015; Lund et al. 2018).

Electrification at the urban scale encompasses strategies to aggregate energy loads for demand response in the urban built environment to reduce the curtailment of variable renewable energy and shifting time-of-use based on smart charging for redistributing energy demands (O'Dwyer et al. 2019). Peak shaving or shifting takes place among frequent interventions at the urban level (Sethi et al. 2020). Business models and utility participation, including municipal level demonstrations, can allow for upscaling (Gjorgievski et al. 2020; Meha et al. 2020). The urban system can support increasing demand-side flexibility in energy systems, including in contexts of 100% renewable energy systems (Drysdale et al. 2019; Thellufsen et al. 2020).

Smart grids in the urban system

Smart electricity grids enable peak demand reductions, energy conservation, and renewable energy penetration, and are a subset of smart energy systems. GHG emission reductions from smart grids range from 10 to 180 $gCO_2\ kWh^{-1}$ (grams of CO_2 per kilowatt-hour) with a median value of 89 $gCO_2\ kWh^{-1}$, depending on the electricity mix, penetration of renewable energy, and the system boundary (Moretti et al. 2017). Smart electricity grids are characterized by bi-directional flows of electricity and information between generators and consumers, although some actors can be both as 'prosumer' (see

Glossary). Two-way power flows can be used to establish peer-to-peer trading (P2P) (Hansen et al. 2020). Business models based on local citizen utilities (Green and Newman 2017; Green et al. 2020; Syed et al. 2020) and community batteries (Mey and Hicks 2019; Green et al. 2020) can support the realization of distributed energy and solar energy cities (Galloway and Newman 2014; Byrne and Taminiau 2016; Stewart et al. 2018; Allan 2020).

Currently, despite power outages that are costly to local economies, the adoption of smart electricity grids or smart energy systems have been slow in many developing regions, including in Sub-Saharan Africa (Westphal et al. 2017; Kennedy et al. 2019). This is due to a number of different factors, such as unreliable existing infrastructure, fractured fiscal authority, lack of electricity access in urban areas, upfront cost, financial barriers, inefficient pricing of electricity, and low consumer education and engagement (Venkatachary et al. 2018; Acakpovi et al. 2019; Cirolia 2020).

Pathways and trade-offs of electrification in urban systems

Urbanization and population density are one of the key drivers for enabling access to electricity across the world with benefits for sustainable development (Aklin et al. 2018). Grid-connected PV systems for urban locations that currently lack electricity access can allow urban areas to leapfrog based on green electrification (Abid et al. 2021). In the Global South, the conversion of public transport to electric transport, especially municipal buses (e.g., Bengaluru, India; Jakarta, Indonesia; Medellín, Colombia; Rio de Janeiro, Brazil; Quito, Ecuador) and micro-mobility (e.g., e-trikes in Manila, Philippines) have been quantified based on reductions in GHG and $PM_{2.5}$ emissions, avoided premature deaths, and increases in life expectancies (IEA 2014; C40 Cities 2018, 2020b,c,d,e). In 22 Latin American cities, converting 100% of buses and taxis in 2030 to electric were estimated to result in a reduction of 300 $MtCO_2$-eq compared to 2017 (ONU Medio Ambiente 2017). Yet the scaling up of electric vehicles in cities can be examined within a larger set of possible social objectives, such as reducing congestion and the prioritization of other forms of mobility.

Electrification requires a layering of policies at the national, state, and local levels. Cities have roles as policy architects, including transit planning (e.g., EV targets and low-emissions zones, restrictions on the types of energy use in new buildings, etc.), implementers (e.g., building codes and compliance checking, financial incentives to encourage consumer uptake of EV's and heat pumps, etc.), and complementary partners to national and state policymaking (e.g., permitting or installation of charging infrastructure) (Broekhoff et al. 2015). The number of cities that have instituted e-mobility targets that aim for a certain percentage of EV's sold, in circulation or registered, is increasing (REN21 2021). Realizing the mitigation potential of electrification will require fiscal and regulatory policies and public investment (Hall et al. 2017a; Deason and Borgeson 2019; Wappelhorst et al. 2020) (see Section 8.5).

EVs are most rapidly deployed when there has been a suite of policies, including deployment targets, regulations and use incentives (e.g., zero-emission zone mandates, fuel economy standards, building codes), financial incentives (e.g., vehicles, chargers), industrial policies (e.g., subsidies), and fleet procurement (IEA 2016b, 2017, 2018, 2020a; Cazzola et al. 2019). The policy mix has included mandates for bus deployment, purchase subsidies, or split ownership of buses and chargers (IEA 2021b) (see Chapter 10). Subsidies are often critical to address the often-higher upfront costs of electric devices. In other instances, the uptake of electric induction stoves was increased through government credit and allotment of free electricity (Martínez et al. 2017; Gould et al. 2018).

Bringing multiple stakeholders together in local decision-making for smart energy systems requires effort beyond usual levels while multi-actor settings can be increased to enable institutional conditions (Lammers and Hoppe 2019). Public participation and community involvement in the planning, design and operation of urban energy projects can be an enabler of decarbonizing local energy demands (Corsini et al. 2019). Cooperation across institutions is important for municipalities that are engaged in strategic energy planning and implementation for smart energy systems (Krog 2019) (see Section 8.5).

Electrification technologies can present potential trade-offs that can be minimized through governance strategies, smart grid technologies, circular economy practices, and international cooperation. One consideration is the increase in electricity demand (see 5.3.1.1). Across 23 megacities in the world (population greater than 10 million people), electrification of the entire gasoline vehicle fleet could increase electricity demand on average by 18% (Kennedy et al. 2018). How grid capacity will be impacted is dependent on the match between daily electricity loads and supply (Tarroja et al. 2018). Materials recycling of electrification technologies are also key to minimising potential environmental and social costs (Church and Crawford 2018; Gaustad et al. 2018; Sovacool et al. 2020) and can ensure electrification reaches its complete mitigation potential. Circular economy strategies are particularly valuable to this goal by creating closed-loop supply chains through recycling, material recovery, repair, and reuse. For instance, the PV Cycle program in Europe prevented more than 30,000 metric tonnes of renewable technology from reaching the waste stream (Sovacool et al. 2020) (see Box 10.7 as well as 'circular economy' in Glossary).

8.4.3.2 Switching to net zero emissions materials and supply chains

For the carbon embodied in supply chains to become net zero, all key infrastructure and provisioning systems will need to be decarbonized, including electricity, mobility, food, water supply, and construction (Seto et al. 2021). The growth of global urban populations that is anticipated over the next several decades will create significant demand for buildings and infrastructure. As cities expand in size and density, there is an increase in the production of mineral-based structural materials and enclosure systems that are conventionally associated with mid- and high-rise urban construction morphologies, including concrete, steel, aluminium, and glass. This will create a significant spike in GHG emissions and discharge of CO_2 at the beginning of each building lifecycle, necessitating alternatives (Churkina et al. 2020).

The initial carbon debt incurred in the production stage, even in sustainable buildings, can take decades to offset through operational stage energy efficiencies alone. Increased reduction in the energy demands and GHG emissions associated with the manufacture of mineral-based construction materials will be challenging, as these industries have already optimized their production processes. Among the category of primary structural materials, it is estimated that final energy demand for steel production can be reduced by nearly 30% compared to 2010 levels, with 12% efficiency improvement for cement (Lechtenböhmer et al. 2016). Even when industries are decarbonized, residual CO_2 emissions will remain from associated chemical reactions that take place in calcination and use of coke from coking coal to reduce iron oxide (Davis et al. 2018). Additionally, carbon sequestration by cement occurs over the course of the building lifecycle in quantities that would offset only a fraction of their production stage carbon spike (Xi et al. 2016; Davis et al. 2018). Moreover, there are collateral effects on the carbon cycle related to modern construction and associated resource extraction. The production of cement, asphalt, and glass requires large amounts of sand extracted from beaches, rivers, and seafloors, disturbing aquatic ecosystems and reducing their capacity to absorb atmospheric carbon. The mining of ore can lead to extensive local deforestation and soil degradation (Sonter et al. 2017). Deforestation significantly weakens the converted land as a carbon sink and in severe cases may even create a net emissions source.

A broad-based substitution of monolithic engineered timber systems for steel and concrete in mid-rise urban buildings offers the opportunity to transform cityscapes from their current status as net sources of GHG emissions into large-scale, human-made carbon sinks. The storage of photosynthetic forest carbon through the substitution of biomass-based structural materials for emissions-intensive steel and concrete is an opportunity for urban infrastructure. The construction of timber buildings for 2.3 billion new urban dwellers from 2020 to 2050 could store between 0.01 and 0.68 $GtCO_2$ per year depending on the scenario and the average floor area per capita. Over thirty years, wood-based construction can accumulate between 0.25 and 20 $GtCO_2$ and reduce cumulative emissions from 4 $GtCO_2$ (range of 7–20 $GtCO_2$) to 2 $GtCO_2$ (range of 0.3–10 $GtCO_2$) (*high confidence*) (Churkina et al. 2020).

Figure 8.17 indicates that new and emerging structural assemblies in engineered timber rival the structural capacity of steel and reinforced concrete while offering the benefit of storing significant quantities of atmospheric carbon (see also Figure 8.22). Mass timber refers to engineered wood products that are laminated from smaller boards or lamella into larger structural components such as glue-laminated (glulam) beams or cross-laminated timber (CLT) panels. Methods of mass-timber production that include finger-jointing, longitudinal and transverse lamination with both liquid adhesive and mechanical fasteners have allowed for the re-formulation of large structural timbers. The parallel-to-grain strength of mass (engineered) timber is similar to that of reinforced concrete (Ramage et al. 2017). As much as half the weight of a given volume of wood is carbon, sequestered during forest growth as a by-product of photosynthesis (Martin et al. 2018). Mass timber is inflammable, but in large sections forms a self-protective charring layer when exposed to fire that will protect the remaining 'cold wood' core. This property, formed as massive structural sections, is recognized in the fire safety regulations of building codes in several countries, which allow mid- and high-rise buildings in timber. Ongoing studies have addressed associated concerns about the vulnerability of wood to decay and the capacity of structural timber systems to withstand seismic and storm related stresses.

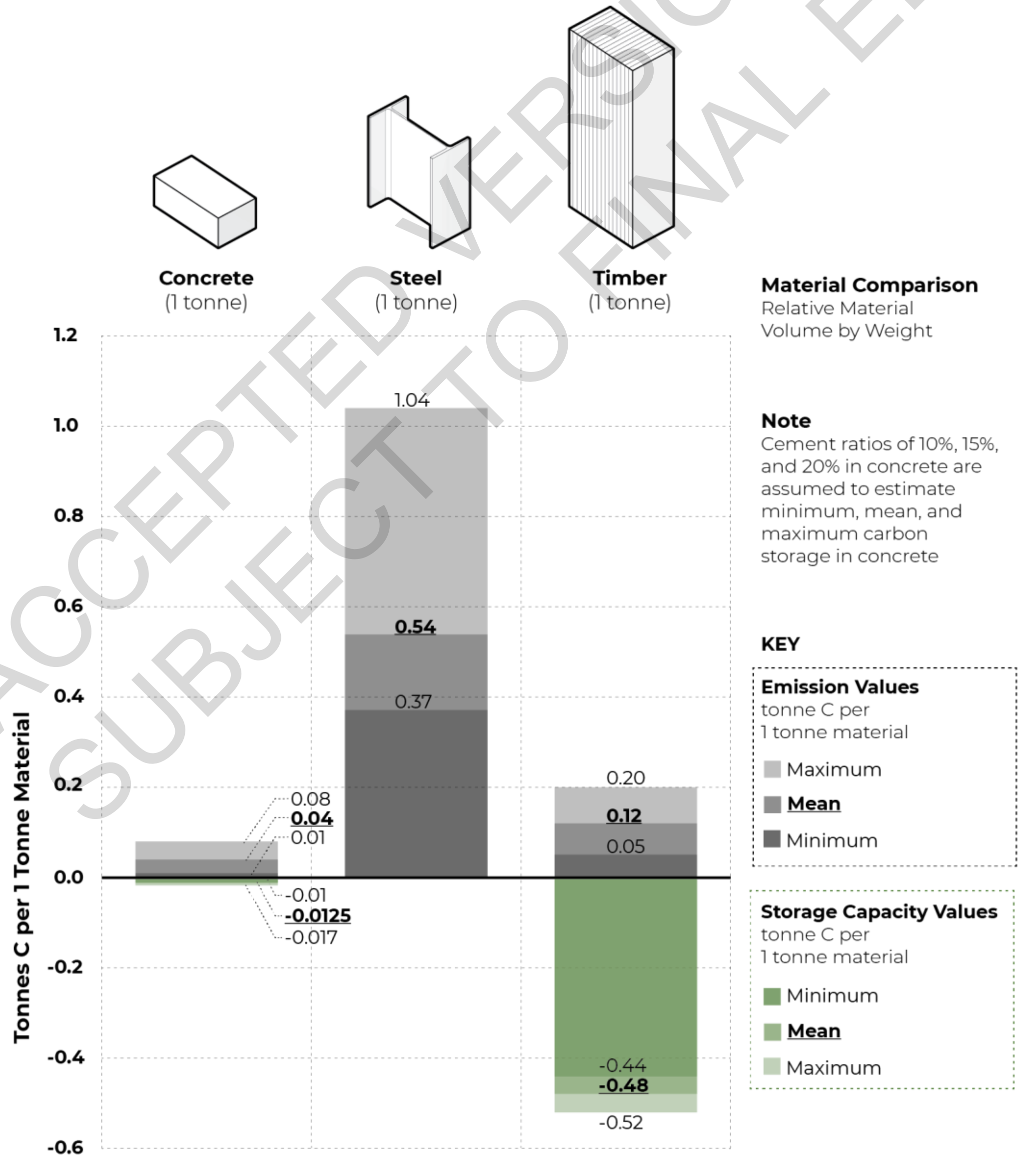


Figure 8.17 Relative volume of a given weight, its carbon emissions, and carbon storage capacity of primary structural materials comparing one tonne of concrete, steel, and timber

Concrete and steel have substantial embodied carbon emissions with minimal carbon storage capacities, while timber stores a considerable quantity of carbon with a relatively small ratio of carbon emissions-to-material volume. The displayed carbon storage of concrete is the theoretical maximum value, which may be achieved after hundreds of years. Cement ratios of 10%, 15%, and 20% are assumed to estimate minimum, mean, and maximum carbon storage in concrete. Carbon storage of steel is not displayed as it is negligible (0.004 tonne C per tonne of steel). The middle-stacked bars represent the mean carbon emission or mean carbon storage values displayed in bold font and underlined. The darker and lighter coloured stacked bars depict the minimum and maximum values. Grey tones represent carbon emissions and green tones are given for storage capacity values. Construction materials have radically different volume-to-weight ratios, as well as material intensity (see representation by a structural column in the upper panel. These differences should be accounted for in the estimations of their carbon storage and emissions (see also Figure 8.22).

Source: Adapted from Churkina et al. (2020)

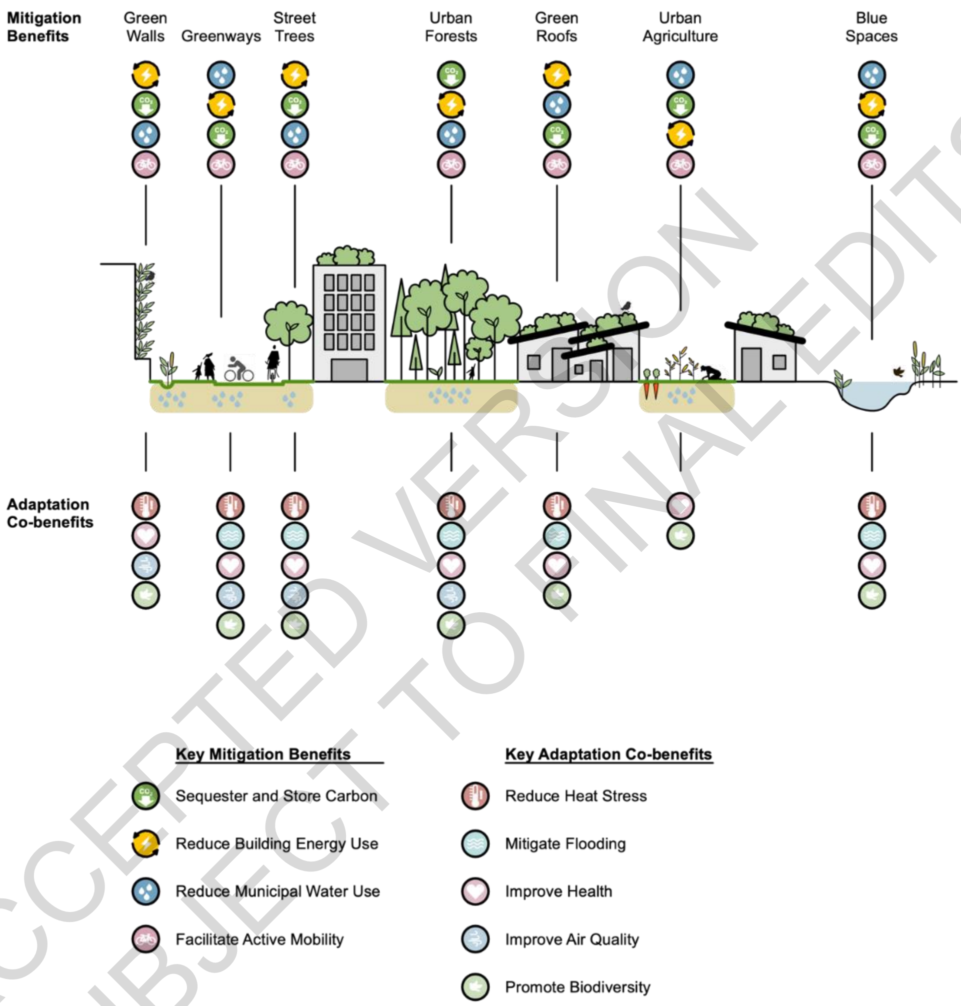
Transitioning to biomass-based building materials, implemented through the adoption of engineered structural timber products and assemblies, will succeed as a mitigation strategy only if working forests are managed and harvested sustainably (Churkina et al. 2020). Since future urban growth and the construction of timber cities may lead to increased timber demand in regions with low forest cover, it is necessary to systematically analyse timber demand, supply, trade, and potential competition for agricultural land in different regions (Pomponi et al. 2020). The widespread adoption of biomass-based urban construction materials and techniques will demand more robust forest and urban land governance and management policies, as well as internationally standardized carbon accounting methods to properly value and incentivize forest restoration, afforestation, and sustainable silviculture.

Expansion of agroforestry practices may help to reduce land-use conflicts between forestry and agriculture. Harvesting pressures on forests can be reduced through the reuse and recycling of wooden components from dismantled timber buildings. Potential synergies between the carbon sequestration capacity of forests and the associated carbon storage capacity of dense mid-rise cities built from engineered timber offer the opportunity to construct carbon sinks deployed at the scale of landscapes, sinks that are at least as durable as other buildings (Churkina et al. 2020). Policies and practices promoting design for disassembly and material reuse will increase their durability.

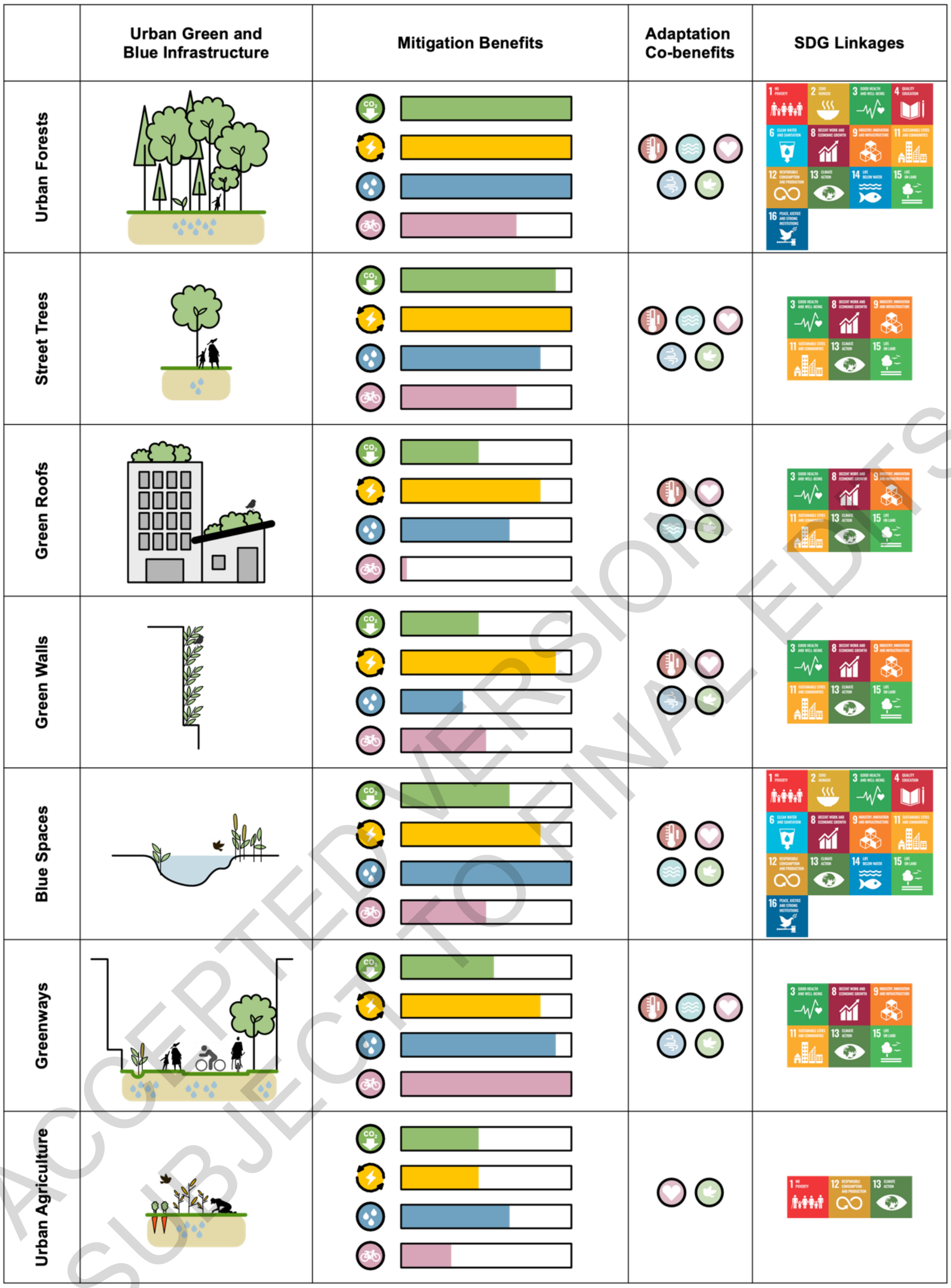
8.4.4 Urban green and blue infrastructure

The findings of AR6 WGI and WGII have underscored the importance of urban green and blue infrastructure for reducing the total warming in urban areas due to its local cooling effect on temperature and its benefits for climate adaptation (IPCC 2021; Cross-Working Group Box 2 in this chapter). Urban green and blue infrastructure in the context of NBS involves the protection, sustainable management, and restoration of natural or modified ecosystems while simultaneously providing benefits for human well-being and biodiversity (IUCN 2021) (see Glossary for additional definitions). As an umbrella concept, urban NBS integrates established ecosystem-based approaches that provide multiple ecosystem services and are important in the context of societal challenges related to urbanization, climate change, and reducing GHG emissions through the conservation and expansion of carbon sinks (Naumann et al. 2014; Raymond et al. 2017) (see Section 8.1.6.1).

Urban green and blue infrastructure includes a wide variety of options, from street trees, parks, and sustainable urban drainage systems (Davis and Naumann 2017), to building-related green roofs or green facades, including green walls and vertical forests (Enzi et al. 2017). Figure 8.18 synthesizes urban green and blue infrastructure based on urban forests, street trees, green roofs, green walls, blue spaces, greenways, and urban agriculture. Key mitigation benefits, adaptation co-benefits, and SDG linkages are represented by types of green and blue infrastructure. Local implementations of urban green and blue infrastructure can pursue these linkages while progressing toward inclusive sustainable urban planning (SDG 11.3) and the provision of safe, inclusive and accessible green and public spaces for all (SDG 11.7) (Butcher-Gollach 2018; Pathak and Mahadevia 2018; Rigolon et al. 2018; Anguelovski et al. 2019; Buyana et al. 2019; Azunre et al. 2021) (see Section 8.2).



Panel a



Panel b

Figure 8.18 Key mitigation benefits, adaptation co-benefits, and SDG linkages of urban green and blue infrastructure

Panel (a) illustrates the potential integration of various green and blue infrastructure strategies within an urban system. Panel (b) evaluates those strategies in the context of their mitigation benefits, adaptation co-benefits, and linkages to the SDGs. Urban forests and street trees provide the greatest mitigation benefit because of their ability to sequester and store carbon while simultaneously reducing building

energy demand. Moreover, they provide multiple adaptation co-benefits and synergies based on the linkages to the SDGs (see Figure 8.4). The assessments of mitigation benefits are dependent on context, scale, and spatial arrangement of each green and blue infrastructure type and their proximity to buildings. Mitigation benefits due to reducing municipal water use are based on reducing wastewater loads that reduce energy use in wastewater treatment plants. The sizes in the bars are illustrative and their relative size is based on the authors' best understanding and assessment of the literature.

8.4.4.1 The mitigation potential of urban trees and associated co-benefits

Due to their potential to store relatively high amounts of carbon compared to other types of urban vegetation, as well as their ability to provide many climate mitigation co-benefits (*medium agreement, limited evidence*), natural area protection and natural forest management in urban areas is an important priority for cities looking to mitigate climate change. Globally, urban tree cover averages 26.5%, but varies from an average of 12% in deserts to 30.4% in forested regions (Nowak and Greenfield 2020).

Global urban tree carbon storage is approximately 7.4 billion tonnes (GtC) given 363 million hectares of urban land, 26.5% tree cover, and an average carbon storage density of urban tree cover of 7.69 kgC/m^2 (kilograms carbon per square metre) (Nowak et al. 2013; World Bank et al. 2013). Estimated global annual carbon sequestration by urban trees is approximately 217 million tonnes (MtC) given an average carbon sequestration density per unit urban tree cover of 0.226 kgC/m^2 (Nowak et al. 2013). With an average plantable (non-tree and non-impervious) space of 48% globally (Nowak and Greenfield 2020), the carbon storage value could nearly triple if all this space is converted to tree cover. In Europe alone, if 35% of the urban surfaces (26450 km^2) were transformed into green surfaces, the mitigation potential based on carbon sequestration would be an estimated 25.9 MtCO$_2$ year^{-1} with the total mitigation benefit being 55.8 MtCO$_2$ year^{-1}, including an energy saving of about 92 TWh year^{-1} (Quaranta et al. 2021). Other co-benefits include reducing urban runoff by about 17.5% and reducing summer temperatures by 2.5°C–6°C (Quaranta et al. 2021).

Urban tree carbon storage is highly dependent on biome. For example, carbon sequestered by vegetation in Amazonian forests is two- to five-times higher compared to boreal and temperate forests (Blais et al. 2005). At the regional level, the estimated carbon storage density rates of tree cover include a range of 3.14–14.1 kgC/m^2 in the United States, 3.85–5.58 kgC/m^2 in South Korea, 1.53–9.67 kgC/m^2 in Barcelona, 28.1–28.9 kgC/m^2 in Leicester, England, and an estimated 6.82 kgC/m^2 in Leipzig, Germany and 4.28 kgC/m^2 in Hangzhou, China (Nowak et al. 2013). At the local scale, above- and below-ground tree carbon densities can vary substantially, as with carbon in soils and dead woody materials. The conservation of natural mangroves have been shown to provide urban mitigation benefits through carbon sequestration, as demonstrated in the Philippines (Abino et al. 2014). Research on urban carbon densities from the Southern hemisphere will contribute to better estimates.

On a per-tree basis, urban trees offer the most potential to mitigate climate change through both carbon sequestration and GHG emissions reduction from reduced energy use in buildings (Nowak et al. 2017). Maximum possible street tree planting among 245 world cities could reduce residential electricity use by about 0.9–4.8% annually (McDonald et al. 2016). Urban forests in the United States reduce building energy use by 7.2%, equating to an emissions reduction of 43.8 MtCO$_2$ annually (Nowak et al. 2017).

Urban trees can also mitigate some of the impacts of climate change by reducing the UHI effect and heat stress, reducing stormwater runoff, improving air quality, and supporting health and well-being in areas where the majority of the world's population resides (Nowak and Dwyer 2007). Urban forest planning and management can maximize these benefits for present and future generations by sustaining optimal tree cover and health (also see SDG linkages in Figure 8.4). Urban and peri-urban (see Glossary) agriculture can also have economic benefits from fruit, ornamental, and medicinal trees (Gopal and Nagendra 2014; Lwasa 2017; Lwasa et al. 2018).

START BOX 8.2 HERE

Box 8.2 Urban carbon storage: An example from New York City

The structure, composition, extent, and growing conditions of vegetation in cities has an influence on their potential for mitigating climate change (Pregitzer et al. 2021). Urban natural areas, particularly forested natural areas, grow in patches and contain many of the same components as non-urban forests, such as high tree density, down woody material, and regenerating trees (see Figure 1).

Urban forested natural areas have unique benefits as they can provide habitat for native plants and animals, protecting local biodiversity in a fragmented landscape (Di Giulio et al. 2009). Forests can have a greater cooling effect on cities than designed greenspaces, and the bigger the forest the greater the effect (Jaganmohan et al. 2016). In New York City, urban forested natural areas have been found to account for the majority of trees estimated in the city (69%), but are a minority of the total tree canopy (25%, or 5.5% of the total city land area) (Pregitzer et al. 2019a). In New York City, natural areas are estimated to store a mean of 263.5 Mg C ha^{-1} (megagram carbon per hectare), adding up to 1.86 TgC (teragram carbon) across the city, with the majority of carbon (86%) being stored in the trees and soils (Pregitzer et al. 2021). These estimates are similar to per-hectare estimates of carbon storage across different pools in non-urban forest types (see Table 1), and 1.5-times greater than estimates for carbon stored in just trees across the entire city (Pregitzer et al. 2021).

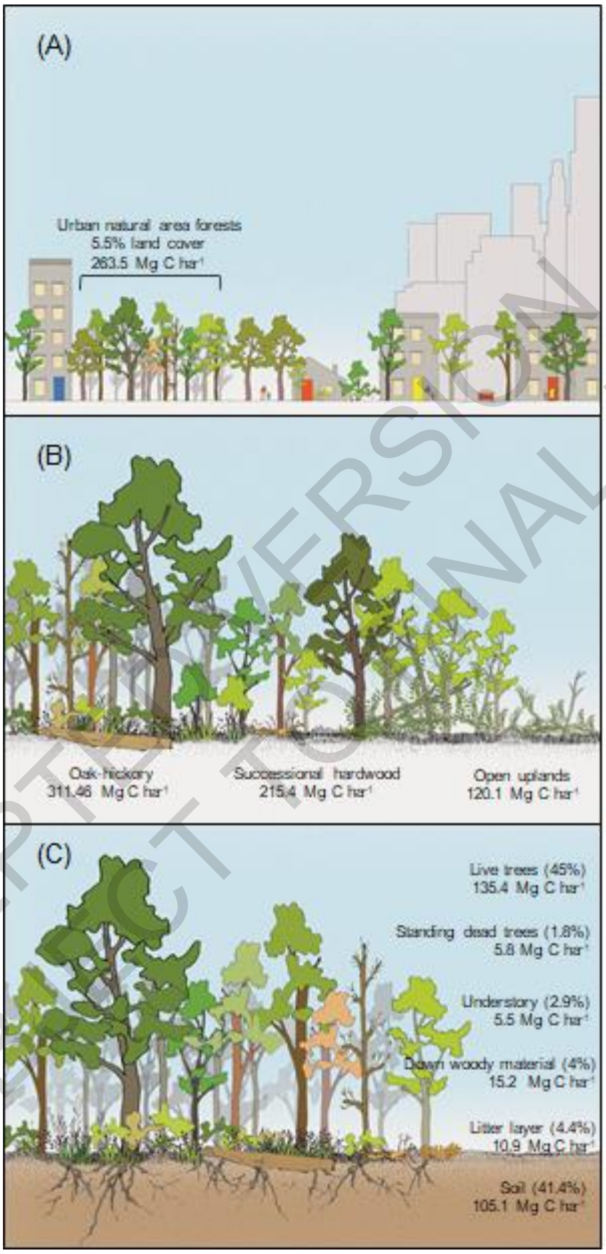
Within urban natural areas, the amount of carbon stored varies widely based on vegetation type, tree density, and the species composition (see Figure 1). The oak-hardwood forest type is one of the most abundant in New York City's natural areas and is characterized by large and long-lived native hardwood tree species, with relatively dense wood. These forests store an estimated 311.5 Mg C ha^{-1}. However, non-native exotic invasive species can be prevalent in the understory vegetation layer (<1m height), and account for about 50% of cover in New York City (Pregitzer et al. 2019b).

This could lead to a trajectory where exotic understory species, which are often herbaceous, out-compete regenerating trees in the understory layer, alter the soil (Ward et al. 2020), and alter the forest canopy (Matthews et al. 2016). A change in New York City's vegetation structure and composition to a more open vegetation type could reduce the carbon storage by over half (open grassland 120.1 Mg C ha^{-1}).

When compared to estimates of carbon storage presented in other studies, the components (pools) of the natural area forests in New York City store carbon in similar proportions to other non-urban forests (see Table 1). This might suggest that in other geographies, similar adjacent non-urban forest types may store similar carbon stocks per unit area (*medium confidence*). However, despite similarities to non-urban forests, the urban context can lead to altered forest function and carbon cycling that should be considered. For example, trees growing in urban areas have been observed to grow at much higher rates due to higher access to light, nutrients, and increased temperatures (Gregg et al. 2003; Reinmann et al. 2020).

Higher growth rates coupled with the UHI effect have also been suggested to yield greater evaporative cooling by urban canopies relative to rural forests (Winbourne et al. 2020). Based on estimates in New York City, it is likely that the majority of tree biomass, and carbon in trees in cities, could be found in urban natural area forest patches (*medium agreement, limited evidence*). More research is needed to map urban natural areas, assess vegetation, and differentiate tree canopy types (natural vs. non-natural) at fine scales within many cities and geographies. Accurate maps, as well as greater understanding of definitions of urban canopies and vegetation, could lead to better accounts for carbon stocks and the many other unique benefits they provide (Raciti et al. 2012; Pregitzer et al. 2019a).

Despite this potential, natural areas are inherently a minority land use type in cities and should be viewed along with other types of urban tree canopy that occur in more designed environments that might out-perform natural areas in other ecosystem services. The mosaic of vegetation characteristics and growing conditions will yield different ecosystem services across cities (Pataki et al. 2011) and should be an important consideration in planning, management, and policy in the future.



Box 8.2, Figure 1 Estimates for carbon storage in natural area forests in New York City

(a) Mean estimated carbon stock per hectare in natural area forests (Pregitzer et al. 2019a, 2021); (b) estimates for carbon stocks vary based on vegetation types; and (c) estimates of the amount of carbon stock in different forest pools per hectare. The proportion of the total estimated carbon stock per pool is out of the total estimated for the entire city (1.86 TgC).

Source: Figure from Pregitzer et al. (2021)

Box 8.2, Table 1 A selection of benchmark reference estimates of different carbon pools sampled and the related urban considerations to contextualize the results from New York City (NYC), United States (US) natural area carbon stocks. The benchmark estimates are intended to provide a point of reference to help contextualize the calculations for carbon pools in NYC's forests. Forest carbon is highly variable and dependent on microclimatic conditions such as moisture, microbial communities, and nutrient availability, all of which can be impacted by human activity in urban or altered environments. Standard errors and 95% confidence intervals can be found in Pregitzer et al. (2021). DBH: diameter at breast height; DWM: down woody material; and FWM: fine woody material.

Source: Pregitzer et al. (2021).

Pool considered in NYC Natural Area	Published Estimates of Carbon Stock (Mg C ha^{-1})	NYC Estimated Carbon Stock (Mg C ha^{-1})	Urban Considerations
Live Trees: All trees (>2 cm DBH) including above and below ground	87.1 - North-eastern US (Smith et al. 2013) 73.3 - NYC assuming 100% cover (Nowak et al. 2013)	135.4	Lower ozone levels, higher CO_2, warmer temperatures, and higher nutrient deposition could lead to increase growth rates and annual carbon sequestration. However, pollutants in soil (e.g., heavy metals), increased pests, and GHGs in the atmosphere (e.g., NO_X and SO_2) could decrease annual tree growth and carbon sequestration (Gregg et al. 2003)
Groundcover: All vegetation growing <1 m height	1.8 - North-eastern US (Smith et al. 2013)	5.5	Anthropogenic disturbance creates canopy gaps that accelerate herbaceous growth; invasive vines are prevalent in urban forests that can alter tree survival and growth and soils (Matthews et al. 2016; Ward et al. 2020)
Standing Dead Trees	5.1 - North-eastern US (Smith et al. 2013) 2.59 - Massachusetts (Liu et al. 2006)	5.8	Removal may occur due to safety considerations
DWM: Coarse (>10 cm) and FWM (>0.1 cm)	9.18 - Coarse woody material – New York state 2.52 - Coarse woody material- Massachusetts (Liu et al. 2006) 6.37 - Fine woody material- New York (Woodall et al. 2013) 3.67 - Fine woody material Northern hardwood; 0 to 227.94 - Northern US (Domke et al. 2016)	15.25 (added together DWM and FWM)	Removal may occur due to safety considerations
Litter and Duff: Depth measured	12 - NYC (Pouyat et al. 2002) 9.36 - Northern hardwood; 0.04 to 86.1, Northern US (Domke et al. 2016)	10.95	Decomposition increases with temperature (Hanson et al. 2003); decreased ozone levels facilitate litter decay (Carreiro et al. 2009)
Mineral Soil (Organic 30 cm)	104 - to 30 cm depth, NYC (Cambou et al. 2018) 50 - to 10 cm depth, NYC (Pouyat et al. 2002)	105.11(30 cm) and 77.78 (10 cm)	UHI and pollution alter the litter chemistry, decomposer organisms, conditions, and resources, which all influence respiration rates (Carreiro et al. 2009); earthworms, prevalent in urban areas, accelerate decay, but some carbon is sequestered in passive pools (Pouyat et al. 2002). Soil could be compacted.

END BOX 8.2 HERE

8.4.4.2 Benefits of green roofs, green walls, and greenways

Green roofs and green walls have potential to mitigate air and surface temperature, improve thermal comfort, and mitigate UHI effects (Jamei et al. 2021; Wong et al. 2021), while lowering the energy demand of buildings (Susca 2019) (see Figure 8.18). Green roofs have the highest median cooling effect in dry climates (3°C) and the lowest cooling effect in hot, humid climates (1°C) (Jamei et al. 2021). These mitigation potentials depend on numerous factors and the scale of implementation. The temperature reduction potential for green roofs when compared to conventional roofs can be about 4°C in winter and about 12°C during summer conditions (Bevilacqua et al. 2016). Green roofs can reduce building heating demands by about 10–30% compared to conventional roofs (Besir and Cuce 2018), 60–70% compared to black roofs, and 45–60% compared to white roofs (Silva et al. 2016). Green walls or facades can provide a temperature difference between air temperature outside and behind a green wall of up to 10°C, with an average difference of 5°C in Mediterranean contexts in Europe (Perini et al. 2017). The potential of saving energy for air conditioning by green facades can be around 26% in summer months. Considerations of the spatial context are essential given their dependence on climatic conditions (Susca 2019). Cities are diverse and emissions savings potentials depend on several factors, while the implementation of green roofs or facades may be prevented in heritage structures.

Green roofs have been shown to have beneficial effects in stormwater reduction (Andrés-Doménech et al. 2018). A global meta-analysis of 75 international studies on the potential of green roofs to mitigate runoff indicate that the runoff retention rate was on average 62% but with a wide range (0–100%) depending on a number of interdependent factors (Zheng et al. 2021). These factors relate to the characteristics of the rainfall event (e.g., intensity) and characteristics of the green roof (e.g., substrate, vegetation type, and size), and of the climate and season type. A hydrologic modelling approach applied to an Italian case demonstrated that implementing green roofs may reduce peak runoff rates and water volumes by up to 35% in a 100% green roof conversion scenario (Masseroni and Cislaghi 2016).

Greenways support stormwater management to mitigate water runoff and urban floods by reducing the water volume (e.g., through infiltration) and by an attenuation or temporal shift of water discharge (Fiori and Volpi 2020; Pour et al. 2020). Using green infrastructure delays the time to runoff and reduces water volume but depends on the magnitude of floods (Qin et al. 2013). Measures are most effective for flood mitigation at a local scale; however, as the size of the catchment increases, the effectiveness of reducing peak discharge decreases (Fiori and Volpi 2020). Reduction of water volume through infiltration can be more effective with rainfall events on a lower return rate. Overall, the required capacity for piped engineered systems for water runoff attenuation and mitigation can be reduced while lowering flow rates, controlling pollution transport, and increasing the capacity to store stormwater (Srishantha and Rathnayake 2017). Benefits for flood mitigation require a careful consideration of the spatial context of the urban area, the heterogeneity of the rainfall events, and characteristics of implementation (Qiu et al. 2021). Maintenance costs and stakeholder coordination are other aspects requiring attention (Mguni et al. 2016).

Providing a connected system of greenspace throughout the urban area may promote active transportation (Nieuwenhuijsen and Khreis 2016), thereby reducing GHG emissions. Soft solutions for improving green infrastructure connectivity for cycling is an urban NBS mitigation measure, although there is *low evidence* for emissions reductions. In the city of Lisbon, Portugal, improvements in cycling infrastructure and bike-sharing system resulted in 3.5-times more cyclists within two years (Félix et al. 2020). In Copenhagen, the cost of cycling (Euro 0.08/km) is declining and is about six times lower than car driving (Euro 0.50/km) (Vedel et al. 2017). In addition, participants were willing to cycle 1.84 km longer if the route has a designated cycle track and 0.8 km more if there are also green surroundings. Changes in urban landscapes, including through the integration of green infrastructure in sustainable urban and transport planning, can support the transition from private motorized transportation to public and physically active transportation in carbon-neutral, more liveable and healthier cities (Nieuwenhuijsen and Khreis 2016; Nieuwenhuijsen 2020). Car infrastructure can be also transferred into public open and green space, such as in the Superblock model in Barcelona's neighbourhoods (Rueda 2019). Health impact assessment models estimated that 681 premature deaths may be prevented annually with this implementation (Mueller et al. 2020) and the creation of greenways in Maanshan, China has stimulated interests in walking or cycling (Zhang et al. 2020).

8.4.5 Socio-behavioural aspects

Urban systems shape the behaviour and social structures of their residents through urban form, energy systems, and infrastructure—all of which provide a range of options for consumers to make choices about residential location, mobility, energy sources, and the consumption of materials, food, and other resources. The relative availability of options across these sectors has implications on urban emissions through individual behaviour. In turn, urban GHG emissions, as well as emissions from the supply chains of cities, are driven by the behaviour and consumption patterns of residents, with households accounting for over 60% of carbon emissions globally (Ivanova et al. 2016). The exclusion of consumption-based emissions and emissions that occur outside of city boundaries as a result of urban activities will lead to significant undercounting to the effect of undercounting 41% of territorial emissions and 4% of global emissions annually, respectively (Wiedmann et al. 2021).

Changes in behaviour across all areas (e.g., transport, buildings, food, etc.) could reduce an individual's emissions by 5.6–16.2% relative to the accumulated GHG emissions from 2011 to 2050 in a baseline scenario modelled with the Global Change Assessment Model (van de Ven et al. 2018). In other models, behaviour change in transport and residential energy use could reduce emissions by 2 $GtCO_2$-eq in 2030 compared to 2019 (IEA 2020b) (see Chapter 5). Voluntary behaviour change can support emissions reduction, but behaviours that are not convenient to change are unlikely to shift without changes to policy (Sköld et al. 2018). Cities can increase the capability of citizens to make sustainable choices by making these choices less onerous, through avenues such as changing urban form to increase locational and mobility options and providing feedback mechanisms to support socio-behavioural change.

Transport emissions can be reduced by options including telecommuting (0.3%), taking closer holidays (0.5%), avoiding short flights (0.5%), using public transit (0.7%), cycling (0.6%), car sharing (1.1%), and carpool commuting (1.2%); all reduction estimates reflect cumulative per capita emission savings relative to baseline emissions for the period 2011–2050, and assume immediate adoption of behavioural changes (van de Ven et al. 2018). Cities can support voluntary shift to walking, cycling, and transit instead of car use through changes to urban form, such as TOD (Kamruzzaman et al. 2015), increased density of form with co-location of activities (Ma et al. 2015; Ding et al. 2017; Duranton and Turner 2018; Masoumi 2019), and greater intersection density and street integration (Koohsari et al. 2016). Mechanisms such as providing financial incentives or disincentives for car use can also be effective in reducing emissions (Wynes et al. 2018) (see Section 8.4.2).

Adopting energy efficient practices in buildings could decrease global building energy demand in 2050 by 33–44% compared to a business-as-usual scenario (Levesque et al. 2019). Reductions in home energy use can be achieved by reducing floor area (0.5–3.0%), utilising more efficient appliances and lighting (2.7–5.0%), optimising thermostat settings (8.3–11%), using efficient heating and cooling technologies (6.7–10%), improving building insulation (2.9–4.0%), optimising clothes washing (5.0–5.7%), and optimising dishwashing (1–1.1%) (Levesque et al. 2019). Building standards and mandates could work towards making these options required or more readily available and accessible. Residential appliance use, water heating, and thermostat settings can be influenced by feedback on energy use, particularly when paired with real-time feedback and/or instructions on how to reduce energy use

(Kastner and Stern 2015; Stern et al. 2016; Wynes et al. 2018; Tiefenbeck et al. 2019). The energy-saving potentials of changing occupant behaviour can range between 10% and 25% for residential buildings, and between 5% and 30% for commercial buildings (Zhang et al. 2018). Households are more likely to invest in energy-related home technologies if they believe it financially benefits (rather than disadvantages) them, increases comfort, or will benefit the natural environment (Kastner and Stern 2015). Social influences and availability of funding for household energy measures also support behaviour change (Kastner and Stern 2015).

8.4.5.1 Increasing locational and mobility options

Spatial planning, urban form, and infrastructure can be utilized to deliberately increase both locational and mobility options for socio-behavioural change in support of urban mitigation. The mitigation impacts of active travel can include a reduction of mobility-related lifecycle CO_2 emissions by about 0.5 tonnes over a year when an average person cycles one trip per day more, and drives one trip per day less, for 200 days a year (Brand et al. 2021). Urban areas that develop and implement effective 15/20-minute city programs are very likely to reduce urban energy use and multiply emission reductions, representing an important cascading effect.

Accessibility as a criterion widens the focus beyond work trips and VMTs, paying attention to a broader set of destinations beyond workplaces, as well as walking and biking trips or active travel. It holds promise for targeting and obtaining greater reductions in GHG emissions in household travel by providing access through walking, biking, and public transit. Accessibility as a criterion for urban form has been embedded in neighbourhood form models since at least the last century and in more recent decades in the urban village concept of the New Urbanism (Duany and Plater-Zyberck 1991) and TODs (Calthorpe 1993). However, accessibility did not gain much traction in urban planning and transportation until the last decade. The experience of cities and metropolitan areas with the COVID-19 pandemic has led to a further resurgence in interest and importance (Handy 2020; Hu et al. 2020), and is becoming a criterion at the core of the concept of the 15/20-minute city (Moreno et al. 2021; Pozoukidou and Chatziyiannaki 2021). Initially, neighbourhoods have been designed to provide quality, reliable services within 15 or 20 minutes of active transport (i.e., walking or cycling), as well as a variety of housing options and open space (Portland Bureau of Planning and Sustainability 2012; Pozoukidou and Chatziyiannaki 2021; State Government of Victoria 2021). Community life circles strategy for urban areas have also emphasized walking access and health (Weng et al. 2019; Wu et al. 2021). The growing popularity of the 15/20-minute city movement has significant potential for reducing VMT/VKT and associated GHG emissions.

8.4.5.2 Avoiding, minimizing, and recycling waste

The waste sector is a significant source of GHG emissions, particularly CH_4 (Gonzalez-Valencia et al. 2016; Nisbet et al. 2019). Currently, the sector remains the largest contributor to urban emissions after the energy sector, even in low-carbon cities (Lu and Li 2019). Since waste management systems are usually under the control of municipal authorities, they are a prime target for city-level mitigation efforts with co-benefits (EC 2015, 2020; Gharfalkar et al. 2015; Herrero and Vilella 2018; Zaman and Ahsan 2019). Despite general agreement on mitigation impacts, quantification remains challenging due to differing assumptions for system boundaries and challenges related to measuring avoided waste (Zaman and Lehmann 2013; Bernstad Saraiva Schott and Cánovas 2015; Matsuda et al. 2018).

The implementation of the waste hierarchy from waste prevention onward, as well as the effectiveness of waste separation at source, involves socio-behavioural options in the context of urban infrastructure (Sun et al. 2018a; Hunter et al. 2019). Managing and treating waste as close to the point of generation as possible, including distributed waste treatment facilities, can minimize transport-related emissions, congestion, and air pollution. Home composting and compact urban form can also reduce waste transport emissions (Oliveira et al. 2017). Decentralized waste management can reinforce source-separation behaviour since the resulting benefits can be more visible (Eisted et al. 2009; Hoornweg and Bhada-Tata 2012; Linzner and Lange 2013). Public acceptance for waste management is greatest when system costs for citizens are reduced, there is greater awareness of primary waste separation at source, and there are positive behavioural spill-over across environmental policies (Milutinović et al. 2016; Boyer and Ramaswami 2017; Díaz-Villavicencio et al. 2017; Slorach et al. 2020). In addition to the choice of technology, the costs of waste management options depends on the awareness of system users that can represent time-dependent costs (Khan et al. 2016; Chifari et al. 2017; Ranieri et al. 2018; Tomić and Schneider 2020). Waste management systems and the inclusion of materials from multiple urban sectors for alternative by-products can increase scalability (Eriksson et al. 2015; Boyer and Ramaswami 2017; D'Adamo et al. 2021). As a broader concept, circular economy approaches can contribute to managing waste (see Box 12.2) with varying emissions impacts (see Section 5.3.4).

The generation and composition of waste varies considerably from region to region and city to city. So do the levels of institutional management, infrastructure, and (informal) work in waste disposal activities. Depending on context, policy priorities are directed towards reducing waste generation and transforming waste to energy or other products in a circular economy (Diaz 2017; Ezeudu and Ezeudu 2019; Joshi et al. 2019; Calderón Márquez and Rutkowski 2020; Fatimah et al. 2020). Similarly, waste generation, waste collection coverage, recycling, and composting rates, as well as the means of waste disposal and treatment, differ widely, including the logistics of urban waste management systems. Multiple factors influence waste generation, and regions with similar urbanization rates can generate different levels of waste per capita (Kaza et al. 2018).

Under conventional practices, municipal solid waste is projected to increase by about 1.4 Gt between 2016 and 2050, reaching 3.4 Gt in 2050 (Kaza et al. 2018). Integrated policymaking can increase the energy, material, and emissions benefits in the waste management sector (Hjalmarsson 2015; Fang et al. 2017; Jiang et al. 2017). Organisational structure and program administration poses demands for institutional capacity, governance, and cross-sectoral coordination for obtaining the maximum benefit (Hjalmarsson 2015; Kalmykova et al. 2016; Conke 2018; Marino et al. 2018; Yang et al. 2018).

The informal sector plays a critical role in waste management, particularly but not exclusively in developing countries (Linzner and Lange 2013; Dias 2016). Sharing of costs and benefits, and transforming informality of waste recycling activities into programs, can support distributional effects (Conke 2018; Grové et al. 2018). Balancing centralized and decentralized waste management options along low-carbon objectives can address potential challenges in transforming informality (de Bercegol and Gowda 2019). Overall, the positive impacts of waste management on employment and economic growth can be increased when informality is transformed to stimulate employment opportunities for value-added products with an estimated 45 million jobs in the waste management sector by 2030 (Alzate-Arias et al. 2018; Coalition for Urban Transitions 2020; Soukiazis and Proença 2020).

8.4.6 Urban-rural linkages

Urban-rural linkages, especially through waste, food, and water, are prominent elements of the urban system, given that cities are open systems that depend on their hinterlands for imports and exports (Pichler et al. 2017), and include resources, products for industrial production or final use (see Section 8.1.6). As supply chains are becoming increasingly global in nature, so are the resource flows with the hinterlands of cities. In addition to measures within the jurisdictional boundaries of cities, cities can influence large upstream emissions through their supply chains, as well as through activities that rely on resources outside city limits. The dual strategy of implementing local actions and taking responsibility for the entire supply chains of imported and exported goods can reduce GHG emissions outside of a city's administrative boundaries (see Figure 8.15).

Waste prevention, minimisation, and management provides the potential of alleviating resource usage and upstream emissions from urban settlements (Swilling et al. 2018; Chen et al. 2020a; Harris et al. 2020). Integrated waste management and zero-waste targets can allow urban areas to maximize the mitigation potential while reducing pressures on land use and the environment. This mitigation option reduces emissions due to (1) avoided emissions upstream in the supply chain of materials based on measures for recycling and the reuse of materials, (2) avoided emissions due to land use changes as well as emissions that are released into the atmosphere from waste disposal, and (3) avoided primary energy (see Glossary) spending and emissions. Socio-behavioural change that reduces waste generation combined with technology and infrastructure according to the waste hierarchy can be especially effective. The mitigation potential of waste-to-energy depends on the technological choices that are undertaken (e.g., anaerobic digestion of the organic fraction), the emissions factor of the energy mix that it replaces, and its broader role within integrated municipal solid management practices (Eriksson et al. 2015; Potdar et al. 2016; Yu and Zhang 2016; Soares and Martins 2017; Alzate-Arias et al. 2018; Islam 2018). The climate mitigation potential of anaerobic digestion plants can increase when power, heat and/or cold is co-produced (Thanopoulos et al. 2020).

Urban food systems, as well as city-regional production and distribution of food, factors into supply chains. Reducing food demand from urban hinterlands can have a positive impact on energy and water demand for food production (Eigenbrod and Gruda 2015) (see 'food system' in Glossary). Managing food waste in urban areas through recycling or reduction of food waste at source of consumption would require behavioural change (Gu et al. 2019). Urban governments could also support shifts towards more climate-friendly diets, including through procurement policies. These strategies have created economic opportunities or have enhanced food security while reducing the emissions that are associated with waste and the transportation of food. Strategies for managing food demand in urban areas would depend on the integration of food systems in urban planning.

Urban and peri-urban agriculture and forestry is pursued by both developing and some developed country cities. There is increasing evidence for economically feasible, socially acceptable, and environmentally supportive urban and peri-urban agricultural enterprises although these differ between cities (Brown 2015; Eigenbrod and Gruda 2015; Blay-Palmer et al. 2019; De la Sota et al. 2019). The pathways include integrated crop-livestock systems, urban agroforestry systems, aquaculture-livestock-crop systems, and crop systems (Lwasa et al. 2015), while the mitigation potential of urban and peri-urban agriculture has *medium agreement and low evidence*. Strategies for urban food production in cities have also relied on recycling nutrients from urban waste and utilisation of harvested rainwater or wastewater.

Systems for water reallocation between rural areas and urban areas will require change by leveraging technological innovations for water capture, water purification, and reducing water wastage either by plugging leakages or changing behaviour in regard to water use (Eigenbrod and Gruda 2015; Prior et al. 2018). Reducing energy use for urban water systems involves reducing energy requirements for water supply, purification, distribution, and drainage (Ahmad et al. 2020). Various levels of rainwater harvesting in urban settings for supplying end-use water demands or supporting urban food production can reduce municipal water demands, including by up to 20% or more in Cape Town (Fisher-Jeffes et al. 2017).

8.4.7 Cross-sectoral integration

There are two broad categories of urban mitigation strategies. One is from the perspective of key sectors, including clean energy, sustainable transport, and construction (Rocha et al. 2017; Álvarez Fernández 2018; Magueta et al. 2018; Seo et al. 2018; Waheed et al. 2018); the coupling of these sectors can be enabled through electrification (see Section 8.4.3.1). The other looks at the needs for emissions through a more systematic or fundamental understanding of urban design, urban form, and urban spatial planning (Wang et al. 2017; Privitera et al. 2018), and proposes synergistic scenarios for their integration for carbon neutrality (Ravetz et al. 2020).

Single-sector analysis in low-carbon urban planning examines solutions in supply, demand, operations, and assets management either from technological efficiency or from a system approach. For example, the deployment of renewable energy technologies for urban mitigation can be evaluated in detail and the transition to zero-carbon energy in energy systems and EVs in the transport sector can bring about a broad picture for harvesting substantial low-carbon potentials through urban planning (Álvarez Fernández 2018; Tarigan and Sagala 2018) (*high agreement, robust evidence*).

The effect of urban carbon lock-in on land use, energy demand, and emissions vary depending on national circumstances (Wang et al. 2017; Pan 2020). Systematic consideration of urban spatial planning and urban forms, such as polycentric urban regions and rational urban population density, is essential not only for liveability but also for achieving net zero GHG emissions as it aims to shorten commuting distances and is able to make use of NBS for energy and resilience (*high agreement, medium evidence*). However, crucial knowledge gaps remain in this field. There is a shortage of consistent and comparable GHG emissions data at the city level and a lack of in-depth understanding of how urban renewal and design can contribute to carbon neutrality (Mi et al. 2019).

An assessment of opportunities suggests that strategies for material efficiency that cross-cut sectors will have greater impact than those that focus one dimensionally on a single sector (UNEP and IRP 2020). In the urban context, this implies using less material by the design of physical infrastructure based on light-weighting and down-sizing, material substitution, prolonged use, as well as enhanced recycling, recovery, remanufacturing, and reuse of materials and related components. For example, light-weight design in residential buildings and passenger vehicles can enable about 20% reductions in lifecycle material-related GHG emissions (UNEP and IRP 2020).

The context of urban areas as the nexus of both sectors (i.e., energy, and urban form and planning) underlines the role of urban planning and policies in contributing to reductions in material-related GHG emissions while enabling housing and mobility services for the benefit of inhabitants. In addition, combining resource efficiency measures with strategic densification can increase the GHG reduction potential and lower resource impacts. While resource efficiency measures are estimated to reduce GHG emissions, land use, water consumption, and metal use impacts from a lifecycle assessment perspective by 24–47% over a baseline, combining resource efficiency with strategic densification can increase this range to about 36–54% over the baseline for a sample of 84 urban settlements worldwide (Swilling et al. 2018).

Evidence from a systematic scoping of urban solutions further indicates that the GHG abatement potential of integrating measures across urban sectors is greater than the net sum of individual interventions due to the potential of realizing synergies when realized in tandem, such as urban energy infrastructure and renewable energy (Sethi et al. 2020). Similarly, system-wide interventions, such as sustainable urban form, are important for increasing the GHG abatement potential of interventions based on individual sectoral projects (Sethi et al. 2020). Overall, the pursuit of inter-linkages among urban interventions are important for accelerating GHG reductions in urban areas (Sethi et al. 2020); this is also important for reducing reliance on carbon capture and storage technologies (CCS) at the global scale (Figures 8.15 and 8.21).

Currently, cross-sectoral integration is one of the main thematic areas of climate policy strategies among the actions that are adopted by signatories to an urban climate and energy network (Hsu et al. 2020c). Although not as prevalent as those for efficiency, municipal administration, and urban planning measures (Hsu et al. 2020c), strategies that are cross-cutting in nature across sectors can provide important emission saving opportunities for accelerating the pace of climate mitigation in urban areas. Cross-sectoral integration also involves mobilizing urban actors to increase innovation in energy services and markets beyond individual energy efficiency actions (Hsu et al. 2020c). Indeed, single-sector versus cross-sector strategies for 637 cities from a developing country can enable an additional 15–36% contribution to the national climate mitigation reduction potential (Ramaswami et al. 2017a). The strategies at the urban level involved those for energy cascading and exchange of materials that connected waste, heat, and electricity strategies (Section 8.5 and Box 8.4).

The feasibility of upscaling multiple response options depends on the urban context as well as the stage of urban development with certain stages providing additional opportunities over others (Dienst et al. 2015; Maier 2016; Affolderbach and Schulz 2017; Roldán-Fontana et al. 2017; Zhao et al. 2017a; Beygo and Yüzer 2017; Lwasa 2017; Pacheco-Torres et al. 2017; Alhamwi et al. 2018; Kang and Cho 2018; Lin et al. 2018; Collaço et al. 2019) (see Figures 8.19 and 8.21, and SM8.2).

8.5 Governance, institutions, and finance

Governance and other institutions act as core components to urban systems by facilitating and managing linkages between different sectors, geographic regions, and stakeholders. This position renders subnational governments and institutions key enablers of climate change mitigation (Seto et al. 2016, 2021; Hsu et al. 2018, 2020c; ; Vedeld et al. 2021) (see Section 8.4.1). Indeed, since AR5 more research has emerged identifying theses actors as vehicles through which to accelerate local-to-global efforts to decarbonize (IPCC 2018a; Hsu et al. 2020b; Salvia et al. 2021; Seto et al. 2021) (see also Chapter 13, and Sections 4.2.3, 14.5.5, 15.6.5 and 16.4.7, and 'subnational actors' in Glossary). The current extent (Section 8.3.3) and projected rise (Section 8.3.4.2) in the urban share of global emissions underscores the transformative global impact of supporting urban climate governance and institutions (see also Section 8.5.2). Further, the multisector approach to mitigation emphasized in this chapter (see Sections 8.4 and 8.6, and Figure 8.21) highlights the need for facilitation across sectors (Hsu et al. 2020c) (see also Figure 8.19).

8.5.1 Multi-level governance

SR1.5 identified multilevel governance (see Glossary for full definition) as an enabling condition that facilitates systemic transformation consistent with keeping global temperatures below 1.5°C (IPCC 2018a, 18–19). The involvement of governance at multiple levels is necessary to enable cities to plan and implement emissions reductions targets (*high confidence*) (Seto et al. 2021) (see Boxes 8.3 and 8.4). Further, regional, national, and international climate goals are most impactful when local governments are involved alongside higher levels, rendering urban areas key foci of climate governance more broadly (*high confidence*) (Fuhr et al. 2018; Kern 2019; Hsu et al. 2020b).

Since AR5, multilevel governance has grown in influence within the literature and has been defined as a framework to understanding the complex interaction of the many players involved in GHG generation and mitigation across geographic scales—the 'vertical' levels of governance from neighbourhoods to the national and international levels, and those 'horizontal' networks of non-state and subnational actors at various scales (Corfee-Morlot et al. 2009; Seto et al. 2014; Castán Broto 2017b; Fuhr et al. 2018; Peng and Bai 2018; Kern 2019), and well as the complex linkages between them (Vedeld et al. 2021). This more inclusive understanding of climate governance provides multiple pathways through which urban actors can engage in climate policy to reduce emissions.

Multilevel, multi-player climate governance in practice

A multilevel, multi-player framework highlights both the opportunities and constraints on local autonomy to engage in urban mitigation efforts (Castán Broto 2017b; Fuhr et al. 2018; Vedeld et al. 2021). When multiple actors—national, regional, and urban policymakers, as well as nonstate actors and civil society—work together to exploit the opportunities, it leads to the most impactful mitigation gains (Melica et al. 2018). This framework also highlights the multiple paths and potential synergies available to actors who wish to pursue mitigation policies despite not having a full slate of enabling conditions (Castán Broto 2017b; Keller 2017; Fuhr et al. 2018; Hsu et al. 2020b,a; Seto et al. 2021).

For example, Section 8.4.3. and 8.4.5 highlight how instigating the electrification of urban energy systems requires a 'layered' approach to policy implementation across different levels of governance (see Section 8.4.3.1 for specific policy mechanisms associated with electrification), with cities playing a key role in setting standards, particularly through mechanisms like building codes (Hsu et al. 2020c; Salvia et al. 2021), as well as through facilitation between stakeholders (e.g., consumers, government, utilities, etc.) to advocate for zero-emissions targets (Linton et al. 2021; Seto et al. 2021). Local governments can minimize trade-offs associated with electrification technologies by enabling circular economy practices and opportunities (Pan et al. 2015; Gaustad et al. 2018; Sovacool et al. 2020). These include public-private partnerships between consumers and producers, financial and institutional support, and networking for stakeholders like entrepreneurs, so as to increase accessibility and efficiency of recycling for consumers by providing a clear path from consumer waste back to the producers (Pan et al. 2015; Prendeville et al. 2018; Fratini et al. 2019). Box 8.3 discusses the mitigation benefits of coordination between local and central government in the context of Shanghai's GHG emissions reductions goals.

Still, there are constraints on urban autonomy that might limit urban mitigation influence. The capacity of subnational governments to autonomously pursue emissions reductions on their own depends on different political systems and other aspects of multilevel governance, such as innovation, legitimacy, and institutional fit, as well as the resources, capacity, and knowledge available to subnational technicians and other officials (Widerberg and Pattberg 2015; Valente de Macedo et al. 2016; Green 2017; Roger et al. 2017). Financing is considered one of the most crucial facets of urban climate change mitigation. It is also considered one of the biggest barriers given the limited financial capacities of local and regional governments (see Section 8.5.4 and 8.5.5).

When sufficient local autonomy is present, local policies have the ability to upscale to higher levels of authority imparting influence at higher geographic scales. Established urban climate leaders with large institutional capacity can influence small and mid-sized cities, or other urban areas with less institutional capacity, to enact effective climate policies, by engaging with those cities through transnational networks and by adopting a public presence of climate leadership (Chan et al. 2015; Kern 2019; Seto et al. 2021) (see Section 8.5.3). Increasingly, subnational actors are also influencing their national and international governments through lobbying efforts that call on them to adopt more ambitious climate goals and provide more support for subnational GHG mitigation effort. These dynamics underscore the importance of relative local autonomy in urban GHG mitigation policy. They also highlight the growing recognition of subnational authorities' role in climate change mitigation by national and international authorities.

The confluence of political will and policy action at the local level, and growing resources offered through municipal and regional networks and agreements, have provided a platform for urban actors to engage in international climate policy (see Section 8.5.3). This phenomena is recognized in the Paris Agreement, which, for the first time in a multilateral climate treaty, referenced the crucial role subnational and nonstate actors like local communities have in meeting the goals set forth in the agreement (UNFCCC 2015). The Durban Platform for Enhanced Action (Widerberg and Pattberg 2015) as well as UN Habitat's NUA and the 2030 Development Agenda are other examples of the international sphere elevating the local level to global influence (Fuhr et al. 2018). Another facet of local-to-global action is the emergence of International Cooperative Initiatives (ICIs) (Widerberg and Pattberg 2015). One such ICI, the City Hall Declaration, was signed alongside the Paris Agreement during the first Climate Summit for Local Leaders. Signatories included hundreds of local government leaders, private sector representatives, and NGOs, who pledged to enact the goals of the Paris Agreement through their own spheres of influence (Cities for Climate 2015). A similar Summit has been held at each subsequent UNFCCC COP. Like transnational climate networks, these platforms provide key opportunities to local governments to further their own mitigation goals, engage in knowledge transfer with other cities and regions, and shape policies at higher levels of authority (Cities for Climate 2015; Castán Broto 2017b).

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Box 8.3 Coordination of fragmented policymaking for low-carbon urban development: example from Shanghai

As a growing megacity in the Global South, Shanghai represents the challenge of becoming low carbon despite its economic growth and population size (Chen et al. 2017). Shanghai was designated as one of the pilot low-carbon cities by the central government. The city utilized a coordination mechanism for joining fragmented policymaking across the city's economy, energy, and environment. The coordination mechanism was supported by a direct fund that enabled implementation of cross-sector policies beyond a single-sector focus across multiple institutions while increasing capacity for enabling a low carbon transition for urban sustainability (Peng and Bai 2020).

Implementation and governance process

In Shanghai, coordination between the central and local governments had an instrumental role for encouraging low-carbon policy experimentation. Using a nested governance framework, the central government provided target setting and performance evaluation while the local government initiated pilot projects for low-carbon development. The policy practices in Shanghai surpassed the top-down targets and annual reporting of GHG emissions, including carbon labelling standards at the local level, pilot programs for transitioning sub-urban areas, and the engagement of public utilities (Peng and Bai 2018).

Towards low-carbon urban development

New policy measures in Shanghai were built upon a series of related policies from earlier, ranging from general energy saving measures to air pollution reduction. This provided a continuum of policy learning for implementing low-carbon policy measures. An earlier policy was a green electricity scheme based on the Jade Electricity Program while the need for greater public awareness was one aspect requiring further attention in policy design (Baeumler et al. 2012), supporting policy-learning for policies later on. The key point here is that low-carbon policies were built on and learned from earlier policies with similar goals.

Outcomes and impacts of the policy mix

Trends during 1998 and 2015 indicate that energy intensity decreased from about 130 ton per million RMB to about 45 ton per million RMB and carbon intensity decreased from about 0.35 Mt per billion RMB to 0.10 Mt per billion RMB (Peng and Bai 2018). These impacts on energy and carbon intensities represent progress while challenges remain. Among the challenges are the need for investment in low carbon technology and increases in urban carbon sinks (Yang and Li 2018) while cross-sector interaction and complexity are increasing.

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8.5.2 Mitigation potential of urban subnational actors

A significant research question that has been paid more attention in both the scientific and policy communities is related to subnational actors' role in and contribution to global climate mitigation. The

2018 UN Environment Programme's (UNEP) annual Emissions Gap report in 2018 included for the first time a special chapter on subnational and non-state (i.e., businesses and private actors) and assessed the landscape of studies aiming to quantify their contributions to global climate mitigation. Non-state action on net zero GHG or CO_2 emissions continues to be emphasized (UNEP 2021) (see Box 8.4). There has been an increase in the number of studies aiming to quantify the overall aggregate mitigation impact of subnational climate action globally. Estimates for the significance of their impact vary widely, from up to 30 $MtCO_2$-eq from 25 cities in the United States in 2030 (Roelfsema 2017), to a 2.3 $GtCO_2$-eq reduction in 2030 compared to a current policy scenario from over 10,239 cities participating in GCoM (Hsu et al. 2018; GCoM 2019). For regional governments, the Under 2 Coalition, which includes 260 governments pledging goals to keep global temperature rise below 2°C, is estimated to reduce emissions by 4.2 $GtCO_2$-eq in 2030, compared to a current policy scenario (Kuramochi et al. 2020).

Some studies suggest that subnational mitigation actions (Roelfsema 2017; Kuramochi et al. 2020) are in addition to national government mitigation efforts and can therefore reduce emissions even beyond current national policies, helping to 'bridge the gap' between emissions trajectories consistent with least-cost scenarios for limiting temperature rise below 1.5°C or 2°C (Blok et al. 2012). In some countries, such as the United States, where national climate policies have been curtailed, the potential for cities and regions' emissions reduction pledges to make up the country's Paris NDC is assessed to be significant (Kuramochi et al. 2020).

These estimates are also often contingent on assumptions that subnational actors fulfil their pledges and that these actions do not result in rollbacks in climate action (i.e., weakening of national climate legislation) from other actors or rebound in emissions growth elsewhere, but data tracking or quantifying the likelihood of their implementation remains rare (Chan et al. 2018; Hsu et al. 2019; Hale et al. 2020; Kuramochi et al. 2020). Reporting networks may attract high-performing cities, suggesting an artificially high level of cities interested in taking climate action or piloting solutions that may not be effective elsewhere (van der Heijden 2018). These studies could also present a conservative view of potential mitigation impact because they draw upon publicly reported mitigation actions and inventory data, excluding subnational actors that may be taking actions but not reporting them (Kuramochi et al. 2020). The nuances of likelihood, and the drivers and obstacles of climate action across different contexts is a key source of uncertainty around subnational actors' mitigation impacts.

8.5.3 Urban climate networks and transnational governance

As of 2019, more than 10,000 cities and regions (Hsu et al. 2020a) have recorded participation in a transnational or cooperative climate action network, which are voluntary membership networks of a range of subnational governments such as cities, as well as regional governments like states and provinces (Hsu et al. 2020a). These organizations, often operating across and between national boundaries, entail some type of action on climate change. Among the most prominent climate networks are GCoM, ICLEI, and C40, all of which ask its members to adopt emission reduction commitments, develop climate action plans, and regularly report on emissions inventories.

Municipal and regional networks and agreements have provided a platform for urban actors to engage in international climate policy (Fraundorfer 2017; Keller 2017; Fuhr et al. 2018; Hsu et al. 2018, 2020b; Westman and Broto 2018; Kern 2019; Seto et al. 2021). Their impact comes through (1) providing resources for cities and regions to reduce their GHG emissions and improve environmental quality more generally, independent of national policy; (2) encouraging knowledge transfer between member cities and regions; and (3) as platforms of national and international policy influence (Castán Broto 2017b; Fuhr et al. 2018).

Subnational governments that participate in transnational climate networks, however, are primarily located in developed countries, particularly Europe and North America, with far less representation in developing countries. In one of the largest studies of subnational climate mitigation action, more than 93% of just over 6,000 quantifiable subnational climate commitments come from cities and regions based in the European Union (NewClimate Institute et al. 2019). Such gaps in geographic coverage have been attributed to factors such as the dominating role of Global North actors in the convening and diffusion of 'best practices' related to climate action (Bouteligier 2013), or the more limited autonomy or ability of subnational or non-state actors in Global South countries to define boundaries and interests separately from national governments, particularly those that exercise top-down decision-making or have vertically-integrated governance structures (Bulkeley et al. 2012). Many of the participating subnational actors from under-represented regions are large mega-cities (of 10 million people or more) that will play a pivotal role in shaping emissions trajectories (Data Driven Yale et al. 2018; NewClimate Institute et al. 2019).

While these networks have proven to be an important resource in local-level mitigation, their long-term effects and impact at larger scales is less certain (Valente de Macedo et al. 2016; Fuhr et al. 2018). Their influence is most effective when multiple levels of governance are aligned in mitigation policy. Nevertheless, these groups have become essential resources to cities and regions with limited institutional capacity and support (Kern 2019) (for more on transnational climate networks and transnational governance more broadly, see Sections 13.5 and 14.5).

START BOX 8.4 HERE

Box 8.4 Net zero targets and urban settlements

Around the world, net zero emissions targets, whether economy-wide or targeting a specific sector (e.g., transport, buildings) or emissions scope (e.g., direct scope 1, or both scope 1 and 2), have been adopted by at least 826 cities and 103 regions that represent 11% of the global population with 846 million people across 6 continents (NewClimate Institute and Data-Driven EnviroLab 2020). In some countries, the share of such cities and regions have reached a critical mass by representing more than 70% of their total populations with or without net zero emissions targets at the national level.

In some cases, the scope of these targets extends beyond net zero emissions from any given sector based on direct emissions (see Glossary) and encompass downstream emissions from a consumption-based perspective with 195 targets that are found to represent economy-wide targets. These commitments range from 'carbon neutrality' (see Glossary) or net zero GHG emissions targets, which entail near elimination of city's own direct or electricity-based emissions but could involve some type of carbon offsetting, to more stringent net zero emissions goals (Data-Driven EnviroLab and NewClimate Institute 2020) (for related definitions, such as 'carbon neutral,' 'net zero CO_2 emissions,' 'net zero GHG emissions' and 'offset,' see Glossary).

Currently, 43% of the urban areas with net zero emissions targets have also put into place related action plans while about 24% have integrated net zero emissions targets into formal policies and legislation (Data-Driven EnviroLab and NewClimate Institute 2020). Moreover, thousands of urban areas have adopted renewable energy-specific targets for power, heating/cooling and transport and about 600 cities are pursuing 100% renewable energy targets (REN21 2019, 2021) with some cities already achieving it.

The extent of realising and implementing these targets with the collective contribution of urban areas to net zero emissions scenarios with sufficient timing and pace of emission reductions will require a coordinated integration of sectors, strategies, and innovations (Swilling et al. 2018; Hsu et al. 2020c; Sethi et al. 2020; UNEP and IRP 2020). In turn, the transformation of urban systems can significantly impact net zero emissions trajectories within mitigation pathways. Institutional capacity, governance, financing, and cross-sector coordination is crucial for enabling and accelerating urban actions for rapid decarbonization.

END BOX 8.4 HERE

8.5.4 Financing urban mitigation

Meeting the goals of the Paris Agreement will require fundamental changes that will be most successful when cities work together with provincial and national leadership and legislation, third-sector leadership, transformative action, and supportive financing. Urban governments often obtain their powers from provincial, state and/or national governments, and are subjected to laws and regulations to regulate development and implement infrastructure. In addition, the sources of revenue are often set at these levels so that many urban governments rely on state/provincial and national government funds for improving infrastructure, especially transit infrastructure. The increasing financialisation of urban infrastructures is another factor that can make it more difficult for local governments to determine infrastructure choices (O'Brien et al. 2019). Urban transit system operations, in particular, are heavily subsidized in many countries, both locally and by higher levels of government. As a result of this interplay of policy and legal powers among various levels of government, the lock-in nature of urban infrastructures and built environments will require multi-level governance response to ensure meeting decarbonization targets. The reliance on state and national policy and/or funding can accelerate or impede the decarbonization of urban environments (McCarney et al. 2011; McCarney 2019).

The world's infrastructure spending is expected to more than double from 2015 to 2030 under a low-carbon and climate resilient scenario. More than 70% of the infrastructure will concentrate in urban areas by requiring USD 4.5-5.4 trillion per year (CCFLA 2015) . However, today's climate finance flows for cities or 'urban climate finance,' estimated at USD 384 billion annually on average in 2017/18, are insufficient to meet the USD 4.5 trillion to USD 5.4 trillion-dollar annual investment needs for urban mitigation actions across key sectors (CCFLA 2015; CPI and World Bank 2021; Negreiros et al. 2021). Low-carbon urban form (e.g., compact, high-density, and mixed-use characteristics) is likely to economize spending in infrastructure along with the application of new technologies and renewable energies that would be able to recover the increasing upfront cost of low-carbon infrastructure from more efficient operating and energy savings (Global Commission on the Economy and Climate 2014; Foxon et al. 2015; Bhattacharya et al. 2016; Floater et al. 2017; Colenbrander et al. 2018b) (*medium evidence, high agreement*).

Governments have traditionally financed a large proportion of infrastructure investment. When budget powers remain largely centralized, intergovernmental transfers will be needed to fund low-carbon infrastructure in cities. During the COVID-19 pandemic, cities tend to rely more on intergovernmental transfers in the form of stimulus packages for economic recovery. Nonetheless, the risk of high carbon lock-ins is likely to increase in rapidly growing cities if long-term urban mitigation strategies are not incorporated into short-term economic recovery actions (Granoff et al. 2016; Floater et al. 2017; Colenbrander et al. 2018b; CPI and World Bank 2021; Negreiros et al. 2021). Indeed, large and complex infrastructure projects for urban mitigation are often beyond the capacity of both national government and local municipality budgets. Additionally, the COVID-19 pandemic necessitates large government expenditures for public health programs and decimates municipal revenue sources for urban infrastructure projects in cities.

To meet the multi-trillion-dollar annual investment needs in urban areas, cities in partnership with international institutions, national governments, and local stakeholders increasingly play a pivotal role in mobilizing global climate finance resources for a range of low-carbon infrastructure projects and related urban land use and spatial planning programs across key sectors (*high confidence*). In particular, national governments are expected to set up enabling conditions for the mobilization of urban climate finance resource by articulating various goals and strategies, improving pricing, regulation and standards, and developing investment vehicles and risk sharing instruments (Qureshi 2015; Bielenberg et al. 2016; Granoff et al. 2016; Floater et al. 2017; Sudmant et al. 2017; Colenbrander et al. 2018b; Zhan and de Jong 2018; Hadfield and Cook 2019; CPI and World Bank 2021; Negreiros et al. 2021).

Indeed, 75% of the global climate finance for both mitigation and adaptation in 2017 and 2018 took the form of commercial financing (e.g., balance sheets, commercial-rate loans, and equity), while 25% came from the form of concessionary financing (e.g., grants, below-market-rate loans, etc.). However, cities in developing countries are facing difficulty making use of commercial financing and gaining access to international credit markets. Cities without international creditworthiness currently rely on local sources, including domestic commercial banks (Global Commission on the Economy and Climate 2014; CCFLA 2015; Floater et al. 2017; Buchner et al. 2019) (*medium evidence, high agreement*).

Cities with creditworthiness have rapidly become issuers of 'green bonds' eligible for renewable energy, energy efficiency, low-carbon transport, sustainable water, waste, and pollution, and other various climate mitigation projects across the global regions since 2013. The world's green bond market reached USD 1 trillion in cumulative issuance, with issuance of USD 280 billion in 2020, during the COVID-19 pandemic. While green municipal bonds still account for a small share of the whole green bond market in 2020, scale is predicted to grow further in emerging markets over the coming years. Green municipal bonds have great potential for cities to expand and diversify their investor base. In addition, the process of issuing green municipal bonds is expected to promote cross-sector cooperation within a city by bringing together various agencies responsible for finance, climate change, infrastructure, planning and design, and operation. Indeed, the demand for green bonds presently outstrips supply as being constantly over-subscripted (Global Commission on the Economy and Climate 2014; Saha and D'Almeida 2017; Amundi and IFC 2021) (*robust evidence, high agreement*).

On the other hand, cities without creditworthiness face difficulty making use of commercial financing and getting access to international credit markets (Global Commission on the Economy and Climate 2014; CCFLA 2015; Floater et al. 2017). The lack of creditworthiness is one of the main problems preventing cities from issuing green municipal bonds in developing countries. As a prerequisite for the application of municipal debt-financing, it is an essential condition for cities to ensure sufficient own revenues from low-carbon urbanization, or the default risk becomes too high for potential investors. Indeed, many cities in developed countries and emerging economies have already accumulated substantial amounts of debts through bond insurances, and on-going debt payments prevent new investments in low-carbon infrastructure projects.

National governments and multilateral development banks might be able to provide support for debt financing by developing municipal creditworthiness programs and issuing sovereign bonds or providing national guarantees for investors (Floater et al. 2017). Another problem with green municipal bonds is the lack of aggregation mechanisms to support various small-scale projects in cities. Asset-backed securities are likely to reduce the default risk for investors through portfolio diversification and create robust pipelines for a bundle of smalls-scale projects (Granoff et al. 2016; Floater et al. 2017; Saha and D'Almeida 2017).

In principle, the upfront capital costs of various low-carbon infrastructure projects, including the costs of urban climate finance (dividend and interest payments), are eventually transferred to users and other stakeholders in the forms of taxes, charges, fees, and other revenue sources. Nevertheless, small cities in developing countries are likely to have a small revenue base, most of which is committed to recurring operating costs, associated with weak revenue collection and management systems. In recent years, there has been scope to apply not only user-based but also land-based funding instruments for the recovery of upfront capital costs (Braun and Hazelroth 2015; Kościelniak and Górka 2016; Floater et al. 2017; Colenbrander et al. 2018b; Zhan and de Jong 2018; Zhan et al. 2018a).

In practice, however, the application of land-based or 'land value capture' funding requires cities to arrange various instruments, including property (both land and building taxes), betterment levies/special assessments, impact fees (exactions), tax increment financing, land readjustment/land pooling, sales of public land/development rights, recurring lease payments, and transfer taxes/stamp duties, across sectors in different urban contexts (Suzuki et al. 2015; Chapman 2017; Walters and Gaunter 2017; Berrisford et al. 2018). Land value capture is expected not only for cities to generate additional revenue streams but also to prevent low-density urban expansion around city-fringe locations. Inversely, land value capture is supposed to perform well when accompanied by low-carbon urban form and private real estate investments along with the application of green building technologies (Suzuki et al. 2015; Floater et al. 2017; Colenbrander et al. 2018b) (*robust evidence, high agreement*).

For the implementation of land-based funding, property rights are essential. However, weak urban-rural governance leads to corruption in land occupancy and administration, especially in developing countries with no land information system or less reliable paper-based land records under a centralized registration system. The lack of adequate property rights seriously discourages low-carbon infrastructure and real estate investments in growing cities.

The emerging application of blockchain technology for land registry and real estate investment is expected to change the governance framework, administrative feasibility, allocative efficiency, public accountability, and political acceptability of land-based funding in cities across developed countries, emerging economies, and developing countries (Graglia and Mellon 2018; Kshetri and Voas 2018). Particularly, the concept of a transparent, decentralized public ledger is adapted to facilitate value-added property transactions on a P2P basis without centralized intermediate parties and produce land-based funding opportunities for low-carbon infrastructure and real estate development district-wide and city-wide in unconventional ways (Veuger 2017; Nasarre-Aznar 2018).

The consolidation of local transaction records into national or supranational registries is likely to support large-scale land formalisation, but most pilot programs are not yet at the scale (Graglia and Mellon 2018). Moreover, the potential application of blockchain for land-based funding instruments is possibly associated with urban form attributes, such as density, compactness, and land use mixture, to disincentivize urban expansion and emissions growth around city-fringe locations (*medium confidence*) (Allam and Jones 2019).

8.5.5 Barriers and enablers for implementation

Irrespective of geography or development level, many cities face similar climate governance challenges such as lacking institutional, financial, and technical capacities (Gouldson et al. 2015; Hickmann and Stehle 2017; Sharifi et al. 2017; Fuhr et al. 2018). Large-scale system transformations are also deeply influenced by factors outside governance and institutions such as private interests and power dynamics (Jaglin 2014; Tyfield 2014). In some cases, these private interests are tied up with international flows of capital. At the local level, a lack of empowerment, high upfront costs, inadequate and uncertain funding for mitigation, diverse and conflicting policy objectives, multiple agencies and actors with diverse interests, high levels of informality, and a siloed approach to climate action are constraining factors to mainstreaming climate action (Beermann et al. 2016; Gouldson et al. 2016; Pathak and Mahadevia 2018; Khosla and Bhardwaj 2019).

Yet urban mitigation options that can be implemented to transform urban systems involve the interplay of multiple enablers and barriers. Based on a framework for assessing feasibility from a multi-dimensional perspective, feasibility is malleable and various enablers can be brought into play to increase the implementation of mitigation options. The scope of this assessment enables an approach for considering multiple aspects that have an impact on feasibility as a tool for policy support (Singh et al. 2020). In Figure 8.19, the assessment framework that is based on geophysical, environmental-ecological, technological, economic, socio-cultural, and institutional dimensions is applied to identify the enablers and/or barriers in implementing mitigation options in urban systems. The feasibility of options may differ across context, time, and scale (see Supplementary Material 8.2). The line of sight upon which the assessment is based includes urban case studies (Lamb et al. 2019) and assessments of land use and spatial planning in IPCC SR1.5 (IPCC 2018a).

Across the enablers and barriers of different mitigation options, urban land use and spatial planning for increasing co-located densities in urban areas has positive impacts in multiple indicators, particularly reducing land use and preserving carbon sinks when the growth in urban extent is reduced and avoided, which if brought into interplay in decision-making, can support the enablers for its implementation. Improvements in air quality are possible when higher urban densities are combined with modes of active transport, electrified mobility as well as urban green and blue infrastructure (see Sections 8.3.4, 8.4 and 8.6). The demands on geophysical resources, including materials for urban development, will depend on whether additional strategies are in place with largely negative impacts under conventional practices. The technological scalability of multiple urban mitigation options is favourable while varying according to the level of existing urban development and scale of implementation (see Tables SM8.3 - SM8.4 in Supplementary Material 8.2).

Similarly, multiple mitigation options have positive impacts on employment and economic growth, especially when urban densities enable productivity. Possible distributional effects, including availability of affordable accommodation and access to greenspace, are best addressed when urban policy packages combine more than one policy objective. Such an approach can provide greater support to urban mitigation efforts with progress towards shifting urban development to sustainability. The electrification of the urban energy system involves multiple enablers that support the feasibility of this mitigation option, including positive impacts on health and well-being. In addition, increases in urban densities can support the planning of district heating and cooling networks that can decarbonize the built environment at scale with technology readiness levels increasing for lower temperature supply options. Preventing, minimizing, and managing waste as an urban mitigation option can be enabled when informality in the sector is transformed to secure employment effects and value addition based on the more circular use of resources (see Tables SM8.3 and SM8.4 in Supplementary Material 8.2, and Sections 8.4.3 and 8.4.5).

As a combined evaluation, integrating multiple mitigation options in urban systems involves the greatest requirement for strengthening institutional capacity and governance through cross-sectoral coordination (see Section 8.4 and 8.6, and Figure 8.21). Notably, integrated action requires significant effort to coordinate sectors and strategies across urban growth typologies (see Section 8.6). Institutional capacity, if not strengthened to a suitable level to handle this process—especially to break out of carbon lock-in—can fall short of the efforts this entails. These conditions can pose barriers for realizing cross-sectoral coordination while the formation of partnerships and stakeholder engagement take place as important enablers. Overcoming institutional challenges for cross-sectoral coordination can support realizing synergies among the benefits that each mitigation option can offer within and across urban systems, including for the SDGs. These include those that can be involved in co-located and walkable urban form together with decarbonizing and electrifying the urban energy system as well as urban green and blue infrastructure, providing the basis for more liveable, resource efficient and compact urban development with benefits for urban inhabitants (see Section 8.2).

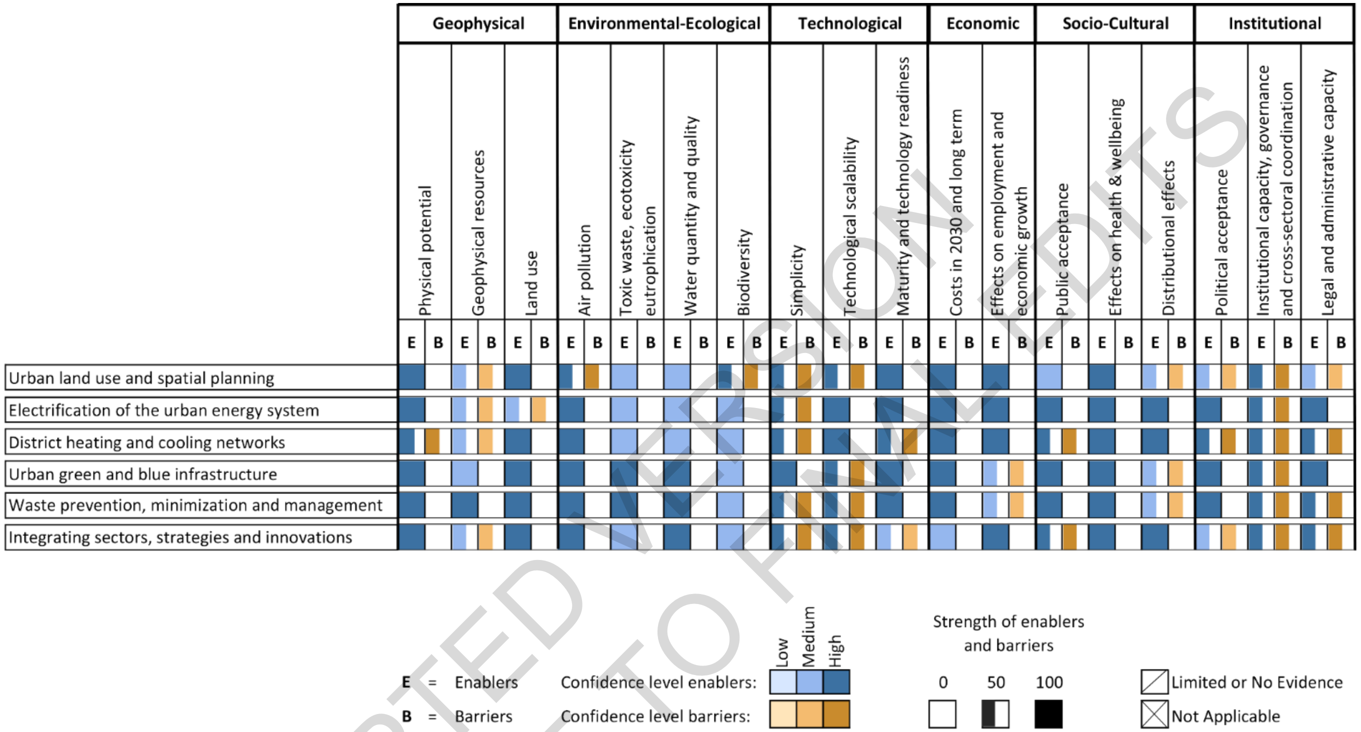

Figure 8.19 Feasibility assessment based on the enablers and barriers of implementing mitigation options for urban systems across multiple dimensions. The figure summarizes the extent to which different factors would enable or inhibit the deployment of mitigation options in urban systems. These factors are assessed systematically based on 18 indicators in 6 dimensions (geophysical, environmental-ecological, technological, economic, socio-cultural, and institutional dimensions). Blue bars indicate the extent to which the indicator enables the implementation of the option (E) and orange bars indicate the extent to which an indicator is a barrier (B) to the deployment of the option, relative to the maximum possible barriers and enablers assessed. The shading indicates the level of confidence, with darker shading signifying higher levels of confidence. Supplementary Material SM8.2 provides an overview of the extent to which the feasibility of options may differ across context, time and scale of implementation (Table SM8.3) and includes line of sight upon which the assessment is based (Table SM8.4). The line of sight builds upon urban case studies in (Lamb et al. 2019) and assessments for land use and urban planning (IPCC 2018a) involving 414 references. The assessment method is further explained in Annex II, Section 11.

8.6 A roadmap for integrating mitigation strategies for different urbanization typologies

The most effective and appropriate packages of mitigation strategies will vary depending on several dimensions of a city. This section brings together the urban mitigation options described in Section 8.4 and assesses the range of mitigation potentials for different types of cities. There is consensus in the literature that mitigation strategies are most effective when multiple interventions are coupled together. Urban-scale interventions that implement multiple strategies concurrently through policy packages are more effective and have greater emissions savings than when single interventions are implemented separately. This is because a citywide strategy can have cascading effects across sectors, that have multiplicative effects on GHG emissions reduction within and outside a city's administrative boundaries. Therefore, city-scale strategies can reduce more emissions than the net sum of individual interventions, particularly if multiple scales of governance are included (see Sections 8.4 and 8.5). Furthermore, cities have the ability to implement policy packages across sectors using an urban systems approach, such as through planning, particularly those that affect key infrastructures (see Figures 8.15, 8.17 and 8.22).

The way that cities are laid out and built will shape the entry points for realising systemic transformation across urban form and infrastructure, energy systems, and supply chains. Section 8.3.1 discusses the ongoing trend of rapid urbanization—and how it varies through different forms of urban development or 'typologies' (see Figure 8.6). Below, Figure 8.20 distils the typologies of urban growth across three categories: emerging, rapidly growing, and established. Urban growth is relatively stabilized in established urban areas with mature urban form while newly taking shape in emerging urban areas. In contrast, rapidly growing urban areas experience pronounced changes in outward and/or upward growth. These typologies are not mutually exclusive, and can co-exist within an urban system; cities typically encompass a spectrum of development, with multiple types of urban form and various typologies (Mahtta et al. 2019).

Taken together, urban form (Figure 8.16) and growth typology (Figure 8.20) can act as a roadmap for cities or sub-city communities looking to identify their urban context and, by extension, the mitigation opportunities with the greatest potential to reduction GHG emissions. Specifically, this considers whether a city is established with existing and managed infrastructure, rapidly growing with new and actively developing infrastructure, or emerging with large amounts of infrastructure build-up. The long lifespan of urban infrastructure locks in behaviour and committed emissions. Therefore, the sequencing of mitigation strategies is important for determining emissions savings in the short- and long-term. Hence, different types of cities will have different mitigation pathways, depending upon a city's urban form and state of that city's urban development and infrastructure; the policy packages and implementation plan that provide the highest mitigation potential for rapidly growing cities with new infrastructures will differ from those for established cities with existing infrastructure.

Mitigation options that involve spatial planning, urban form, and infrastructure—particularly co-located and mixed land use, as well as TOD—provide the greatest opportunities when urban areas are rapidly growing or emerging (see Section 8.4.2). Established urban areas that are already compact and walkable have captured mitigation benefits from these illustrative strategies to various extents. Conversely, established urban areas that are dispersed and auto-centric have foregone these opportunities with the exception of urban infill and densification that can be used to transform or continue to transform the existing urban form. Figure 8.21 underscores that urban mitigation options and illustrative strategies differ by urban growth typologies and urban form. Cities can identify their entry points for sequencing mitigation strategies.

The emissions reduction potential of urban mitigation options further varies based on governance contexts, institutional capacity, economic structure, as well as human and physical geography.

According to the development level, for instance, urban form can remain mostly planned or unplanned, taking place spontaneously, with persistent urban infrastructure gaps remaining (Lwasa et al. 2018; Kareem et al. 2020). Measures for closing the urban infrastructure gap while addressing 'leapfrogging' opportunities (see Glossary) for mitigation and providing co-benefits represent possibilities for shifting development paths for sustainability (see Cross-Chapter Box 5 in Chapter 4).

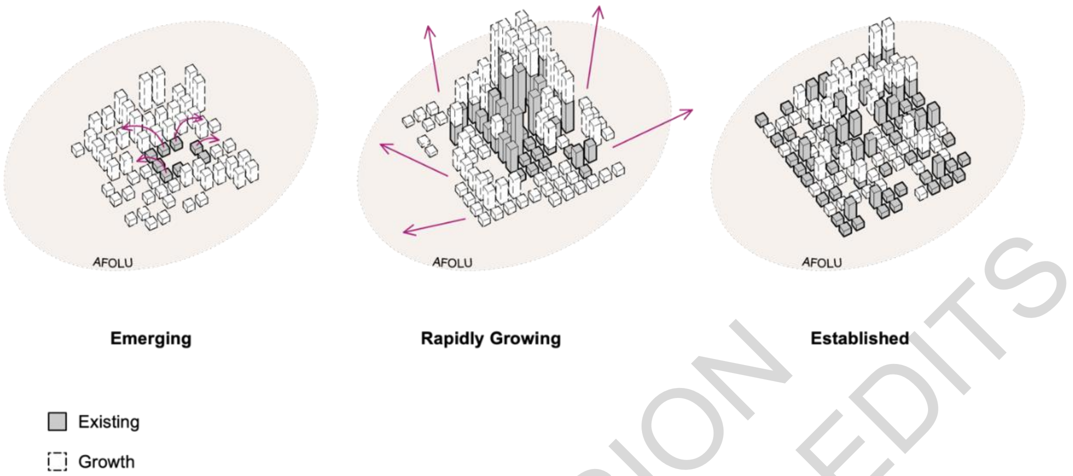

Figure 8.20 Urban Growth Typologies

Urban growth typologies define the main patterns of urban development, synthesized from Mahtta et al. (2019) and Lall et al. (2021)

Emerging urban areas are undergoing the build-up of new infrastructure. These are new urban areas that are budding out. Rapidly growing urban areas are undergoing significant changes in either outward and/or upward growth, accompanied by large-scale development of new urban infrastructure. Established urban areas are relatively stable with mature urban form and existing urban infrastructures. Each of these typologies represents different levels of economic development and state of urbanization. Rapidly growing urban areas that are building up through vertical development are often those with higher levels of economic development. Rapidly growing urban areas that are building outward through horizontal expansion occurs at lower levels of economic development and are land intensive. Like with urban form, different areas of a single city can undergo different growth typologies. Therefore a city will be comprised of multiple urban growth typologies.

Source: Synthesized and adapted from Mahtta et al. (2019) and Lall et al. (2021)

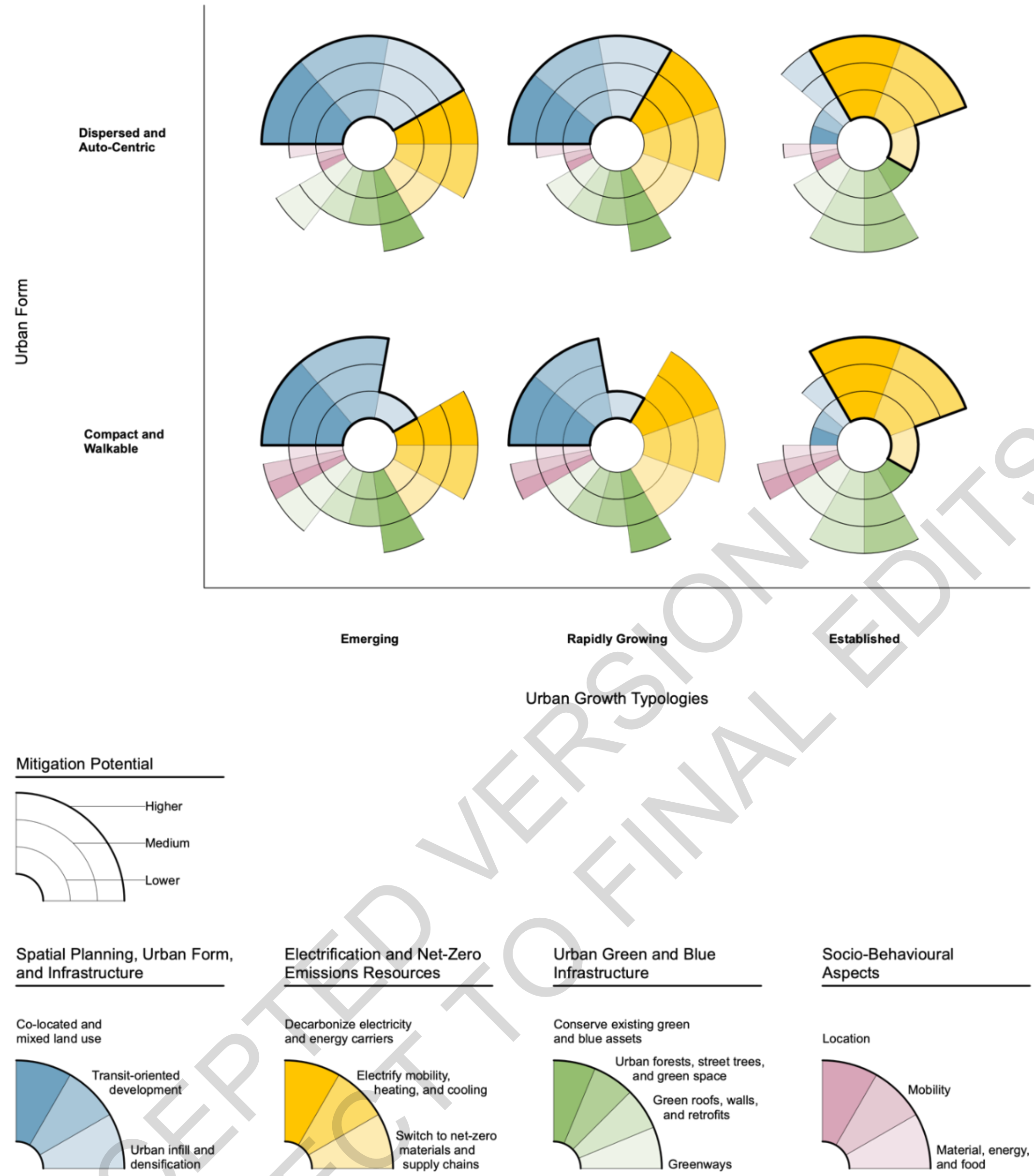

Figure 8.21 Priorities and potentials for packages of urban mitigation strategies across typologies of urban growth (Figure 8.20) and urban form (Figure 8.16)

The horizontal axis represents urban growth typologies based on emerging, rapidly growing, and established urban areas. The vertical axis shows the continuum of urban form, from compact and walkable, to dispersed and auto-centric. Urban areas can first locate their relative positioning in this space according to their predominant style of urban growth and urban form. The urban mitigation options are bundled across four broad sectors of mitigation strategies: (1) spatial planning, urban form, and infrastructure (blue); (2) electrification and net zero emissions resources (yellow); (3) urban green and blue infrastructure (green); and (4) socio-behavioural aspects (purple). The concentric circles indicate lower, medium, and higher mitigation potential considering the context of the urban area. For each city type (circular graphic) the illustrative urban mitigation strategy that is considered to provide the greatest cascading effects across mitigation opportunities is represented by a section that is larger relative to others; those strategy sections outlined in black are 'entry points' for sequencing of strategies. Within each of the larger strategy sections (i.e.., spatial planning, urban green and blue infrastructure, etc.), the size of the sub-strategy sections are equal and do not suggest any priority or sequencing. The relative sizes of the strategies and extent of mitigation potential are illustrative and based on the authors' best understanding and assessment of the literature.

8.6.1 Mitigation opportunities for *established* cities

Established cities will achieve the largest GHG emissions savings by replacing, repurposing, or retrofitting the building stock, encouraging modal shift, electrifying the urban energy system, as well as infilling and densifying urban areas.

Shifting pathways to low-carbon development for established cities with existing infrastructures and locked-in behaviours and lifestyles is admittedly challenging. Urban infrastructures such as buildings, roads, and pipelines often have long lifetimes that lock-in emissions, as well as institutional and individual behaviour. Although the expected lifetime of buildings varies considerably by geography, design, and materials, typical lifespans are at minimum 30 years to more than 100 years.

Cities where urban infrastructure has already been built have opportunities to increase energy efficiency measures, prioritize compact and mixed-use neighbourhoods through urban regeneration, advance the urban energy system through electrification, undertake cross-sector synergies, integrate urban green and blue infrastructure, encourage behavioural and lifestyle change to reinforce climate mitigation, and put into place a wide range of enabling conditions as necessary to guide and coordinate actions in the urban system and its impacts in the global system. Retrofitting buildings with state of the art deep energy retrofit measures could reduce emissions of the existing stock by about 30–60% (Creutzig et al. 2016a) and in some cases up to 80% (Ürge-Vorsatz et al. 2020) (see Section 8.4.3).

Established cities that are compact and walkable are likely to have low per capita emissions, and thus can keep emissions low by focusing on electrification of all urban energy services and using urban green and blue infrastructure to sequester and store carbon while reducing urban heat stress. Illustrative mitigation strategies with the highest mitigation potential are decarbonizing electricity and energy carriers while electrifying mobility, heating, and cooling (see Table 8.3 and Figure 8.19). Within integrated strategies, the importance of urban forests, street trees, and green space as well as green roofs, walls, and retrofits, also have high mitigation potential (see Section 8.4.4 and Figure 8.18).

Established cities that are dispersed and auto-centric are likely to have higher per capita emissions and thus can reduce emissions by focusing on creating modal shift and improving public transit systems in order to reduce urban transport emissions, as well as focusing on infilling and densifying. Only then can the urban form constraints on locational and mobility options be increased. Among mitigation options based on spatial planning, urban form, and infrastructure, urban infill and densification has priority. For these cities, the use of urban green and blue infrastructure will be essential to offset residual emissions that cannot be reduced because their urban form is already established and difficult to change.

System-wide energy savings and emissions reductions for low-carbon urban development is widely recognized to require both behavioural and structural changes (Zhang and Li 2017). Synergies between social and ecological innovation can reinforce the sustainability of urban systems while decoupling energy usage and economic growth (Hu et al. 2018; Ma et al. 2018). In addition, an integrated sustainable development approach that enables cross-sector energy efficiency, sustainable transport, renewable energy, and local development in urban neighbourhoods can address issues of energy poverty (Pukšec et al. 2018). In this context, cross-sectoral, multi-scale, and public-private collaborative action is crucial to steer societies and cities closer to low-carbon futures (Hölscher et al. 2019). Such action includes those for guiding residential living area per capita, limiting private vehicle growth, expanding public transport, improving the efficiency of urban infrastructure, enhancing urban carbon pools, and minimizing waste through sustainable, ideally circular, waste management (Lin et al. 2018). Through a coordinated approach, urban areas can be transformed into hubs for renewable and distributed energy, sustainable mobility, as well as inclusivity and health (Newman et al. 2017; Newman 2020).

Urban design for existing urban areas include strategies for urban energy transitions for carbon neutrality based on renewable energy, district heating for the city centre and suburbs, as well as green and blue interfaces (Pulselli et al. 2021). Integrated modelling approaches for urban energy system planning, including land-use and transport and flexible demand-side options, is increased when municipal actors are also recognized as energy planners (Yazdanie and Orehounig 2021) (see Section 8.4.3). Enablers for action can include the co-design of infill residential development through an inclusive and participatory process with citizen utilities and disruptive innovation that can support net zero carbon power while contributing to 1.5°C pathways, the SDGs, and affordable housing simultaneously (Wiktorowicz et al. 2018). Cross-sectoral strategies for established cities, including those taking place among 120 urban areas, also involve opportunities for sustainable development (Kılkış 2019, 2021b).

A shared understanding for urban transformation through a participatory approach can largely avoid maladaptation and contribute to equity (Moglia et al. 2018). Transformative urban futures that are radically different from the existing trajectories of urbanization, including in developing countries, can remain within planetary boundaries while being inclusive of the urban poor (Friend et al. 2016). At the urban policy level, an analysis of 12,000 measures in urban-level monitoring emissions inventories based on the mode of governance further suggests that local authorities with lower population have primarily relied on municipal self-governing while local authorities with higher population more frequently adopted regulatory measures as well as financing and provision (Palermo et al. 2020b). Policies that relate to education and enabling were uniformly adopted regardless of population size (Palermo et al. 2020b). Multi-disciplinary teams, including urban planners, engineers, architects, and environmental institutions, can support local decision-making capacities, including for increasing energy efficiency and renewable energy considering building intensity and energy use (Mrówczyńska et al. 2021) (see also Section 8.5).

8.6.2 Mitigation opportunities for *rapidly growing* cities

Rapidly growing cities with new and actively developing infrastructures can avoid higher future emissions through using urban planning to co-locate jobs and housing, and achieve compact urban form; leapfrogging to low-carbon technologies; electrifying all urban services, including transportation, cooling, heating, cooking, recycling, water extraction, wastewater recycling, etc.; and preserving and managing existing green and blue assets.

Rapidly growing cities have significant opportunities for integrating climate mitigation response options in earlier stages of urban development, which can provide even greater opportunities for avoiding carbon lock-in and shifting pathways towards net zero GHG emissions. In growing cities that are expected to experience large increases in population, a significant share of urban development remains to be planned and built. The ability to shift these investments towards low-carbon development earlier in the process represents an important opportunity for contributing to net zero GHG emissions at the global scale. In particular, evidence suggests that investment in low-carbon development measures and re-investment based on the returns of the measures even without considering substantial co-benefits can provide tipping points for climate mitigation action and reaching peak emissions at lower levels while decoupling emissions from economic growth, even in fast-growing megacity contexts with well-established infrastructure (Colenbrander et al. 2017).

At the same time, some of the rapidly growing cities in developing countries can have existing walkable urban design that can be maintained and supported with electrified urban rail plus renewable-energy-based solutions to avoid a shift to private vehicles (Sharma 2018). In addition, community-based distributed renewable electricity can be applicable for the regeneration of informal settlements rather than more expensive informal settlement clearance (Teferi and Newman 2018). Scalable options for decentralized energy, water, and wastewater systems, as well as spatial planning and urban agriculture and forestry, are applicable to urban settlements across multiple regions simultaneously (Lwasa 2017).

Rapidly urbanizing areas can experience pressure for rapid growth in urban infrastructure to address growth in population. This challenge can be addressed with coordinated urban planning and support from enabling conditions for pursuing effective climate mitigation (see Section 8.5 and Box 8.3). The ability to mobilize low-carbon development will also increase opportunities for capturing co-benefits for urban inhabitants while reducing embodied and operational emissions. Transforming urban growth, including its impacts on energy and materials, can be carefully addressed with the integration of cross-sectoral strategies and policies.

Rapidly growing cities have entry points into an integrated strategy based on spatial planning, urban form and infrastructure (see Figure 8.21). For rapidly growing cities that may be co-located and walkable at present, remaining compact is better ensured when co-location and mixed land use as well as TOD continues to be prioritized (see Section 8.4.2). Concurrently, ensuring that electricity and energy carriers are decarbonized while electrifying mobility, heating and cooling will support the mitigation potential of these cities. Along with an integrated approach across other illustrative strategies, switching to net zero materials and supply chains holds importance (see Section 8.4.3). Cities that remain compact and walkable can provide a greater array of locational and mobility options to the inhabitants that can be adopted for mitigation benefits. Rapidly growing cities that may currently be dispersed and auto-centric can capture high mitigation potential through urban infill and densification. Conserving existing green and blue assets, thereby protecting sources of carbon storage and sequestration, as well as biodiversity, have high potential for both kinds of existing urban form, especially when the rapid growth can be controlled.

8.6.3 Mitigation opportunities for *new and emerging* cities

New and emerging cities have unparalleled potential to become low or net zero emissions urban areas while achieving high quality of life by creating compact, co-located, and walkable urban areas with mixed land use and TOD, that also preserve existing green and blue assets.

The fundamental building blocks that make up the physical attributes of cities, such as the layout of streets, the size of the city blocks, the location of where people live versus where they work, can affect and lock in energy demand for long time periods (Seto et al. 2016) (see Section 8.4.1). A large share of urban infrastructures that will be in place by 2050 has yet to be constructed and their design and implementation will determine both future GHG emissions as well as the ability to meet mitigation goals (Creutzig et al. 2016a) (see Figure 8.10 and Table 8.1). Thus, there are tremendous opportunities for new and emerging cities to be designed and constructed to be low-emissions while providing high quality of life for their populations.

The UN International Resource Panel (IRP) estimates that building future cities under conventional practices will require a more than doubling of material consumption, from 40 billion tonnes annually in 2010 to about 90 billion tonnes annually by 2050 (Swilling et al. 2018). Thus, the demand that new and emerging cities will place on natural resource use, materials, and emissions can be minimized and avoided only if urban settlements are planned and built much differently than today, including minimized impacts on land use based on compact urban form, lowered use of materials, and related cross-sector integration, including energy-driven urban design for sustainable urbanization.

Minimising and avoiding raw material demands depend on alternative options while accommodating the urban population. In addition, operational emissions that can be committed by new urban infrastructure can range between 8.5 $GtCO_2$ and 14 $GtCO_2$ annually up to 2030 (Erickson and Tempest 2015). Buildings and road networks are strongly influenced by urban layouts, densities, and specific uses. Cities that are planned and built much differently than today through light-weighting, material substitution, resource efficiency, renewable energy, and compact urban form, have the potential to support more sustainable urbanization and provide co-benefits for inhabitants (see Figures 8.17 and 8.22).

In this context, illustrative mitigation strategies that can serve as a roadmap for emerging cities includes priorities for co-located and mixed land use, as well as TOD, within an integrated approach (see Table 8.3 and Figure 8.19). This has cascading effects, including conserving existing green and blue assets (e.g., forests, grasslands, wetlands, etc.), many of which sequester and store carbon. Priorities for decarbonizing electricity and energy carriers while electrifying mobility, heating, and cooling take place within the integrated approach (see Section 8.4.3). Increasing greenways and permeable surfaces, especially from the design of emerging urban areas onward, can be pursued, also for adaptation co-benefits and linkages with the SDGs (see Section 8.4.4 and Figure 8.18).

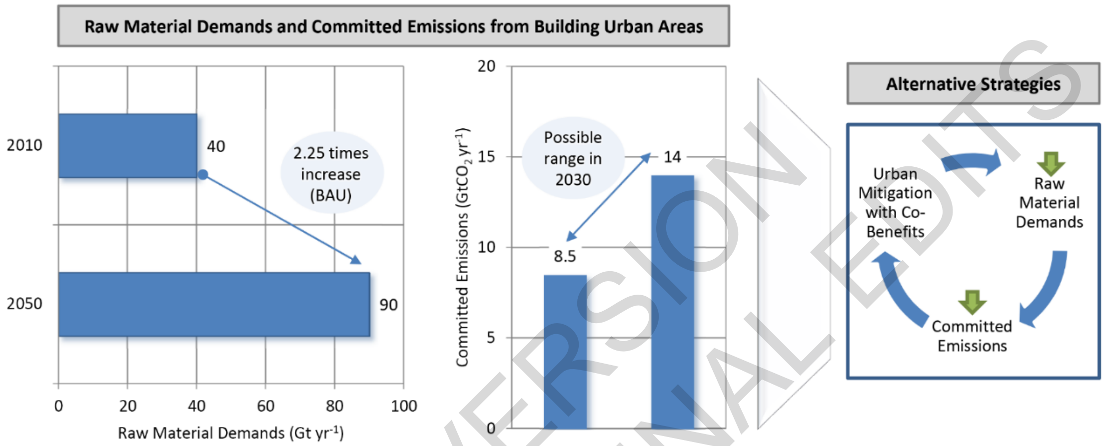

Figure 8.22 Raw material demands and committed emissions from building urban areas

The horizontal bars represent the projected increase in raw material demands in the year 2050. The vertical bars represent the possible range of committed CO_2 emissions in 2030. The importance of alternative solutions to reduce raw material demands and committed emissions while increasing co-benefits is represented by the circular process on the right side.

Source: Drawn using data from Erickson and Tempest (2015) and Swilling et al. (2018)

In low energy-driven urban design, parameters are evaluated based on the energy performance of the urban area in the early design phase of future urban development (Shi et al. 2017b). Energy-driven urban design generates and optimizes urban form according to the energy performance outcome (Shi et al. 2017b). Beyond the impact of urban form on building energy performance, the approach focuses on the interdependencies between urban form and energy infrastructure in urban energy systems. The process can provide opportunities for both passive options for energy-driven urban design, such as the use of solar gain for space heating, or of thermal mass to moderate indoor temperatures, as well as active options that involve the use of energy infrastructure and technologies while recognising interrelations of the system. Future urban settlements can also be planned and built with net zero CO_2 or net zero GHG emissions, as well as renewable energy targets, in mind. Energy master planning of urban areas that initially target net zero operational GHG emissions can be supported with energy master planning from conceptual design to operation, including district scale energy strategies (Charani Shandiz et al. 2021).

Integrated scenarios across sectors at the local level can decouple resource usage from economic growth (Hu et al. 2018) and enable 100% renewable energy scenarios (Zhao et al. 2017a; Bačeković and Østergaard 2018). Relative decoupling is obtained (Kalmykova et al. 2015) with increasing evidence for turning points in per capita emissions, total emissions, or urban metabolism (Chen et al. 2018b; Shen et al. 2018). The importance of integrating energy and resource efficiency in sustainable and low-carbon city planning (Dienst et al. 2015), structural changes, as well as forms of disruptive social innovation, such as the 'sharing economy' (see Glossary), is also evident based on analyses for multiple cities, including those that can be used to lower the carbon footprints of urban areas relative to sub-urban areas (Chen et al. 2018a).

To minimize carbon footprints, new cities can utilize new intelligence functions as well as changes in energy sources and material processes. Core design strategies of a compact city can be facilitated by data-driven decision-making so that new urban intelligence functions are holistic and pro-active rather than reactive (Bibri 2020). In mainstream practices, for example, many cities use environmental impact reviews to identify potentially negative consequences of individual development projects on environmental conditions in a piecemeal project basis.

New cities can utilize: system-wide analyses of construction materials, or renewable power sources, that minimize ecosystem disruption and energy use, through the use of lifecycle assessments for building types permitted in the new city (Ingrao et al. 2019); urban-scale metabolic impact assessments for neighbourhoods in the city (Pinho and Fernandes 2019); strategic environmental assessments (SEAs) that go beyond the individual project and assess plans for neighbourhoods (Noble and Nwanekezie 2017); or the modelling of the type and location of building masses, tree canopies and parks, and temperature (surface conditions) and prevailing winds profiles to reduce the combined effects of climate change and UHI phenomena, thus minimising the need for air conditioning (Matsuo and Tanaka 2019).

Resource-efficient, compact, sustainable, and liveable urban areas can be enabled with an integrated approach across sectors, strategies, and innovations. From a geophysical perspective, the use of materials with lower lifecycle GHG impacts, including the use of timber in urban infrastructure and the selection of urban development plans, with lower material and land demand can lower the emission impacts of existing and future cities (Müller et al. 2013; Carpio et al. 2016; Liu et al. 2016a; Ramage et al. 2017; Shi et al. 2017a; Stocchero et al. 2017; Bai et al. 2018; Zhan et al. 2018b; Swilling et al. 2018; Xu et al. 2018b; UNEP and IRP 2020) (see Figure 8.17). The capacity to implement relevant policy instruments in an integrated and coordinated manner within a policy mix while leveraging multilevel support as relevant can increase the enabling conditions for urban system transformation (Agyepong and Nhamo 2017; Roppongi et al. 2017).

The integration of urban land use and spatial planning, electrification of urban energy systems, renewable energy district heating and cooling networks, urban green and blue infrastructure, and circular economy can also have positive impacts on improving air and environmental quality with related co-benefits for health and well-being (Diallo et al. 2016; Nieuwenhuijsen and Khreis 2016; Shakya 2016; Liu et al. 2017; Ramaswami et al. 2017a; Sun et al. 2018b; Tayarani et al. 2018; Park and Sener 2019; González-García et al. 2021). Low-carbon development options can be implemented in ways that reduce impacts on water use, including water use efficiency, demand management, and water recycling, while increasing water quality (Koop and van Leeuwen 2015; Topi et al. 2016; Drangert and Sharatchandra 2017; Lam et al. 2017, 2018; Vanham et al. 2017; Kim and Chen 2018). The ability for enhancing biodiversity while addressing climate change depends on improving urban metabolism and biophilic urbanism towards urban areas that are able to regenerate natural capital (Thomson and Newman 2018; IPBES 2019b).

There are readily available solutions for low-carbon urban development that can be further supported by new emerging ones, such as tools for optimising the impact of urban form on energy infrastructure (Hu et al. 2015; Shi et al. 2017b; Xue et al. 2017; Dobler et al. 2018; Egusquiza et al. 2018; Pedro et al. 2018; Soilán et al. 2018). The costs of low-carbon urban development are manageable and enhanced with a portfolio approach for cost-effective, cost-neutral, and re-investment options with evidence across different urban typologies (Colenbrander et al. 2015, 2017; Gouldson et al. 2015;

Nieuwenhuijsen and Khreis 2016; Saujot and Lefèvre 2016; Sudmant et al. 2016; Brozynski and Leibowicz 2018).

Low-carbon urban development that triggers economic decoupling can have a positive impact on employment and local competitiveness (Kalmykova et al. 2015; Chen et al. 2018b; García-Gusano et al. 2018; Hu et al. 2018; Shen et al. 2018). In addition, sustainable urban transformation can be supported with participatory approaches that provide a shared understanding of future opportunities and challenges where public acceptance increases with citizen engagement and citizen empowerment as well as an awareness of co-benefits (Blanchet 2015; Bjørkelund et al. 2016; Flacke and de Boer 2017; Gao et al. 2017; Neuvonen and Ache 2017; Sharp and Salter 2017; Wiktorowicz et al. 2018; Fastenrath and Braun 2018; Gorissen et al. 2018; Herrmann et al. 2018; Moglia et al. 2018). Sustainable and low-carbon urban development that integrates issues of equity, inclusivity, and affordability, while safeguarding urban livelihoods, providing access to basic services, lowering energy bills, addressing energy poverty, and improving public health can also improve the distributional effects of existing and future urbanization (Friend et al. 2016; Claude et al. 2017; Colenbrander et al. 2017; Ma et al. 2018; Mrówczyńska et al. 2018; Pukšec et al. 2018; Wiktorowicz et al. 2018) (see Section 8.2).

Information and communications technologies can play an important role for integrating mitigation options at the urban systems level for achieving zero-carbon cities. Planning for decarbonisation at the urban systems level involves integrated considerations of the interaction among sectors, including synergies and trade-offs among households, businesses, transport, land use, and lifestyles. The utilisation of big data, artificial intelligence and Internet of Things (IoT) technologies can be used to plan, evaluate and integrate rapidly progressing transport and building technologies, such as autonomous EVs, zero energy buildings and districts as an urban system, including energy-driven urban design (Creutzig et al. 2020; Yamagata et al. 2020). Community level energy sharing systems will contribute to realising the decarbonization potential of urban systems at community scale, including in smart cities (see Section 4.2.5.9 in Chapter 4, Box 10.2 in Chapter 10 and Cross-Chapter Box 11 in Chapter 16).

8.5 Knowledge Gaps

While there is growing literature on urban NBS, which encompasses urban green and blue infrastructure in cities, there is still a knowledge gap regarding how these climate mitigation actions can be integrated in urban planning and design, as well as their mitigation potential, especially for cities that have yet to be built. In moving forward with the research agenda on cities and climate change science, transformation of urban systems will be critical; however, understanding this transformation and how best to assess mitigation action remain key knowledge gaps (Butcher-Gollach 2018; Pathak and Mahadevia 2018; Rigolon et al. 2018; Anguelovski et al. 2019; Buyana et al. 2019; Trundle 2020; Azunre et al. 2021).

There is a key knowledge gap in respect to the potential of the informal sector in developing country cities. Informality extends beyond illegality of economic activities to include housing, locally developed off-grid infrastructure, and alternative waste management strategies. Limited literature and understanding of the mitigation potential of enhanced informal sector is highlighted in the key research agenda on cities from the cities and climate change science conference (Prieur-Richard et al. 2018).

City-level models and data for understanding of urban systems is another knowledge gap. With increased availability of open data systems, big data and computing capacities, there is an opportunity for analysis of urban systems (Frantzeskaki et al. 2019).

While there is much literature on urban climate governance, there is still limited understanding of the governance models and regimes that support multi-level decision making for mitigation and climate action in general. Transformative climate action will require changing relationships between actors to utilize the knowledge from data and models and deepen understanding of the urban system to support decision-making.

8.6.4 COVID-19 and cities

The COVID-19 pandemic has disrupted many aspects of urban life while raising questions about urban densities, transportation, public space, and other urban issues. The impact of COVID-19 on urban activity and urban GHG emissions may offer insights into urban emissions and their behavioural drivers and may include structural shifts in emissions that last into the future. The science is unclear as to the links between urban characteristics and COVID-19, and involves multiple aspects. For example, some research shows higher COVID-19 infection rates with city size (e.g., Dalziel et al. 2018; Stier et al. 2021), as well as challenges to epidemic preparedness due to high population density and high volume of public transportation (Layne et al. 2020; Lee et al. 2020). Other research from 913 metropolitan areas shows that density is unrelated to COVID-19 infection rates and, in fact, has been inversely related to COVID-19 mortality rates when controlled by metropolitan population.

Dense counties are found to have significantly lower mortality rates, possibly due to such advantages as better health care systems as well as greater adherence to social-distancing measures (Hamidi et al. 2020). Sustainable urbanization and urban infrastructure that address the SDGs can also improve preparedness and resilience against future pandemics. For example, long-term exposure to air pollution has been found to exacerbate the impacts of COVID-19 infections (Wu et al. 2020b), while urban areas with cleaner air from clean energy and greenspace, can provide advantages.

Some studies indicate that socio-economic factors, such as poverty, racial and ethnic disparities, and crowding are more significant than density in COVID-19 spread and associated mortality rate (Borjas 2020; Maroko et al. 2020; Lamb et al. 2021). The evidence for the connection between household crowding and the risk of contagion from infectious diseases is also strong. A 2018 World Health Organisation (WHO) systematic review of the effect of household crowding on health concluded that a majority of studies of the risk of non-tuberculosis infectious diseases, including flu-related illnesses, were associated with household crowding (Shannon et al. 2018).

Though preliminary, some studies suggest that urban areas saw larger overall declines in emissions because of lower commuter activity and associated emissions. For example, researchers have explored the COVID-19 impact in the cities of Los Angeles, Baltimore, Washington, DC, and San Francisco Bay Area in the United States. In the San Francisco region, a decline of 30% in anthropogenic CO_2 was observed, which was primarily due to changes in on-road traffic (Turner et al. 2020). Declines in the Washington, DC/Baltimore region and in the Los Angeles urban area were 33% and 34%, respectively, in the month of April compared to previous years (Yadav et al. 2021).

At the global scale COVID-related lock-down and travel restrictions reduced daily CO_2 emissions by -17% in early April 2020 compared to 2019 values (Le Quéré et al. 2020; Liu et al. 2020b), though subsequent studies have questioned the accuracy of the indirect proxy data used (Gurney et al. 2021b; Oda et al. 2021). Research at the national scale in the United States found that daily CO_2 emissions declined -15% during the late March to early June time period (Gillingham et al. 2020). Sector analysis indicates that gasoline transportation and electricity generation contributed to the majority of the April-May 2020 decline (Gurney et al. 2021b). Research in China estimated that the first quarter of 2020 saw an 11.5% decline in CO_2 emissions relative to 2019 (Zheng et al. 2020; Han et al. 2021). In Europe, estimates indicated a -12.5% decline in the first half of 2020 compared to 2019 (Andreoni 2021). Rebound to pre-COVID trajectories has been evidenced following the ease of travel restrictions (Gurney et al. 2021b; Le Quéré et al. 2021). It remains unclear to what extent COVID resulted in any structural change in the underlying drivers of urban emissions.

Changes in local air pollution emissions, particularly due to altered transportation patterns, have caused temporary air quality improvements in many cities around the world (see critical review by a Adam et al. 2021). Many outdoor air pollutants, such as particulates, nitrogen dioxide, carbon monoxide, and volatile organic compounds declined during national lockdowns. Levels of tropospheric ozone, however, remained constant or increased. A promising transformation that has been observed in many cities is an increase in the share of active travel modes such as cycling and walking (Sharifi and Khavarian-Garmsir 2020). While this may be temporary, other trends, such as increased rates of teleworking and/or increased reliance on smart solutions that allow remote provision of services provide an unprecedented opportunity to transform urban travel patterns (Belzunegui-Eraso and Erro-Garcés 2020; Sharifi and Khavarian-Garmsir 2020).

Related to the transport sector, the pandemic has resulted in concerns regarding the safety of public transport modes, which has resulted in significant reductions in public transport ridership in some cities (Bucsky 2020; de Haas et al. 2020) while providing opportunities for urban transitions in others (Newman AO 2020). Considering the significance of public transportation for achieving low-carbon and inclusive urban development, appropriate response measures could enhance health safety of public transport modes and regain public trust (Sharifi and Khavarian-Garmsir 2020). Similarly, there is a perceived correlation between the higher densities of urban living and the risk of increased virus transmission (Hamidi et al. 2020; Khavarian-Garmsir et al. 2021).

While city size could be a risk factor with higher transmission in larger cities (Hamidi et al. 2020; Stier et al. 2021), there is also evidence showing that density is not a major risk factor and indeed cities that are more compact have more capacity to respond to and control the pandemic (Hamidi et al. 2020). Considering the spatial pattern of density, even distribution of density can reduce the possibility of crowding that is found to contribute to the scale and length of virus outbreak in cities. Overall, more research is needed to better understand the impacts of density on outbreak dynamics and address public health concerns for resilient cities.

Cities could seize this opportunity to provide better infrastructure to further foster active transportation. This could, for example, involve measures, such as expanding cycling networks and restricting existing streets to make them more pedestrian- and cycling-friendly contributing to health and adaptation co-benefits as discussed in Section 8.2 (Sharifi 2021). Strengthening the science-policy interface is another consideration that could support urban transformation (also see Cross-chapter Box 1 in Chapter 1).

8.6.5 Future urban emissions scenarios

The urban share of global emissions is significant and is expected to increase in the coming decades. This places emphasis on the need to expand development of urban emissions scenarios within climate mitigation scenarios (Gurney et al. 2021a). The literature on globally comprehensive analysis of urban emissions within the existing IPCC scenario framework remain very limited curtailing understanding of urban emissions tipping points, mitigation opportunities and overall climate policy complexity. A recent review of the applications of the SSP/RCP scenario framework recommends downscaling global SSPs to improve the applicability of this framework to regional and local scales (O'Neill et al. 2020). This remains an urgent need and will require multi-disciplinary research efforts, particularly as net zero emissions targets are emphasized.

8.6.6 Urban emissions data

Though there has been a rapid rise in quantification and analysis of urban emissions, gaps remain in comprehensive global coverage, particularly in the Global South, and reliance on standardized frameworks and systematic data is lacking (Gurney and Shepson 2021; Mueller et al. 2021). The development of protocols by (BSI 2013; Fong et al. 2014; ICLEI 2019b) that urban areas can use to organize emissions accounts has been an important step forward, but no single agreed-upon reporting framework exists (Lombardi et al. 2017; Chen et al. 2019b; Ramaswami et al. 2021). Additionally, there is no standardisation of emissions data and limited independent validation procedures (Gurney and Shepson 2021). This is partly driven by the recognition that urban emissions can be conceptualized using different frameworks, each of which has a different meaning for different urban communities (see section 8.1.6.2). Equally important is the recognition that acquisition and analysis of complex data used to populate urban GHG inventory protocols remains a barrier for local practitioners (Creutzig et al. 2019). The limited standardization has also led to incomparability of the many individual or city cluster analyses that have been accomplished since AR5. Finally, comprehensive, global quantification of urban emissions remains incomplete in spite of recent efforts (Moran et al. 2018; Zheng et al. 2018; Harris et al. 2020; Jiang et al. 2020; Wei et al. 2021; Wiedmann et al. 2021).

Similarly, independent verification or evaluation of urban GHG emissions has seen a large number of research studies (e.g., Wu et al. 2016; Sargent et al. 2018; Whetstone 2018; Lauvaux et al. 2020). This has been driven by the recognition that self-reported approaches may not provide adequate accuracy to track emissions changes and provide confidence for mitigation investment (Gurney and Shepson 2021).

The most promising approach to independent verification of urban emissions has been the use of urban atmospheric monitoring (direct flux and/or concentration) as a means to assess and track urban GHG emissions (Davis et al. 2017). However, like the basic accounting approach itself, standardization and practical deployment and scaling is an essential near-term need.

Frequently Asked Questions

FAQ 8.1 Why are urban areas important to global climate change mitigation?

Over half of the world's population currently resides in urban areas—a number forecasted to increase to nearly 70% by 2050. Urban areas also account for a growing proportion of national and global emissions depending on emissions scope and geographic boundary. These trends are projected to grow in the coming decades; in 2100, some scenarios show the urban share of global emissions above 80%, with 63% being at the minimum for any scenario (with the shares being in different contexts of emissions reduction or increase) (Sections 8.3.3 and 8.3.4). As such, urban climate change mitigation considers the majority of the world's population, as well some of the key drivers of global emissions. In general, emissions scenarios with limited outward urban land expansion are also associated with a smaller rise in global temperature (Section 8.3.4).

The urban share of global emissions and its projected growth stem in part from urban carbon lock-in—that is, the path dependency and inertia of committed emissions through the long lifespan of urban layout, infrastructures, and behaviour. As such, urban mitigation efforts that address lock-in can significantly reduce emissions (Section 8.4.1). Electrification of urban energy systems in tandem with implementing multiple urban-scale mitigation strategies, could reduce urban emissions by 90% by 2050--thereby significantly reducing global emissions (Section 8.3.4). Urban areas can also act as points of intervention to amplify synergies and co-benefits for accomplishing the Sustainable Development Goals (Section 8.2).

FAQ 8.2 What are the most impactful options cities can take to mitigate urban emissions, and how can these be best implemented?

The most impactful urban mitigation plans reduce urban GHG emissions by considering the long lifespan of urban layout and urban infrastructures (Section 8.4.1 and 8.6). Chapter 8 identifies three overarching mitigation strategies with the largest potential to decrease current, and avoid future, urban emissions: (1) reduce urban energy consumption across all sectors including through spatial planning and infrastructure that supports compact, walkable urban form (Section 8.4.2); (2) decarbonize through electrification of the urban energy system, and switch to net zero emissions resources (i.e., low-carbon infrastructure) (Section 8.4.3); and (3) enhance carbon sequestration through urban green and blue infrastructure (e.g., green roofs, urban forests and street trees, etc.), which can also offer multiple co-benefits like reducing ground temperatures and supporting public health and well-being (Section 8.4.4). Integrating these mitigation strategies across sectors, geographic scales, and levels of governance will yield the greatest emissions savings (Sections 8.4 and 8.5).

A city's layout, patterns, and spatial arrangements of land use, transportation systems, and built environment (urban form), as well as its state and form(s) of development (urban growth typology), can inform the most impactful emissions savings 'entry point' and priorities for urban mitigation strategies (Sections 8.4.2 and 8.6). For rapidly growing and emerging urban areas, there is the opportunity to avoid carbon lock-in by focusing on urban form that promotes low-carbon infrastructure and enables low-impact behaviour facilitated by co-located medium to high densities of jobs and housing, walkability, and transit-oriented development (Sections 8.6.2 and 8.6.3). For established cities, strategies include electrification of the grid and transport, and implementing energy efficiency across sectors (Section 8.6.1).

FAQ 8.3 How do we estimate global emissions from cities, and how reliable are the estimates?

There are two different emissions estimation techniques applied, individually or in combination, to the four frameworks outlined in Section 8.1.6.2 to estimate urban GHG emissions: 'top-down' and 'bottom-up.' The top-down technique uses atmospheric GHG concentrations and atmospheric modelling to estimate direct (scope 1) emissions (see Glossary). The bottom-up technique estimates emissions using local activity data or direct measurements such as in smokestacks, traffic data, energy consumption information, and building use. Bottom-up techniques will often include 'indirect emissions (see Glossary) from purchased electricity (scope 2) and the urban supply chain (scope 3). Inclusion of supply-chain emissions often requires additional data such as consumer purchasing data and supply chain emission factors. Some researchers also take a hybrid approach combining top-down and bottom-up estimation techniques to quantify territorial emissions. Individual self-reported urban inventories from cities have shown chronic underestimation when compared to estimates using combined top-down/bottom-up atmospherically calibrated estimation techniques.

No approach has been systematically applied to all cities worldwide. Rather, they have been applied individually or in combination to subsets of global cities. Considerable uncertainty remains in estimating urban emissions. However, top-down approaches have somewhat more objective techniques for uncertainty estimation in comparison to bottom-up approaches. Furthermore, supply chain estimation typically has more uncertainty than direct or territorial emission frameworks.

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Chapter 9: Buildings

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Date of Draft: 28/11/2021

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Executive summary

Global Greenhouse Gas (GHG) emissions from buildings were in 2019 at 12 $GtCO_2eq$., equivalent to 21% of global GHG emissions that year, out of which 57% were indirect emissions from offsite generation of electricity and heat, 24% direct emissions produced onsite and 18% were embodied emissions from the use of cement and steel (*high evidence, high agreement*). More than 95% of emissions from buildings were CO_2 emissions, CH_4 and N_2O represented 0.08%, and emissions from halocarbon contributed by 3% to global GHG emissions from buildings. If only CO_2 emissions would be considered, the share of CO_2 emissions from buildings out of global CO_2 emissions increases to 31%. Global final energy demand from buildings reached 128.8 EJ in 2019, and global electricity demand was slightly above 43 EJ. The former accounted for 31% of global final energy demand and the latter for 18% of global electricity demand. Residential buildings consumed 70% of global final energy demand from buildings. Over the period 1990-2019, global CO_2 emissions from buildings increased by 50%, global final energy demand grew by 38 and global final electricity demand increased by 161% (*high evidence, high agreement*) {9.3}.

Drivers of GHG emissions in the building sector were assessed using the SER (Sufficiency, Efficiency, Renewable) framework. Sufficiency measures tackle the causes of GHG emissions by avoiding the demand for energy and materials over the lifecycle of buildings and appliances. Sufficiency differs from efficiency in that the latter is about the continuous short-term marginal technological improvements, which allows doing less with more in relative terms without considering the planetary boundaries, while the former is about long-term actions driven by non-technological solutions (i.e., land use management and planning), which consume less in absolute term and are determined by biophysical processes. Sufficiency addresses the issue of a fair consumption of space and resources. The remaining carbon budget, and its normative target for distributional equity, is the upper limit of sufficiency, while requirements for a decent living standard define the minimum level of sufficiency. The SER framework introduces a hierarchical layering which reduces the cost of constructing and using buildings without reducing the level of comfort of the occupant. Sufficiency interventions in buildings include the optimisation of the use of building, repurposing unused existing buildings, prioritising multi-family homes over single-family buildings, and adjusting the size of buildings to the evolving needs of households by downsizing dwellings. Sufficiency measures do not consume energy during the use phase of buildings.

In most regions, historical improvements in efficiency have been approximately matched by growth in floor area per capita. Implementing sufficiency measures that limit growth in floor area per capita, particularly in developed regions, reduces the dependence of climate mitigation on technological solutions (*medium evidence, medium agreement*). At a global level, up to 17% of the mitigation potential could be captured by 2050 through sufficiency interventions (*medium evidence, medium agreement*). Sufficiency is an opportunity to avoid locking buildings in carbon-intensive solutions. Density, compacity, building typologies, bioclimatic design, multi-functionality of space, circular use of materials, use of the thermal mass of buildings (to store heat for the cold season and to protect occupants from high temperatures (i.e. heatwaves), when designing energy services, moving from ownership to usership of appliances and towards more shared space, are among the sufficiency measures already implemented in the leading municipalities. At the global level, the main drivers of emissions include (i) population growth, especially in developing countries, (ii) increase in floor area per capita, driven by the increase of the size of dwellings while the size of households kept decreasing, especially in developed countries, (iii) the inefficiency of the newly constructed buildings, especially in developing countries, and the low renovation rates and ambition level in developed countries when existing buildings are renovated, iv) the increase in use, number and size of appliances and equipment, especially ICT and cooling, driven by the growing welfare (income), and (v) the continued reliance on fossil fuel based electricity and heat slow decarbonisation of energy supply. These factors taken together are projected to continue driving GHG emissions in the building sector in the future (*high evidence, high agreement*) {9.2, 9.3, 9.4, 9.5, 9.6, and 9.9}.

Bottom-up studies show a mitigation potential up to 85% in Europe and North America and up to 45% in Asia Pacific Developed compared to the baselines by 2050, even though they sometimes decline (*robust evidence, high agreement*). In developing countries, bottom-up studies estimate the potential of up to 40-80% in 2050, as compared to their sharply growing baselines (*medium evidence, high agreement*). The aggregation of results from all these bottom-up studies translates into a global mitigation potential by 2050 of at least 8.2 $GtCO_2$, which is equivalent to 61% of their baseline scenario. The largest mitigation potential (5.4 $GtCO_2$) is available in developing countries while developed countries will be able to mitigate 2.7 $GtCO_2$. These potentials represent the low estimates, and the real potential is likely to be higher. These estimated potentials would be higher if embodied emissions in buildings and those from halocarbons would be included (*low evidence, high agreement*) {9.3, 9.6,}.

The development, since Assessment Report 5 (AR5), of integrated approaches to construction and retrofit of buildings has led to the widespread of zero energy/carbon buildings in all climate zones. The complementarity and the interdependency of measures lead to cost reduction while optimising the mitigation potential grasped and avoiding the lock-in-effect. The growing consideration of integrated approach to construction of new buildings as well as to the renovation of existing buildings results in a lower relevance of the step-by-step approach to renovate buildings and to breaking down the potential into cost categories, as to deliver deep mitigation and cost savings technologies and approaches shall be applied together in an integrated and interdependent manner (*medium evidence, high agreement*). The potential associated with the sufficiency measures as well as the exchange of appliances, equipment, and lights with efficient ones is at cost below USD0 tCO_2^{-1} (*high evidence, high agreement*). The construction of high-performance buildings will become by 2050 a business-as-usual technology with costs below USD20 tCO_2^{-1} in developed countries and below USD100 tCO_2^{-1} in developing countries (*medium evidence, high agreement*). For existing buildings, there have been many examples of deep retrofits where additional costs per CO_2 abated are not significantly higher than those of shallow retrofits. However, for the whole stock they tend to be in cost intervals of 0-200USD tCO_2^{-1} and >200USD tCO_2^{-1} (*medium evidence, medium agreement*) . Literature emphasizes the critical role of the decade between in 2020 and 2030 in accelerating the learning of know-how and skills to reduce the costs and remove feasibility constrains for achieving high efficiency buildings at scale and set the sector at the pathway to realize its full potential (*high evidence, high agreement*) {9.6, 9.9}.

The decarbonisation of buildings is constrained by multiple barriers and obstacles as well as limited flow of finance (*robust evidence, high agreement*). The lack of institutional capacity, especially in developing countries, and appropriate governance structures slow down the decarbonisation of the global building stock (*medium evidence, high agreement*). The building sector stands out for its high heterogeneity, with many different building types, sizes, and operational uses. Its segment representing rented property faces principal/agent problems where the tenant benefits from the decarbonisation investment made by the landlord. The organisational context and the governance structure could trigger or hinder the decarbonisation of buildings (*high evidence, high agreement*). Global investment in the decarbonisation of buildings was estimated at USD164 billion in 2020, not enough to close the investment gap (*robust evidence, high agreement*) {9.9}.

Policy packages based on the SER (Sufficiency, Efficiency, Renewables) framework could grasp the full mitigation potential of the global building stock (*medium evidence, high agreement*). Low ambitious policies will lock buildings in carbon for decades as buildings last for decades if not centuries (*high evidence, high agreement*). Building energy codes is the main regulatory instrument to reduce emissions from both new and existing buildings (*high evidence, high agreement*). Most advanced building energy codes include bioclimatic design requirements to capture the sufficiency potential of buildings, efficiency requirements by using the most efficient technologies and requirements to increase the integration of renewable energy solutions to the building shape. Some announced building energy codes extend these requirements from the use phase to the whole building lifecycle. Building energy codes are proven to be especially effective if compulsory and combined with other regulatory instruments such as minimum energy performance standard for appliances and equipment, especially if the performance level is set at the level of the best available technologies in the market (*robust evidence, high agreement*). Market-based instruments such as carbon taxes with recycling of the revenues and personal or building carbon allowances also contribute to foster the decarbonisation of the building sector (*robust evidence, high agreement*) . Requirements to limit the use of land and property taxes are also considered effective policies to limit urban sprawl and to prioritise multi-family buildings over single-family homes (*medium evidence, high agreement*) {9.9}.

Actions are needed to adapt buildings to future climate while ensuring wellbeing for all. The expected heatwaves will inevitably increase cooling needs to limit the health impacts of climate change (*medium evidence, high agreement*). Global warming will impact cooling and heating needs but also the performance, durability and safety of buildings, especially historical and coastal ones, through changes in temperature, humidity, concentrations of CO_2 and chloride, and sea level rise. Adaptation measures to cope with climate change may increase the demand for energy and materials leading to an increase in GHG emissions if not mitigated. Sufficiency measures such as bioclimatic design of buildings, which consider the expected future climate, and includes natural ventilation, white walls and nature-based solutions (i.e., green roofs) will decrease the demand for cooling. Shared cooled spaces with highly efficient cooling solutions are among the mitigation strategies which can limit the effect of the expected heatwaves on people health. Sufficiency, efficiency, and renewable energy can be designed to reduce buildings' vulnerability to climate change impacts (*medium evidence, high agreement*) {9.7, 9.8}.

Well-designed and effectively implemented mitigation actions in the buildings sector have significant potential for achieving the United Nations Sustainable Development Goals. The impacts of mitigation actions in the building sector go far beyond the goal of climate action (SDG13) and contribute to further meeting fifteen other SDGs. Mitigation actions in the building sector bring health gains through improved indoor air quality and thermal comfort as well as reduced financial stresses in all world regions. Overall decarbonised building stock contribute to wellbeing and has significant macro- and micro-economic effects, such as increased productivity of labour, job creation, reduced poverty, especially energy poverty, and improved energy security that ultimately reduces net costs of mitigation measures in buildings (*high evidence, high agreement*) {9.8}.

COVID-19 emphasised the importance of buildings for human wellbeing. However, the lockdown measures implemented to avoid the spread of the virus have also stressed the inequalities in the access for all to suitable and healthy buildings, which provide natural daylight and clean air to their occupants (*low evidence, high agreement*). Meeting the new WHO health requirements, has also put an emphasis on indoor air quality, preventive maintenance of centralised mechanical heating, ventilation, and cooling systems. Moreover, the lockdown measures have led to spreading the South Korean concept of *officetel* (office-hotel) to many countries and to extending it to *officetelschool*. The projected growth, prior to the COVID-19, of 58% of the global residential floor area by 2050 compared to the 290 billion m^2yr^{-1} in 2019 might well be insufficient. Addressing the new needs for more residential buildings may not, necessarily mean constructing new buildings, especially in the global North. Repurposing existing non-residential buildings, no longer in use due to the expected spread of teleworking triggered by the health crisis and enabled by digitalization, could be the way to overcome the new needs for *officetelschool* buildings triggered by the health crisis (*low evidence, high confidence*) {9.1, 9.2}.

9.1 Introduction

Total GHG emissions in the building sector reached 12 $GtCO_2eq$. in 2019, equivalent to 21% of global GHG emissions that year, of which 57% were indirect CO_2 emissions from offsite generation of electricity and heat, followed by 24% of direct CO_2 emissions produced on-site and 18% from the production of cement and steel used for construction and/or refurbishment of buildings. If only CO_2 emissions would be considered, the share of buildings CO_2 emissions increases to 31% out of global CO_2 emissions. Energy use in residential and non-residential buildings contributed 50% and 32% respectfully, while embodied emissions contributed 18% to global building CO_2 emissions. Global final energy demand from buildings reached 128.8 EJ in 2019, equivalent to 31% of global final energy demand. Residential buildings consumed 70% out of global final energy demand from buildings. Electricity demand from buildings was slightly above 43 EJ in 2019, equivalent to more than 18% of global electricity demand. Over the period 1990-2019, global CO_2 emissions from buildings increased by 50%, global final energy demand grew by 38%, with 54% increase in non-residential buildings and 32% increase in residential ones. Among energy carriers, the growth in global final energy demand was strongest for electricity, which increased by 161%.

There is growing scientific evidence about the mitigation potential of the building sector and its contribution to the decarbonisation of global and regional energy systems, and to meeting Paris Agreement goals and Sustainable Development Goals (SDGs) (IPCC, 2018; IEA, 2019b; IEA 2019c). Mitigation interventions in buildings are heterogeneous in many different aspects, from building components (envelope, structure, materials, etc.) to services (shelter, heating, etc.), to building types (residential and non-residential, sometimes also called commercial and public), to building size, function, and climate zone. There are also variations between developed and developing countries in mitigation interventions to implement, as the former is challenged by the renovation of existing buildings while the latter is challenged by the need to accelerate the construction of new buildings.

This chapter aims at updating the knowledge on the building sector since the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) (Ürge-Vorsatz et al. 2014). Changes since AR5 are reviewed, including: the latest development of building service and components (Section 9.2), findings of new building related GHG emission trends (Section 9.3), latest technological (Section 9.4) and non-technological (Section 9.5) options to mitigate building GHG emissions, potential emission reduction from these measures at global and regional level (Section 9.6), links to adaptation (Section 9.7) and sustainable development (Section 9.8), and sectoral barriers and policies (Section 9.9).

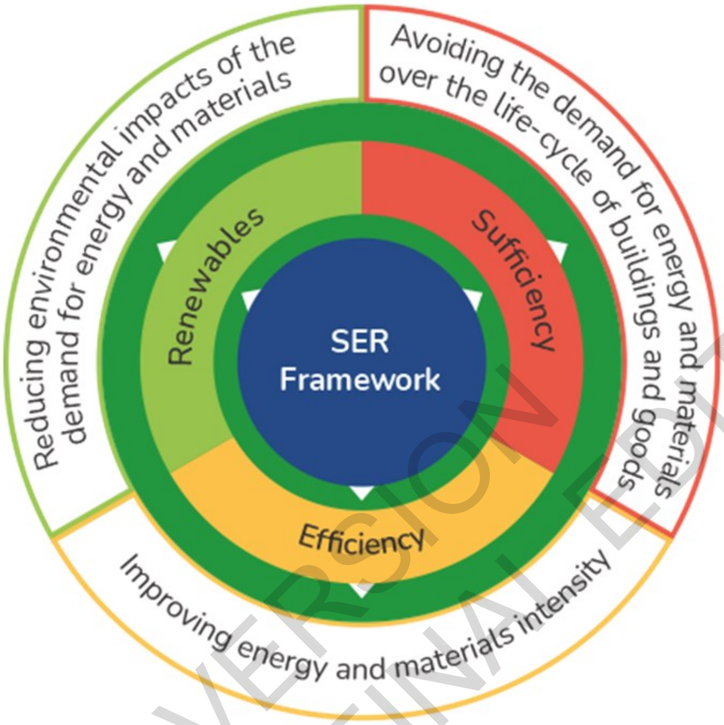
The chapter introduces the concept of sufficiency, identified in the literature as a mitigation strategy with high potential, and is organised around the Sufficiency-Efficiency-Renewables (SER) framework (Box 9.1).

START BOX 9.1 HERE

Box 9.1 SER (sufficiency-efficiency-renewables) framework

The SER framework was introduced, late nineties, by a French NGO (Negawatt) (Negawatt 2017) advocating for a decarbonised energy transition. In 2015, the SER framework was considered in the design of the French energy transition law and the French energy transition agency (ADEME) is developing its 2050 scenario based on the SER framework.

The three pillars of the SER framework include (i) sufficiency, which tackles the causes of the environmental impacts of human activities by avoiding the demand for energy and materials over the lifecycle of buildings and goods, (ii) efficiency, which tackles the symptoms of the environmental impacts of human activities by improving energy and material intensities, and (iii) the renewables pillar, which tackles the consequences of the environmental impacts of human activities by reducing the carbon intensity of energy supply (Box 9.1 Figure 1). The SER framework introduces a hierarchical layering, sufficiency first followed by efficiency and renewable, which reduces the cost of constructing and using buildings without reducing the level of comfort of the occupant.



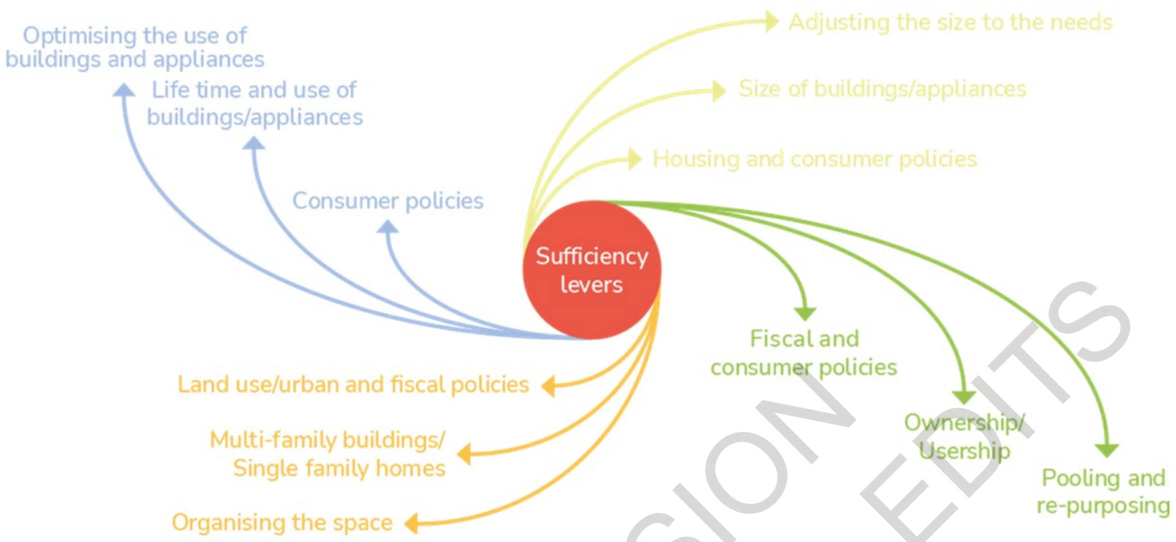
Box 9.1 Figure 1 SER framework applied to the building sector

Source: Saheb 2021

Sufficiency is not a new concept, its root goes back to the Greek word "*sôphrosunè*", which was translated in Latin to "*sobrietas*", in a sense of "*enough*" (Cézard and Mourad 2019). The sufficiency concept was introduced to the sustainability policy debate by (Sachs 1993) and to academia by (Princen 2003a). Since 1997, Thailand considers sufficiency, which was framed already in 1974 as Sufficiency Economy Philosophy, as a new paradigm for development with the aim of improving human wellbeing for all by shifting development pathways towards sustainability (Mongsawad 2012). The Thai approach is based on three principles (i) moderation, (ii) reasonableness, and (iii) self-immunity. Sufficiency goes beyond the dominant framing of energy demand under efficiency and behaviour. Sufficiency is defined as avoiding the demand for materials, energy, land, water and other natural resources while delivering a decent living standard for all within the planetary boundaries (Saheb 2021b, Princen 2005)**.** Decent living standards are a set of essential material preconditions for human wellbeing which includes shelter, nutrition, basic amenities, health care, transportation, information, education, and public space (Rao and Baer 2012; Rao and Min 2018; Rao et al. 2019). Sufficiency addresses the issue of a fair consumption of space and resources. The remaining carbon budget, and its normative target for distributional equity, is the upper limit of sufficiency, while requirements for a decent living standard define the minimum level of sufficiency. Sufficiency differs from efficiency in that the latter is about the continuous short-term marginal technological improvements which allow doing more with less in relative terms without considering the planetary boundaries, while the former is about long-term actions driven by non-technological solutions (i.e. land use management and planning), which consume less in absolute-term and are determined by the biophysical processes (Princen 2003b).

Applying sufficiency principles to buildings requires (i) optimising the use of buildings, (ii) repurposing unused existing ones, (iii) prioritising multi-family homes over single-family buildings, and (iv) adjusting the size of buildings to the evolving needs of households by downsizing dwellings (Box 9.1

Figure 2) (Sandberg 2018) (Stephan et al. 2013)(Duffy 2009)(Fuller and Crawford 2011)(Wilson and Boehland 2005)(McKinlay et al. 2019)(Sandberg 2018)(Huebner and Shipworth 2017)(Ellsworth-Krebs 2020) (Berrill et al. 2021).



Box 9.1 Figure 2 Sufficiency interventions and policies in the building sector

Source: Saheb 2021

Downsizing dwellings through cohousing strategies by repurposing existing buildings and clustering apartments when buildings are renovated and by prioritising multi-family buildings over single-family homes in new developments (Sandberg 2018) (Stephan et al. 2013)(Duffy 2009)(Fuller and Crawford 2011)(Wilson and Boehland 2005)(McKinlay et al. 2019)(Sandberg 2018)(Huebner and Shipworth 2017)(Ellsworth-Krebs 2020) (Ivanova and Büchs 2020) (Berrill and Hertwich 2021) are among the sufficiency measures that avoid the demand for materials in the construction phase and energy demand for heating, cooling and lighting in the use phase, especially if the conditioned volume and window areas are reduced (Duffy 2009) (Heinonen and Junnila 2014). Less space also means less appliances and equipment and changing preferences towards smaller ones (Aro 2020). Cohousing strategies provide users, in both new and existing buildings, a shared space (i.e, for laundry, offices, guest rooms and dining rooms) to complement their private space. Thus, reducing per capita consumption of resources including energy, water and electricity (Klocker et al. 2012)(Natascha Klocker 2017), while offering social benefits such as limiting loneliness of elderly people and single parents (Riedy et al. 2019)(Wankiewicz 2015). Senior cooperative housing communities and eco-villages are considered among the cohousing examples to scale-up (Kuhnhenn et al. 2020). Local authorities have an important role to play in the metamorphosis of housing by proposing communal spaces to be shared (J. Williams 2008)(Marckmann et al. 2012) through urban planning and land use policies (Duffy 2009)(Newton et al. 2017). Thus, encouraging inter-generational cohousing as well as interactions between people with different social backgrounds (Lietaert 2010)(J. Williams 2008). Progressive tax properties based on a cap in the per-capita floor area are also needed to adapt the size of dwellings to households' needs (Murphy 2015) (Akenji 2021).

Efficiency, and especially energy efficiency and more recently resource efficiency, and the integration of renewable to buildings are widespread concepts since the oil crisis of the seventies, while only most advanced building energy codes consider sufficiency measures (IEA 2013). Efficiency and renewable technologies and interventions are described in 9.4 and 9.9.

A systematic categorisation of policy interventions in the building sector through the SER framework (Box 9.1 Figure 1) enables identification of the policy areas and instruments to consider for the decarbonisation of the building stock, their overlaps as well as their complementarities. It also shows that sufficiency policies go beyond energy and climate policies to include land use and urban planning policies as well as consumer policies suggesting a need for a different governance including local authorities and a bottom-up approach driven by citizen engagement.

END BOX 9.1 HERE

Compared to AR5, this assessment introduces four novelties (i) the scope of CO_2 emissions has been extended from direct and indirect emissions considered in AR5 to include embodied emissions, (ii) beyond technological efficiency measures to mitigate GHG emissions in buildings, the contribution of non-technological, in particular of sufficiency measures to climate mitigation is also considered, (iii) compared to SR1.5, the link to sustainable development, well-being and decent living standard for all has been further developed and strengthened, and finally (iv) the active role of buildings in the energy system by making passive consumers prosumers is also assessed.

COVID-19 emphasised the importance of buildings for human wellbeing, however, the lockdown measures implemented to avoid the spread of the virus has also stressed the inequalities in the access for all to suitable and healthy buildings, which provide natural daylight and clean air to their occupants (see also Cross-Chapter Box 1 in Chapter 1). COVID-19 and the new health recommendations (World Health Organization 2021) emphasised the importance of ventilation and the importance of indoor air quality (Wei et al. 2020)(J. et al. 2011)(Guyot et al. 2018)(William 2013)(Fisk 2015). The health crisis has also put an emphasis on preventive maintenance of centralised mechanical heating, ventilation, and cooling systems. Moreover, the lockdown measures have led to spreading the South Korean concept of *officetel* (office-hotel) (Gohaud and Baek 2017) to many countries and to extending it to *officetelschool*. Therefore, the projected growth, prior to the COVID-19, of 58% of the global residential floor area by 2050 compared to the 290 billion m^2 yr^{-1} in 2019 might well be insufficient. However, addressing the new needs for more residential buildings may not, necessarily mean constructing new buildings. In fact, repurposing existing non-residential buildings, no longer in use due to the expected spread of teleworking triggered by the health crisis and enabled by digitalisation, could be the way to overcome the new needs for *officetelschool* triggered by the health crisis.

The four novelties introduced in this assessment link the building sector to other sectors and call for more sectoral coupling when designing mitigation solutions. Guidelines and methodologies developed in Chapters 1, 2, 3, 4 and 5 are adopted in this chapter. Detailed analysis in building GHG emissions is discussed based on Chapter 2 and scenarios to assess future emissions and mitigation potentials were selected based on Chapters, 3 and 4. There are tight linkages between this chapter and Chapter 6, 7, 8, 10 and 11, which are sectoral sectors. This chapter focusses more on individual buildings and building clusters, while Chapter 8 discusses macro topics in urban areas. Findings of this chapter provides contribution to cross-sectoral prospection (Chapter 12), policies (Chapter 13), international cooperation (Chapter 14), investment and finance (Chapter 15), innovation (Chapter 16), and sustainable development (Chapter 17).

9.2 Services and components

This section mainly details the boundaries of the building sector; mitigation potentials are evaluated in the following sections.

9.2.1 Building types

Building types and their composition affect the energy consumption for building operation as well as the GHG emissions (Hachem-Vermette and Singh 2019). They also influence the energy cost (MacNaughton et al. 2015) therefore, an identification of building type is required to understand the heterogeneity of this sector. Buildings are classified as residential and non-residential buildings. Residential buildings can be classified as slums, single-family house and multi-family house or apartment/flats building. Single-family house can be divided between single-family detached (including cottages, house barns, etc.) and single-family attached (or terrace house, small multi-family, etc.). Another classification is per ownership: owner-occupiers, landlords, and owners' association/condominiums.

Non-residential buildings have a much broader use. They include cultural buildings (which include theatres and performance, museums and exhibits, libraries, and cultural centres), educational buildings (kindergarten, schools, higher education, research centre, and laboratories), sports (recreation and training, and stadiums), healthcare buildings (health, wellbeing, and veterinary), hospitality (hotel, casino, lodging, nightlife buildings, and restaurants and bars), commercial buildings and offices (institutional buildings, markets, office buildings, retail, and shopping centres), public buildings (government buildings, security, and military buildings), religious buildings (including worship and burial buildings), and industrial buildings (factories, energy plants, warehouses, data centres, transportation buildings, and agricultural buildings).

9.2.2 Building components and construction methods

An understanding of the methods for assembling various materials, elements, and components is necessary during both the design and the construction phase of a building. A building can be broadly divided into parts: the substructure which is the underlying structure forming the foundation of a building, and the superstructure, which is the vertical extension of a building above the foundation.

There is not a global classification for the building components. Nevertheless, Figure 9.1 tries to summarise the building components found in literature (Asbjørn 2009; Ching 2014; Mañá Reixach 2000). The buildings are divided in the substructure and the superstructure. The substructure is the foundation of the building, where the footing, basement, and plinth are found. The superstructure integrates the primary elements (heavyweight walls, columns, floors and ceilings, roofs, sills and lintels, and stairs), the supplementary components (lightweight walls and curtain walls), the completion components (doors and windows), the finishing work (plastering and painting), and the buildings services (detailed in Section 9.3).

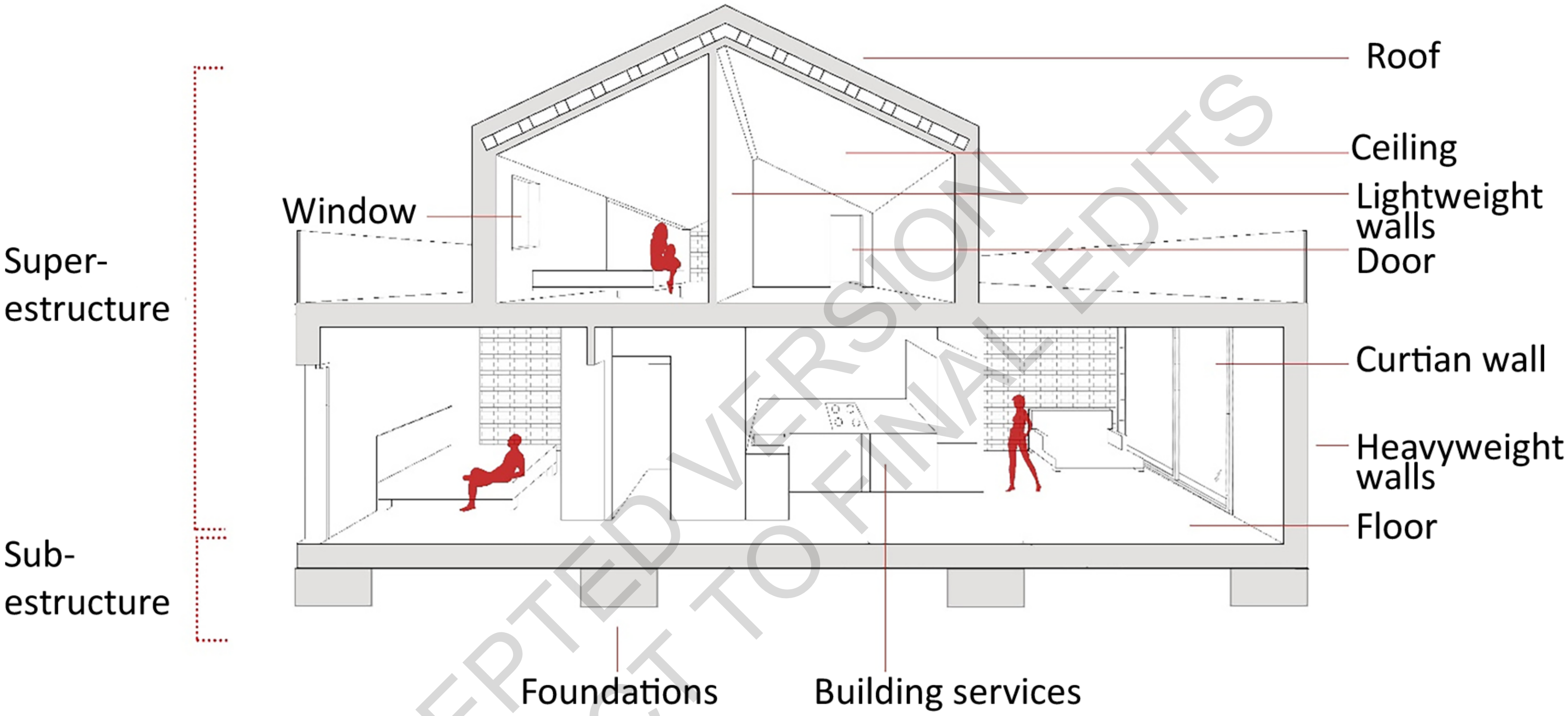


Figure 9.1 The main building components

At a global level, from historical perspective (from the Neolithic to the present), building techniques have evolved to be able to solve increasingly complex problems. Vernacular architecture has evolved over many years to address problems inherent in housing. Through a process of trial and error, populations have found ways to cope with the extremes of the weather. The industrial revolution was the single most important development in human history over the past three centuries. Previously, building materials were restricted to a few manmade materials (lime mortar and concrete) along with those available in nature as timber and stone. Metals were not available in sufficient quantity or consistent quality to be used as anything more than ornamentation. The structure was limited by the capabilities of natural materials; this construction method is called on-site construction which all the work is done sequentially at the buildings site. The Industrial Revolution changed this situation dramatically, new building materials emerged (cast-iron, glass structures, steel-reinforced concrete, steel). Iron, steel and concrete were the most important materials of the nineteenth century (De Villanueva Domínguez 2005; Wright 2000). In that context, prefabricated buildings (prefabrication also known as pre-assembly or modularization) appeared within the so-called off-site construction. Prefabrication has come to mean a method of construction whereby building elements and materials, ranging in size from a single component to a complete building, are manufactured at a distance from the final building location. Prefabricated buildings have been developed rapidly since World War II and are widely used all over the world (Pons 2014; Moradibistouni et al. 2018)

Recently, advances in technology have produced new expectations in terms of design possibilities. In that context, 3D printing seems to have arrived. 3D printing may allow in the future to build faster, cheaper and more sustainable (Agustí-Juan et al. 2017; García de Soto et al. 2018). At the same time, it might introduce new aesthetics, new materials, and complex shapes that will be printed at the click of a mouse on our computers. Although 3D printing will not replace architectural construction, it would allow optimization of various production and assembly processes by introducing new sustainable construction processes and tools (De Schutter et al. 2018). Nevertheless, what is clear is that 3D printing is a technology still in development, with a lot of potentials and that it is advancing quite quickly (Hager et al. 2016; Stute et al. 2018; Wang et al. 2020).

9.2.3 Building services

Building services make buildings more comfortable, functional, efficient, and safe. In a generic point of view, building services include shelter, nutrition, sanitation, thermal, visual, and acoustic comfort, entertainment, communications, elevators, and illumination. In a more holistic view building services are classified as shown in Figure 9.2.

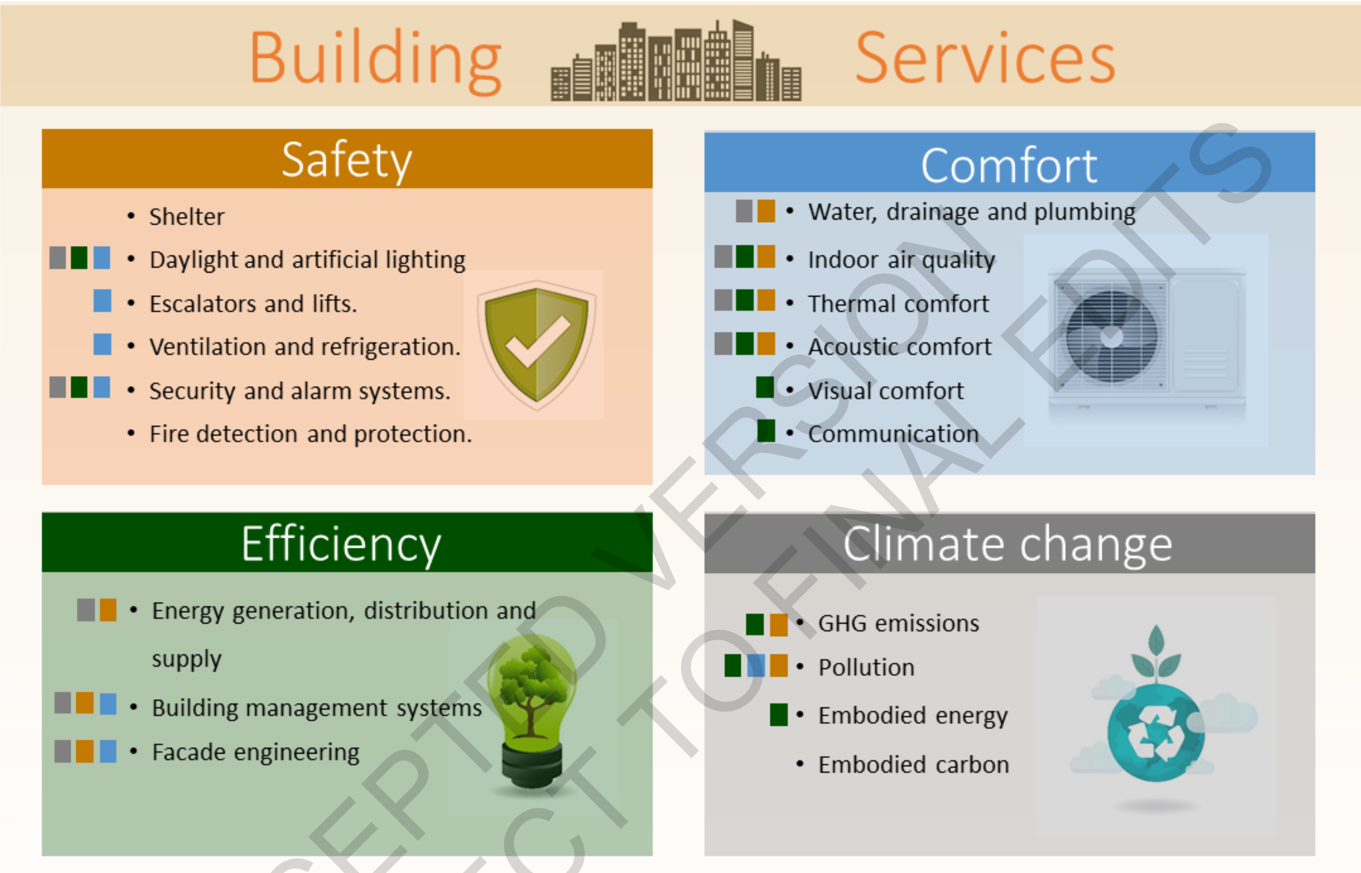


Figure 9.2 Classification of building services.

The coloured small rectangles to the left of each building service denote to which other classifications that building service may relate to a lesser extent.

Source: adapted from Vérez and Cabeza 2021a

A building management system is a system of devices configured to control, monitor, and manage equipment in or around a building or building area and is meant to optimize building operations and reduce cost (Kelsey Carle Schuster, Youngchoon Park 2019). Recent developments include the integration of the system with the renewable energy systems (D.Arnone, V.Croce, G.Paterno 2016), most improved and effective user interface (Rabe et al. 2018), control systems based on artificial intelligence and IoT (Farzaneh et al. 2021).

The use of air conditioning systems in buildings will increase with the experienced rise in temperature (Davis and Gertler 2015; De Falco et al. 2016) (Figure 9.8). This can ultimately lead to high energy consumption rates. Therefore, adoption of energy efficient air conditioning is pertinent to balance the provision of comfortable indoor conditions and energy consumption. Some of the new developments that have been done include ice refrigeration (Xu et al. 2017), the use of solar photovoltaic power in the air conditioning process (Burnett et al. 2014), and use of common thermal storage technologies (De Falco et al. 2016) all of which are geared towards minimizing energy consumption and greenhouse gas emissions.

Building designs have to consider provision of adequate ventilation. Natural ventilation reduces energy consumption in buildings in warm climates compared to air conditioning systems (Azmi et al. 2017; Taleb 2015). Enhanced ventilation has higher benefits to the public health than the economic costs involved (MacNaughton et al. 2015).

On the refrigeration systems, the recent developments include the use of solar thermoelectric cooling technologies as an energy efficient measure (Liu et al. 2015b); use of nanoparticles for energy saving (Azmi et al. 2017) to mention some.

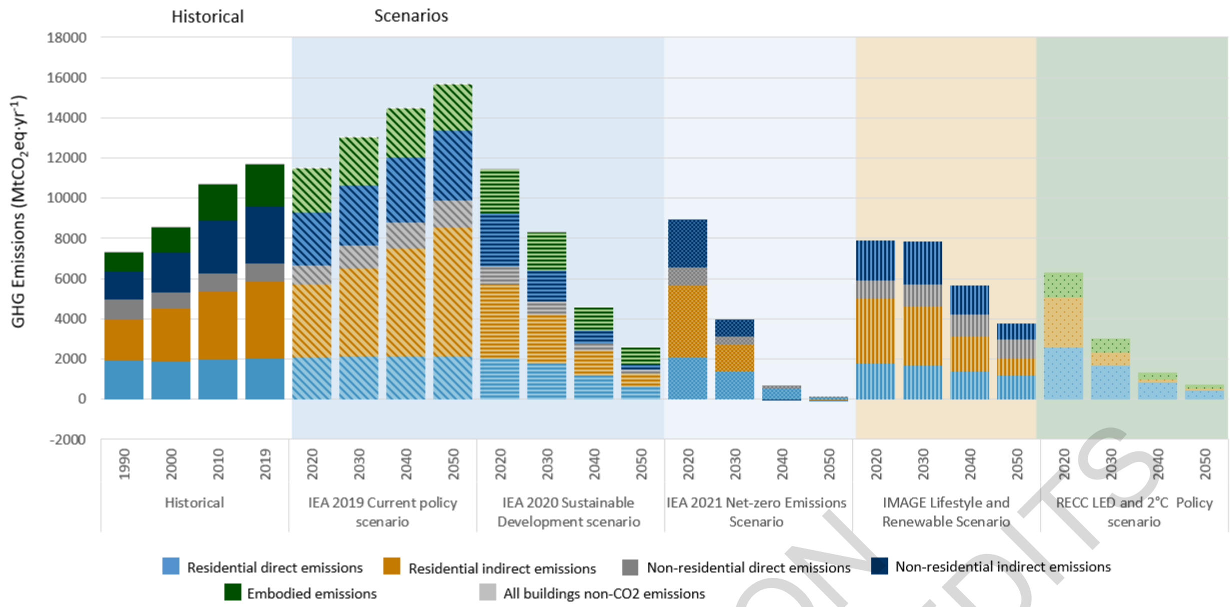
(Lambertz et al. 2019) stated that when evaluating the environmental impact of buildings, building services are only considered in a very simplified way. Moreover, it also highlights that the increasing use of new technologies such as Building Information Modelling (BIM) allows for a much more efficient and easier calculation process for building services, thus enabling the use of more robust and complete models. Furthermore, recent studies on building services related to climate change (Vérez and Cabeza 2021a) highlight the importance of embodied energy (Parkin et al. 2019) (see Section 9.4).

9.3 New developments in emission trends and drivers

9.3.1 Past and future emission trends

Total GHG emissions in the building sector reached 12 $GtCO_2eq$. in 2019, equivalent to 21% of global GHG emissions that year. 57% of GHG emissions from buildings were indirect CO_2 emissions from generation of electricity and heat off-site, 24% were direct CO_2 emissions produced on-site, and 18% were from the production of cement and steel used for construction and refurbishment of buildings (Figure 9.3a) (see Cross-Chapter Box 3 and Cross-Working Group Box 1 in Chapter 3). Halocarbon emissions were equivalent to 3% of global building GHG emissions in 2019. In the absence of the breakdown of halocarbon emissions per end-use sectors, they have been calculated for the purpose of this chapter, by considering that 60% of global halocarbon emissions occur in buildings (Hu et al. 2020). CH_4 and N_2O emissions were negligible, representing 0.08% each out of the 2019 global building GHG emissions. Therefore, this chapter considers only CO_2 emissions from buildings. By limiting the scope of the assessment to CO_2 emissions, the share of emissions from buildings increases to 31% of global 2019 CO_2 emissions. Energy use in residential and non-residential buildings contributed 50% and 32% respectfully, while embodied emissions contributed 18% to global building CO_2 emissions.

(a) Global



(b) Regional

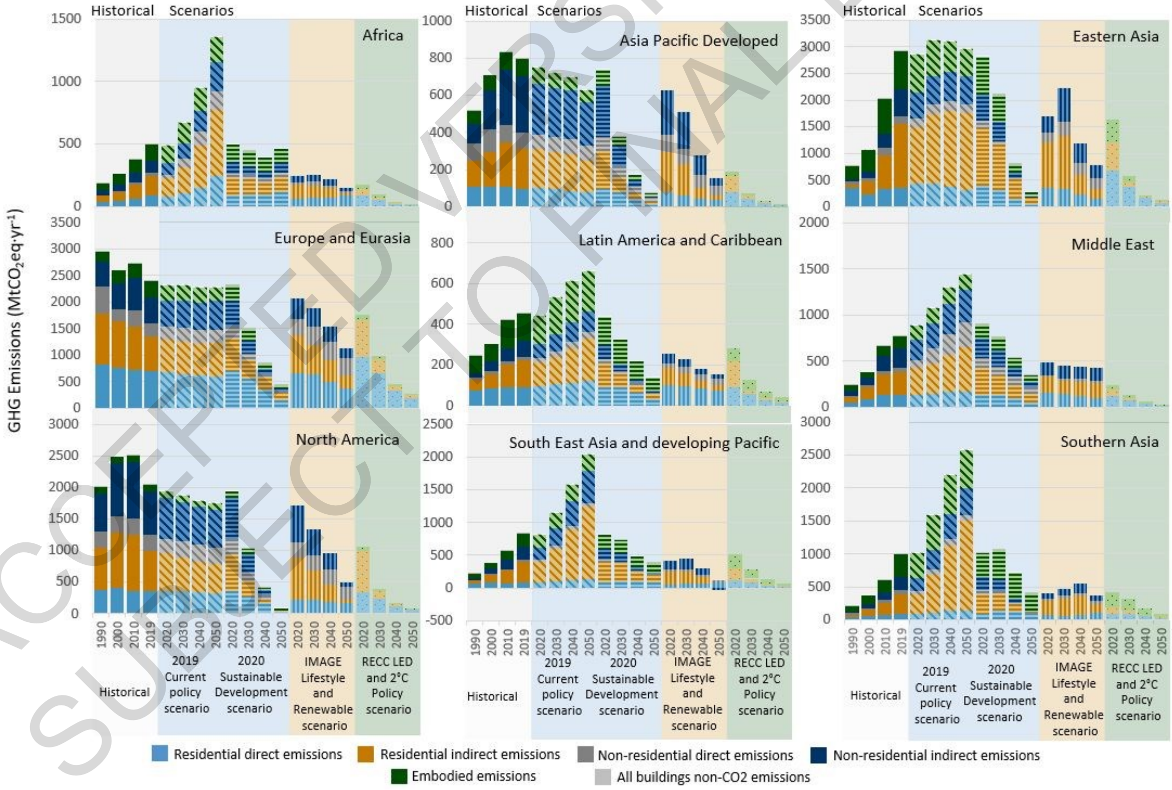


Figure 9.3 Building GHG emissions: historical based on IEA data and future emissions based on two IEA scenarios (sustainable development, and net zero emissions), IMAGE Lifestyle-Renewable scenario and Resource Efficiency and Climate Change-Low Energy Demand scenario (RECC-LED). RECC-LED data include only space heating and cooling and water heating in residential buildings. The IEA current policies scenario is included as a baseline scenario (IEA current policies scenario)

Over the period 1990-2019, global CO_2 emissions from buildings increased by 50%. Global indirect CO_2 emissions increased by 92%, driven by the increase of fossil fuels-based electrification, while global direct emissions decreased by 1%. At regional level, emissions in residential buildings decreased in developed countries, except in Asia-Pacific developed, while they increased in developing countries.

The highest decrease was observed in Europe and Eurasia, with 13.6% decrease of direct emissions and 33% decrease of indirect emissions, while the highest increase of direct emissions occurred in Middle East, 198%, and the highest increase of indirect emissions occurred in Eastern Asia, 2258%. Indirect emissions from non-residential buildings increased in all regions. The highest increase occurred in Eastern Asia, 1202%, and the lowest increase occurred in Europe and Central Asia, 4%, where direct emissions from non-residential buildings decreased by 51%. Embodied emissions have also increased in all regions. The highest increase occurred in Southern Asia, 334%, while the lowest increase occurred in North America, 4%. (Figure 9.3b).

Future emissions were assessed using four global scenarios and their respective baselines (Box 9.2). The selection of the scenarios was based on the features of each scenario, the geographic scope, and the data availability to analyse future building emissions based on the SER framework (Box 9.1).

START BOX 9.2 HERE

Box 9.2 Scenarios used for the purpose of this chapter

Three out of the four scenarios selected, and their related baselines, are based on top-down modelling and were submitted to AR6 scenario database, which includes in total 931 scenarios with a building module (Annex III; see also Cross-Chapter Box 3, Box 3.1, and Box 3.2 in Chapter 3). A fourth scenario, not included in AR6 scenario database, and based on a bottom-up modelling approach was added.

The main features of these scenarios are shortly described below while the underlying modelling approaches are described in Annex III. Each scenario is assessed compared to its baseline scenario:

International Energy Agency (IEA) scenarios:

2021 Net Zero Emissions by 2050 Scenario (NZE) is a normative scenario, which sets out a narrow but achievable pathway for the global energy sector to achieve net zero CO_2 emissions by 2050 (IEA 2021a)

2020 Sustainable Development Scenario (SDS)*,* which integrates the impact of COVID-19 on health outcomes and economies. It is also a normative scenario, working backwards from climate, clean air, and energy access goals. SDS examines what actions would be necessary to achieve these goals. The near-term detail is drawn from the IEA Sustainable Recovery Plan, which boosts economies and employment while building cleaner and more resilient energy systems (IEA 2020a).

Analysis of the IEA scenarios above was conducted compared to the 2019 Current Policies Scenario, which shows what happens if the world continues along its present path (IEA 2020a), and considered as a baseline scenario.

IMAGE-Lifestyle-Renewable (***LiRE***) scenario is based on an updated version of the SSP2 baseline, while also meeting the RCP2.6 radiative forcing target using carbon prices, together with the increased adoption of additional lifestyle changes, by limiting the growth in the floor area per capita in developed countries as well as the use of appliances. Regarding energy supply, IMAGE-LiRE assumes increased electrification and increased share of renewable in the energy mix (Detlef Van Vuuren et.al 2021).

Resource Efficiency and Climate Change-Low Energy Demand (RECC-LED) scenario is produced by a global bottom-up model, which assesses contributions of resource efficiency to climate change mitigation. RECC-LED estimates the energy and material flows associated with housing stock growth, driven by population and the floor area per capita (Pauliuk et al. 2021). This scenario is informed by the Low Energy Demand Scenario (LED), which seeks convergence between developed and developing countries in the access to decent living standard (Grubler et al. 2018).

For consistency between the four scenarios, aggregation of regions in this chapter differs from the one of the IPCC. Europe and Eurasia have been grouped into one single region.

END BOX 9.2 HERE

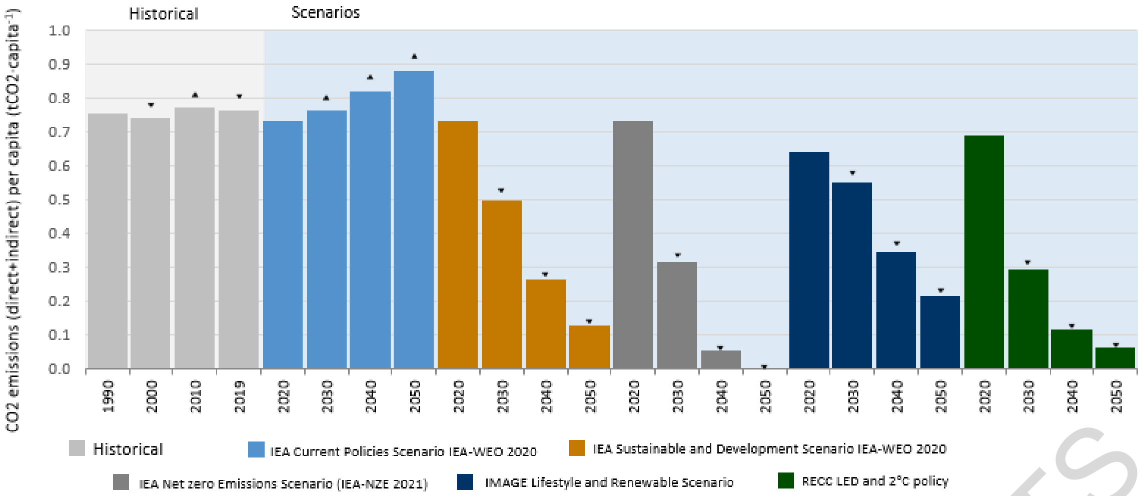
The IEA-NZE scenario projects emissions from the global building stock to be lowered to 29 $MtCO_2$ by 2050 against 1.7 $GtCO_2$ in the IEA-SDS and 3.7 $GtCO_2$ in IMAGE-LiRE Scenario. These projections can be compared to IEA-CPS in which global emissions from buildings were projected to be at 13.5 $GtCO_2$ in 2050, which is equivalent to the 2018 emissions level (Figure 9.3a). By 2050, direct emissions from residential buildings are projected to be lowered to 108 $MtCO_2$ in the IEA-NZE, this is four times less than the projected direct emissions in RECC-LED scenario, six times less than those under the IEA-SDS and eleven times less than those in the IMAGE-LiRE scenario.

In the IEA-NZE scenario, indirect emissions are projected to be below zero by 2050 for both residential and non-residential buildings, while residual indirect emissions from residential buildings are projected to be 125 $MtCO_2$ in RECC-LED, 634 $MtCO_2$ in IEA-SDS, and 842$GtCO_2$ in IMAGE-LiRE. Residual indirect emissions from non-residential buildings are projected to be at 1.7 $GtCO_2$ in IEA SDS and double of this in IMAGE-LiRE scenario (Figure 9.3a). Compared to IEA-SDS, the highest decrease of emissions in IEA-NZE is expected to occur after 2030. Direct emissions from residential buildings in IEA-NZE are projected to be, by 2030, at 1.37 $GtCO_2$, against 1.7 $GtCO_2$ in the three other scenarios. The highest cut in emissions in IEA-NZE and in IMAGE-LiRE occur through the decarbonisation of energy supply.

At regional level, by 2050, the lowest emissions are projected to occur in developed Asia and Pacific, with 6.73 $MtCO_2$ under RECC-LED scenario and 12.4 $MtCO_2$ under the IEA-SDS, and the highest emissions are projected to occur in Europe and Eurasia in all three scenarios, with 152 $MtCO_2$ in IEA-SDS, 199 $MtCO_2$ in RECC-LED scenario and 381 $MtCO_2$ in IMAGE-LiRE scenario. Emissions in Africa are projected to decrease to 10 $MtCO_2$ in RECC-LED, this is nine time less than those of 2019, while they are projected to increase by 25% in IEA-SDS compared to those of 2019. Compared to IEA-SDS and IMAGE-LiRE, RECC-LED projects the highest decreases, over the period 2020-2030, of direct emissions in residential buildings in all regions, up to 45% in Asia-Pacific developed and Eastern Asia and the highest decreases of indirect emissions, ranging from 52% in Eastern Asia to 86% in Latin America and Caribbean. Over the same period, the IEA-SDS projects the highest decreases of indirect emissions to occur in Asia Pacific developed and North America. IMAGE-LiRE projects the lowest decreases of emissions over the same decade in almost all regions (Figure 9.3b).

Emissions per capita from residential buildings at a global level reached 0.85 tCO_2 per person in 2019. The four scenarios assessed projects a decrease of the global per capita emissions by 2050, ranging from 0 tCO_2 in IEA NZE 0.21 tCO_2 per person in IMAGE-LiRE, a 75% lower than those of 2019 (Figure 9.4a). There are great differences in the projected per capita emissions under each scenario different scenarios across the regions (Figure 9.4b). Compared to IEA SDS and IMAGE-LiRE scenarios, RECC-LED projects the lowest emissions per capita in all regions by 2050. Emissions per capita in Europe and Eurasia are projected to be the highest in all scenarios by 2050, ranging from 0.26 tCO_2 in RECC-LED and 0.31tCO_2 in IEA SDS to 0.65 tCO_2 in IMAGE-LiRE.

(a) Global



(b) Regional

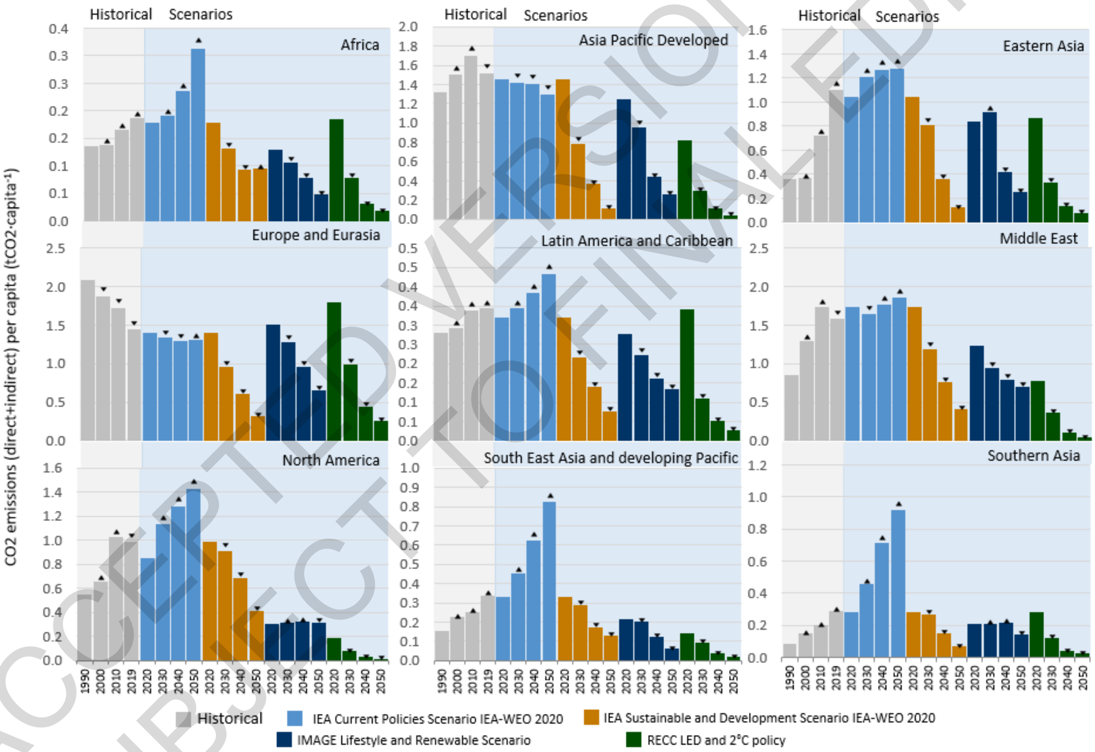


Figure 9.4 Per capita emissions: historical based on IEA data and future emissions based on two IEA scenarios (sustainable development, and net zero emissions), IMAGE Lifestyle-Renewable scenario and Resource Efficiency and Climate Change-Low Energy Demand scenario (RECC-LED). RECC-LED data include only space heating and cooling and water heating in residential buildings. The IEA current policies scenario is included as a baseline scenario (IEA current policies scenario)

9.3.2 Drivers of CO_2 emissions and their climate impact

Building specific drivers of GHG emissions in the four scenarios described above are assessed using an index decomposition analysis with building specific identities and reflecting the three pillars of the SER framework (sufficiency, efficiency, renewables). Broad drivers of GHG emissions such as GDP and population are analysed using a Kaya decomposition in Chapter 2. Previous decompositions analysing drivers of global GHG emissions in the building sector have either assessed only the impact of GDP and population as drivers of GHG emissions (Lamb et al. 2021) or the impact of building specific drivers on energy demand and not on CO_2 emissions (Ürge-Vorsatz et al., 2015, IPCC AR5, 2014, IEA, 2020, ODYSSEE, 2020). For this assessment, the decomposition was conducted for energy-related CO_2 emissions for residential buildings only, due to lack of data for non-residential buildings.

The attribution of changes in emissions in the use phase to changes in the drivers of population, sufficiency, efficiency, and carbon intensity of energy supply is calculated using additive log-mean divisia index decomposition analysis (Ang and Zhang 2000). The decomposition of emissions into four driving factors is shown in Eq. 1, where m^2 refers to total floor area, *EJ* refers to final energy demand, and Mt_{CO2} refers to the sum of direct and indirect CO_2 emissions in the use phase. The allocation of changes in emissions between two cases *k* and *k-1* to changes in a single driving factor *D* is shown in Eq. 2. To calculate changes in emissions due to a single driver such as population growth, *D* will take on the value of population in the two compared cases. The superscript *k* stands for the case, defined by the time period and scenario of the emissions, e.g., IEA CPS Baseline scenario in 2050. When decomposing emissions between two cases *k* and *k-1*, either the time-period, or the scenario remains constant. The decomposition was done at the highest regional resolution available from each model output, and then aggregated to regional or global level. For changes in emissions within a scenario over time, the decomposition is done for every decade, and the total 2020-2050 decomposition is then produced by summing decompositions of changes in emissions each decade.

Equation 9.1

$$CO2_{total}^{k} = Pop \times \frac{m^2}{Pop} \times \frac{EJ}{m^2} \times \frac{Mt_{CO2}}{EJ} = Pop \times Suff \times Eff \times Ren$$

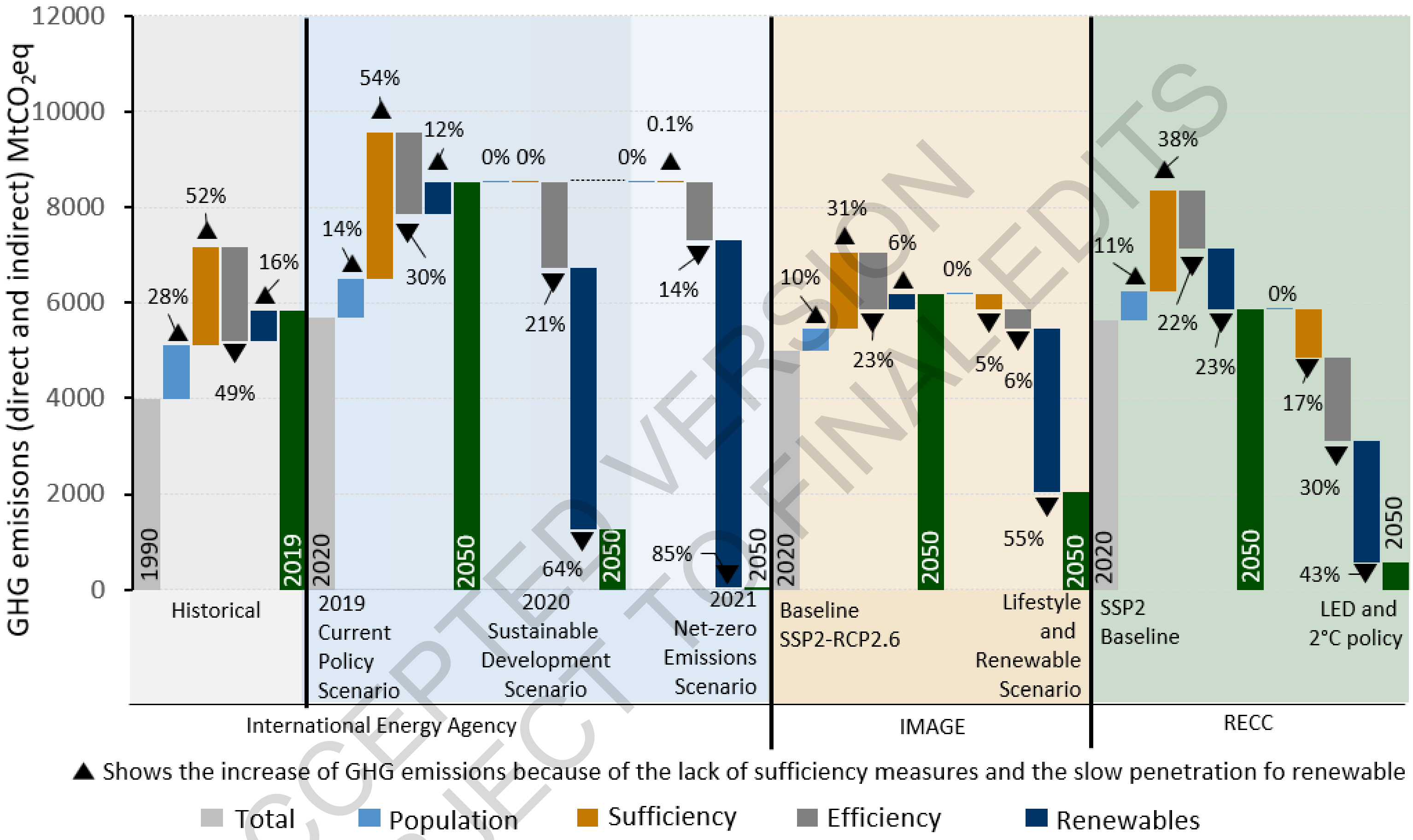
Equation 9.2

$$\Delta CO2_{,D}^{k,k-1} = \frac{CO2 - CO2_{total}^{k-1}}{ln(CO2_{total}^{k}) - ln(CO2_{total}^{k-1})} \times ln\left(\frac{D^k}{D^{k-1}}\right)$$

Over the period 1990-2019, population growth accounted for 28% of the growth in global emissions in residential buildings, the lack of sufficiency policies (growth in floor area per capita) accounted for 52% and increasing carbon intensity of the global energy mix accounted for 16%. Efficiency improvement contributed to decreasing global emissions from residential buildings by 49% (

a). The sufficiency potential was untapped in all regions over the same period while the decarbonisation of the supply was untapped in developing countries and to some extent in Asia Pacific developed. The highest untapped sufficiency and supply decarbonisation potentials occurred in Southern Asia where the lack of sufficiency measures has led to increasing emissions by 185% and the high carbon intensity of the energy mix has led to increasing emissions by 340%. In developed countries, the highest untapped sufficiency potential occurred in Asia Pacific developed region. Middle East is the only region where efficiency potential remained untapped (Figure 9.5b).

1 **(a) Global**



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(b) Regional

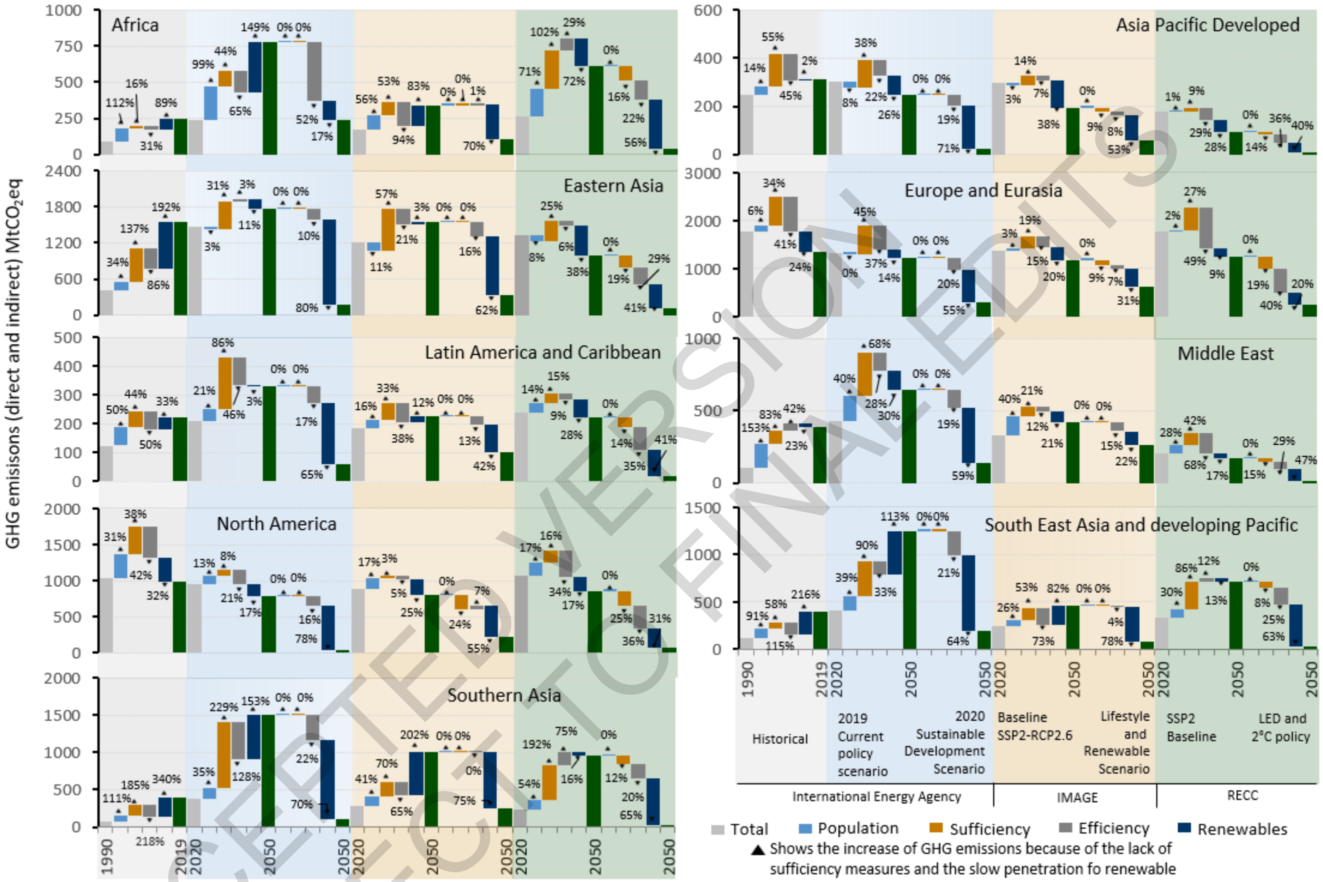
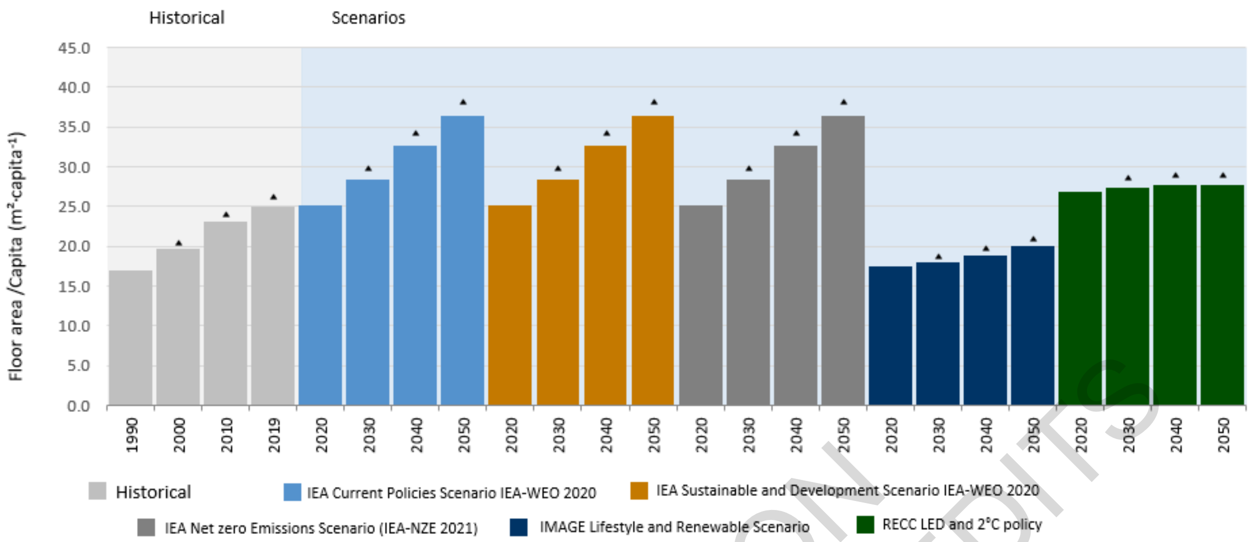


Figure 9.5 **Decompositions of changes in historical residential energy emissions 1990-2019, changes in emissions projected by baseline scenarios for 2020-2050, and differences between scenarios in 2050 using scenarios from three models: IEA, IMAGE, and RECC. RECC-LED data include only space heating and cooling and water heating in residential buildings (a) Global resolution, and (b) for nine world regions. Emissions are decomposed based on changes in driver variables of population, sufficiency (floor area per capita), efficiency (final energy per floor area), and renewables (GHG emissions per final energy). 'Renewables' is a summary term describing changes in GHG intensity of energy supply. Emission projections to 2050, and differences between scenarios in 2050, demonstrate mitigation potentials from the dimensions of the SER framework realised in each model scenario. In most regions, historical improvements in efficiency have been approximately matched by growth in floor area per capita. Implementing sufficiency measures that limit growth in floor area per capita, particularly in developed regions, reduces the dependence of climate mitigation on technological solutions**

Scenarios assessed show an increase of the untapped sufficiency potential at the global level over the period 2020-2050. The highest untapped sufficiency potential occurs in IEA scenarios as there are no changes in the floor area per capita across different scenarios. The lack of sufficiency measures in current policies will contribute to increasing emissions by 54%, offsetting the efficiency improvement effect. By setting a cap in the growth of the floor area per capita in developed countries, 5% of emission reductions in IMAGE-LiRE scenario derives from sufficiency. However, compared to 2020, the lack of sufficiency measures in the baseline scenario will contribute to increasing emissions by 31%. RECC-LED scenario shows the highest global sufficiency potential captured compared to its baseline scenario in 2050 as this scenario assumes a reduction in the floor area per capita in developed countries and slower floor area growth in emerging economies. The four scenarios show a higher contribution of the decarbonisation of energy supply to reducing emissions than the reduction of energy demand through sufficiency and efficiency measures (Figure 9.6a). At regional level, the emissions reduction potential from sufficiency is estimated at 25% in North America under both IMAGE-LiRE and RECC-LED scenarios and at 19% in both Eastern Asia and Europe/Eurasia regions (Figure 9.6b). The highest decarbonisation potential due to growth of renewable energy is 75% in Southern Asia under IMAGE-LiRE scenario.

There is a growing literature on the decarbonisation of end-use sectors while providing decent living standard for all (Rao and Min 2018)(Rao et al. 2019)(Rao and Pachauri 2017) (Grubler et al. 2018), (Millward-Hopkins et al. 2020). The floor area per capita is among the gaps identified in the convergence between developed and developing countries in the access to decent living (Kikstra et al. 2021) while meeting energy needs. In the Low Energy Demand (LED) scenario, 30 m^2 per capita is the converging figure assumed by 2050 (Grubler et al. 2018) while in the Decent Living with minimum Energy (DLE) scenario, (Millward-Hopkins et al. 2020) assumes 15 m^2 per capita.

(a) Global



(b) Regional

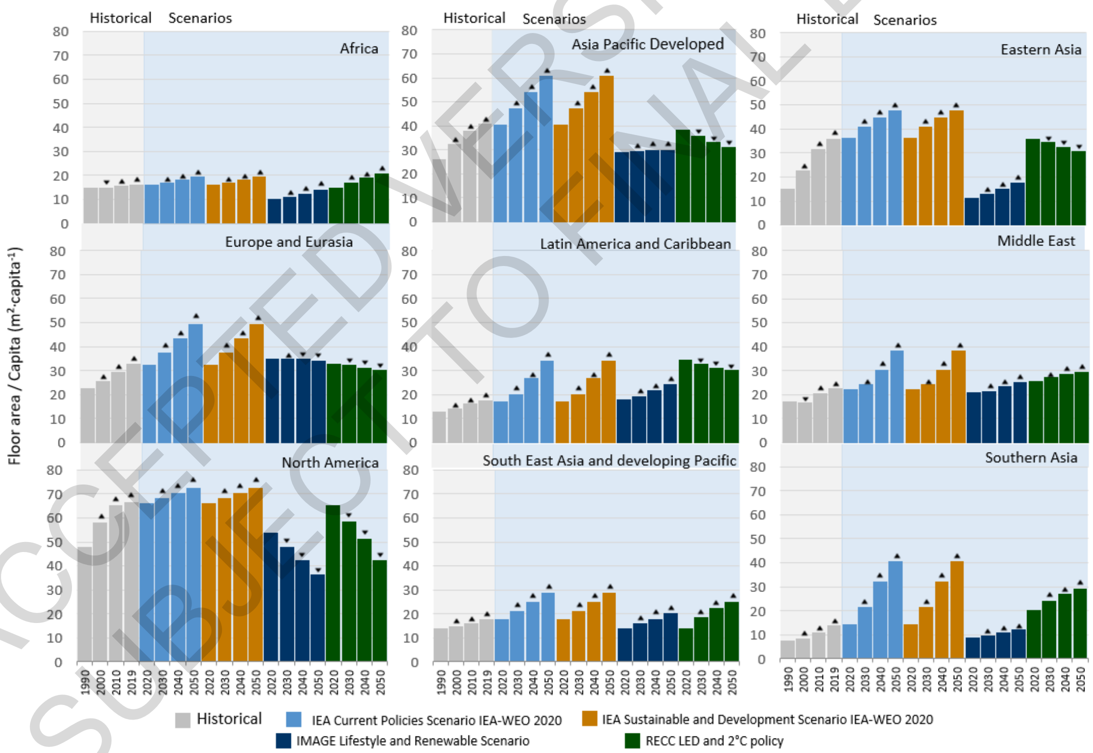


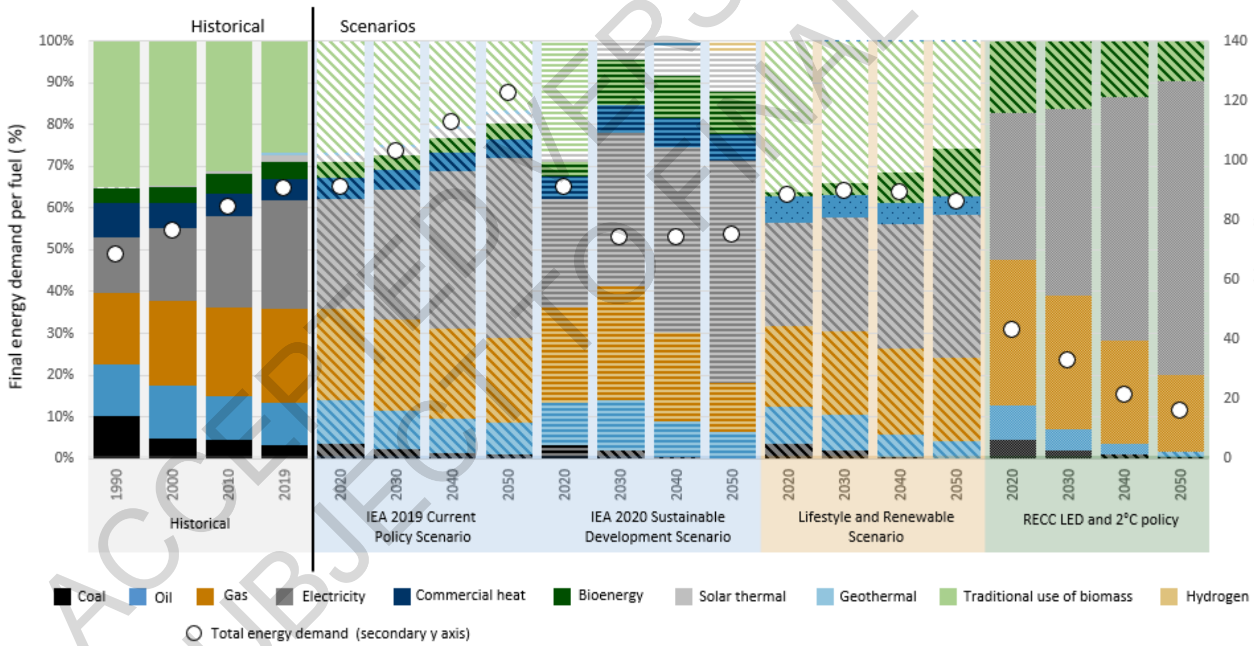
Figure 9.6 Per capita floor area: historical based on IEA data and future emissions based on two IEA scenarios (sustainable development, and net zero emissions), IMAGE Lifestyle-Renewable scenario and Resource Efficiency and Climate Change-Low Energy Demand scenario (RECC-LED). RECC-LED data include only space heating and cooling and water heating in residential buildings. The IEA current policies scenario is included as a baseline scenario (IEA current policies scenario)

Overall, the global residential building stock grew by almost 30% between 2005 and 2019. However, this growth was not distributed equally across regions and three out of the four scenarios assessed do not assume a convergence, by 2050, in the floor area per capita, between developed and developing countries. Only RECC-LED implements some convergence between developed countries and emerging economies to a range of 20-40 m² per capita. IEA scenarios assume a growth in the floor area per capita in all regions with the highest growth in developed countries, up to 72 m² per capita in North America from 66 m² per capita in 2019. IMAGE-LiRE projects a floor area per capita in Africa at 14 m² per person. This is lower than the one of 2019, which was at 16 m² per capita (Figure 9.6). Beyond capturing the sufficiency potential by limiting the growth in the floor area per capita in developed countries while ensuring decent living standard, the acceptability of the global scenarios by developing countries is getting attraction in academia (Hickel et al. 2021).

9.3.3 Energy demand trends

Global final energy demand from buildings reached 128.8 EJ in 2019, equivalent to 31% of global final energy demand. The same year, residential buildings consumed 70% out of global final energy demand from buildings. Over the period 1990-2019, global final energy demand from buildings grew by 38%, with 54% increase in non-residential buildings and 32% increase in residential ones. At regional level, the highest increase of final energy demand occurred in Middle East and Africa in residential buildings and in all developing Asia in non-residential ones. By 2050, global final energy demand from buildings is projected to be at 86 EJ in IEA NZE, 111 EJ in IEA SDS and 138 EJ in IMAGE-LiRE. RECC-LED projects the lowest global final energy demand, at 15.7 EJ by 2050, but this refers to water heating, space heating and cooling in residential buildings only (Figure 9.7a).

(a) Global



(b) Regional

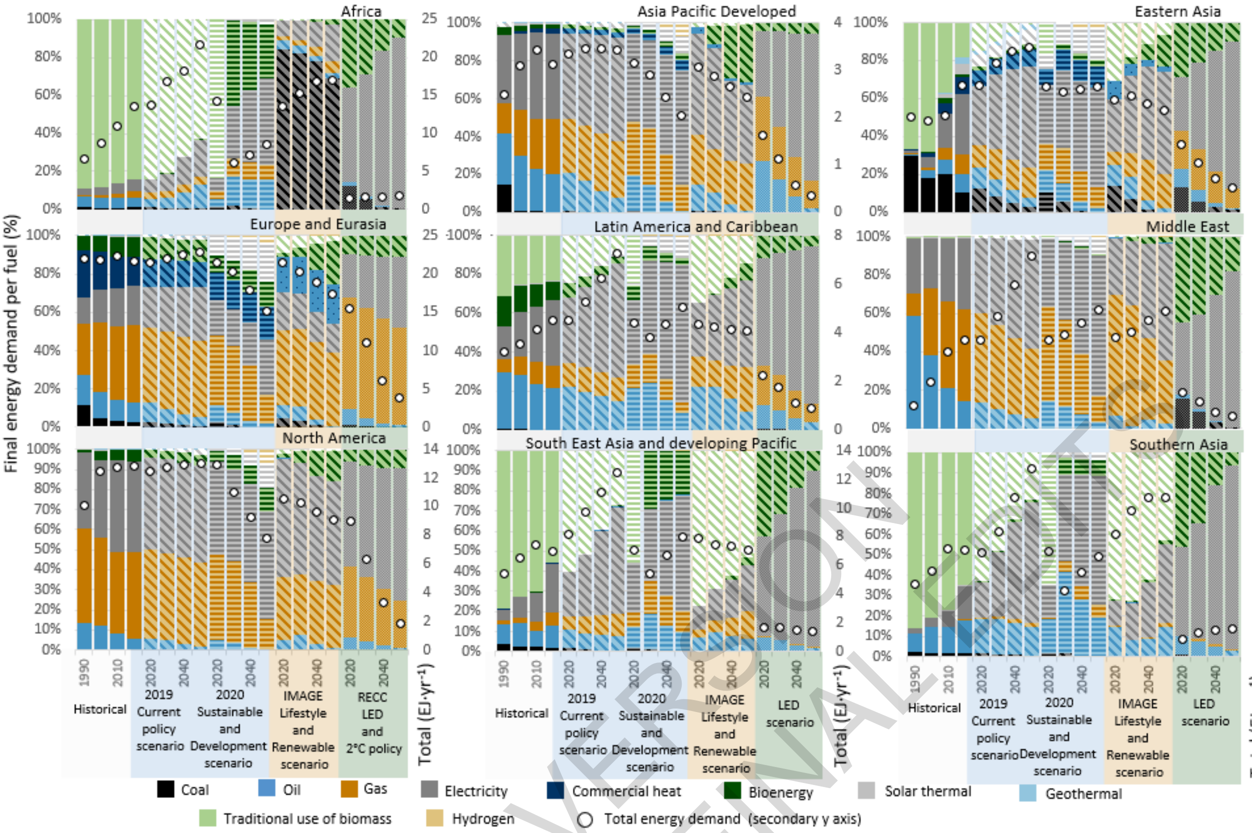


Figure 9.7 Final energy demand per fuel: historical based on IEA data and future emissions based on two IEA scenarios (sustainable development, and net zero emissions), IMAGE Lifestyle-Renewable scenario and Resource Efficiency and Climate Change-Low Energy Demand scenario (RECC-LED). RECC-LED data include only space heating and cooling and water heating in residential buildings. The IEA current policies scenario is included as a baseline scenario (IEA current policies scenario)

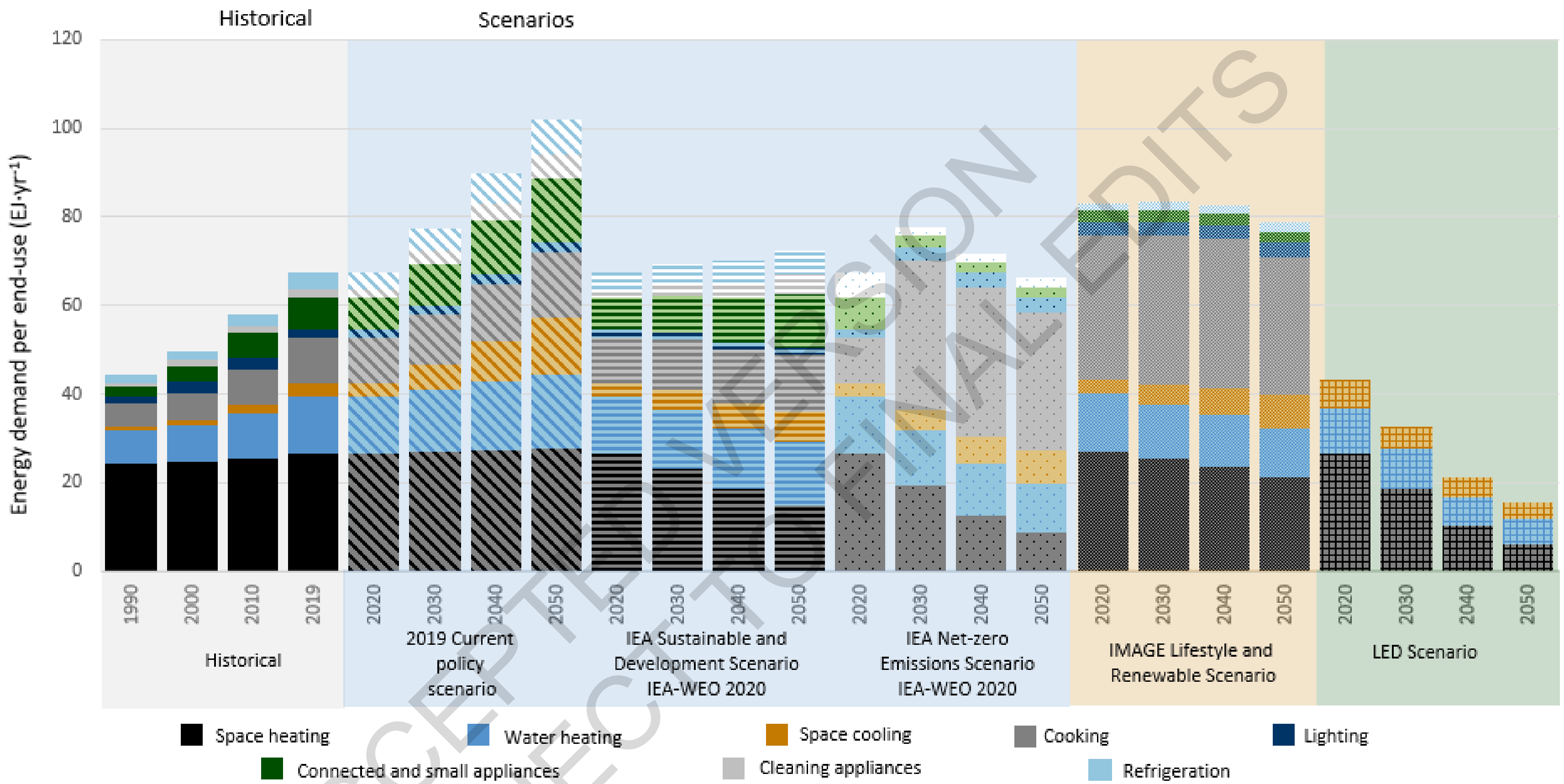
Over the period 1990-2019, the use of coal decreased at a global level by 59% in residential buildings and 52% in non-residential ones. Solar thermal experienced the highest increase, followed by geothermal and electricity. However, by 2019, solar thermal and geothermal contributed by only 1% each to global final energy demand, while electricity contributed by 51% in non-residential buildings and 26% in residential ones. The same year, gas contributed by 26% to non-residential final energy demand and 22% to residential final energy demand, which makes gas the second energy carrier used in buildings after electricity. Over the period 1990-2019, the use of gas grew by 75% in residential buildings and by 46% in non-residential ones. By 2050, RECC-LED projects electricity to contribute by 71% to final energy demand in residential buildings, against 62% in IEA-NZE and 59% in IMAGE-LiRE. IEA-NZE is the only scenario to project less than 1% of gas use by 2050 in residential buildings while the contribution of electricity to energy demand of non-residential buildings is above 60% in all scenarios. At regional level, the use of coal in buildings is projected to disappear while the use of electricity is projected to be above 50% in all regions by 2050 (Figure 9.7b).

Hydrogen emerged in the policy debate as an important energy carrier for the decarbonisation of the energy system. In the case of the building sector, depending on how hydrogen is sourced (see Box 12.3 in Chapter 12), converting gas grids to hydrogen might be an appealing option to decarbonise heat without putting additional stress on the electricity grids. However, according to (Elements energy Ltd 2018; Broad et al. 2020; Frazer-Nash Consultancy 2018; Gerhardt et al. 2020) (Strbac et al. 2018) the delivered cost of heat from hydrogen would be much higher than the cost of delivering heat from heat pumps, which could also be used for cooling. Repurposing gas grids for pure hydrogen networks will also require system modifications such as replacement of piping and replacement of gas boilers and cooking appliances, a factor cost to be considered when developing hydrogen roadmaps for buildings. There are also safety and performance concerns with domestic hydrogen appliances (Frazer-Nash Consultancy 2018). Over the period 1990-2019, hydrogen was not used in the building sector and scenarios assessed show a very modest role for hydrogen in buildings by 2050 (Figure 9.7).

In developed countries, biomass is used for generating heat and power leading to reduction of indirect emissions from buildings (Ortwein 2016)(IEA et al. 2020a). However, according to (IEA 2019b) despite the mitigation potential of biomass, if the wood is available locally, its use remains low in developed countries. Biomass is also used for efficient cook stoves and for heating using modern appliances such as pellet-fed central heating boilers. In developing countries, traditional use of biomass is characterised by low efficiency of combustion (due to low temperatures) leading to high levels of pollutants and CO output, as well as low efficiency of heat transfer. The traditional use of biomass is associated with public health risks such as pre mature deaths related to inhaling fumes from cooking (Dixon et al. 2015; Van de Ven et al. 2019; Taylor et al. 2020; IEA 2019b). According to (Hanna et al. 2016) policies failed in improving the use of biomass. Over the period 1990-2019, the traditional use of biomass decreased by 1% and all scenarios assessed do not project any traditional use of biomass by 2050. Biomass is also used for the construction of buildings, leading to low embodied emissions compared to concrete (Pauliuk et al. 2021; Hart and Pomponi 2020; Heeren et al. 2015a)

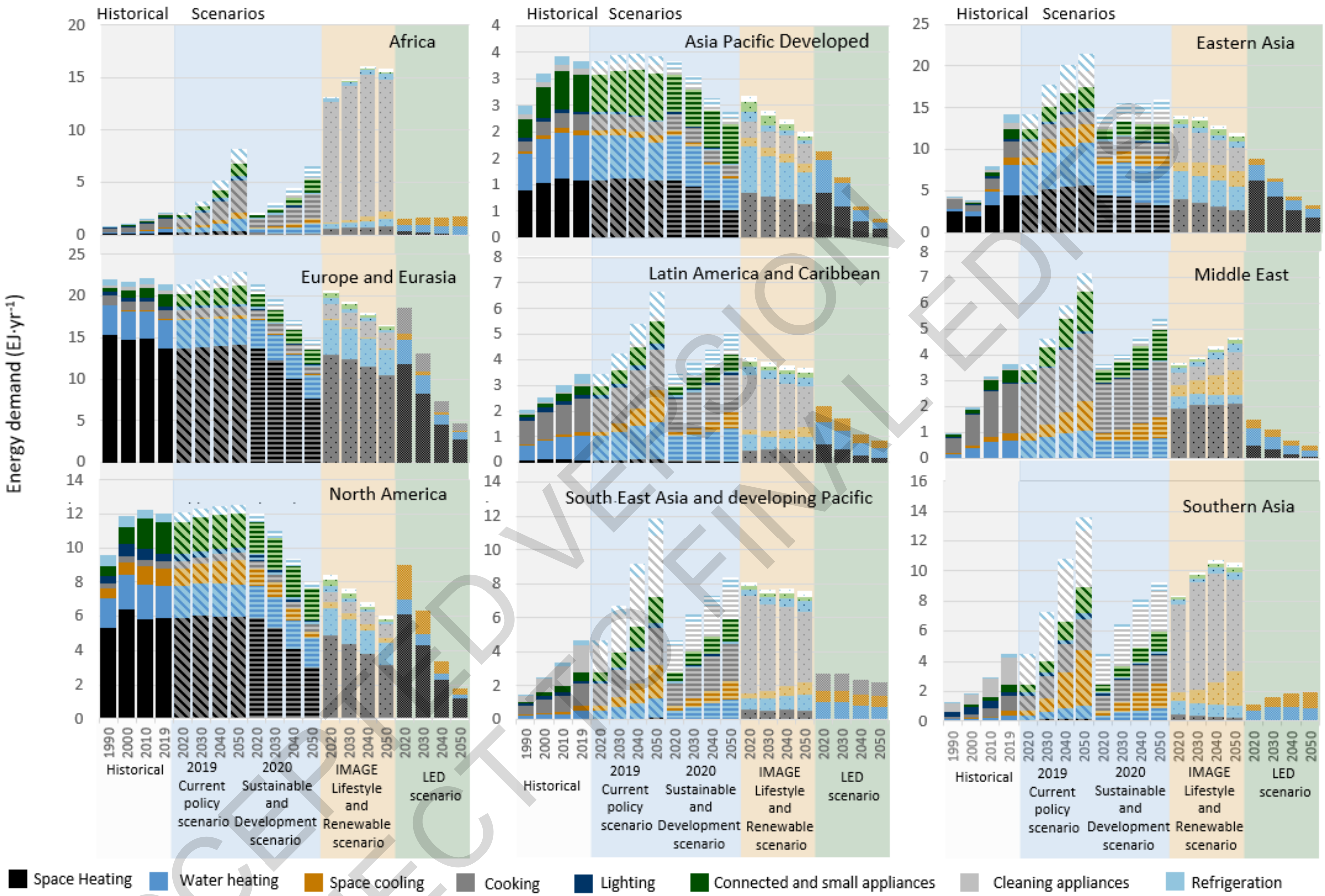
Over the period 1990-2019, space heating was the dominant end-use in residential buildings at a global level, followed by water heating, cooking, and connected and small appliances (Figure 9.8a). However, energy demand from connected and small appliances experienced the highest increase, 280%, followed by cooking, 89%, cooling, 75%, water heating, 73% and space heating, around 10%. Space heating energy demand is projected to decline over the period 2020-2050 in all scenarios assessed. RECC-LED projects the highest decrease, 77%, of space heating energy demand, against 68% decrease in the IEA NZE. IMAGE-LiRE projects the lowest decrease of heating energy demand, 21%. To the contrary, all scenarios confirm cooling as a strong emerging trend (Box 9.3) and project an increase of cooling energy demand. IMAGE-LiRE projects the highest increase, 143% against 45% in the IEA-NZE while RECC-LED projects the lowest increase of cooling energy demand, 32%.

(a) Global



Historical
Scenarios
Energy demand per end-use (EJ·yr⁻¹)
120
100
80
60
40
20
0
1990
2000
2010
2019
2020
2030
2040
2050
Historical
2019 Current policy scenario
IEA Sustainable and Development Scenario IEA-WEO 2020
IEA Net-zero Emissions Scenario IEA-WEO 2020
IMAGE Lifestyle and Renewable Scenario
LED Scenario
Space heating
Water heating
Space cooling
Cooking
Lighting
Connected and small appliances
Cleaning appliances
Refrigeration

1 **(b) Regional**



2
3 **Figure 9.8 Energy per end use: historical based on IEA data and future emissions based on two IEA scenarios (sustainable development, and net zero emissions),**
4 **IMAGE Lifestyle-Renewable scenario and Resource Efficiency and Climate Change-Low Energy Demand scenario (RECC-LED). RECC-LED data include only**
5 **space heating and cooling and water heating. The IEA current policies scenario is included as a baseline scenario (IEA current policies scenario)**

There are great differences in the contribution of each end-use to the regional energy demand (Figure 9.8b). In 2019, more than 50% of residential energy demand in Europe and Eurasia was used for space heating while there was no demand for space heating in Middle East, reflecting differences in climatic conditions. To the contrary, the share of energy demand from cooking out of total represented 53% in the Middle East against 5% in Europe-Eurasia reflecting societal organisations. The highest contribution of energy demand from connected and small appliances to the regional energy demand was observed in 2019 in the Asia Pacific developed, 24%, followed by the region of Southern Asia, Southeast Asia and Developing Pacific, with 17%. Energy demand from cooling was at 9% out of total energy demand of Southern Asia, Southeast Asia and Developing Pacific and at 8% in both Middle East and North America while it was at 1% in Europe in 2019.

The increased cooling demand can be partly explained by the increased ownership of room air-conditioners per dwellings in all regions driven by increased wealth and the increased ambient temperatures due to global warming (Cayla et al. 2011) (Liddle and Huntington 2021) (Box 9.3). The highest increase, 32%, in ownership of room air-conditioners was observed in Southern Asia and Southeast Asia and developing Pacific while Europe, Latin America and Caribbean countries, Eastern Asia and Africa experienced an increase of 21% in households' ownership of room air-conditioners. The lowest increases in room air-conditioners ownership were observed in the Middle East and North America with 1% and 8% each as these two markets are almost saturated. All scenarios assessed project an increase of ownership of cooling appliances in all regions over the period 2020-2050.

Energy demand from connected and small appliances was, at a global level, above 7 EJ in 2019 (Figure 9.8a). However, it is likely that global energy demand from connected and small appliances is much higher as reported data do not include all the connected and small appliances used by households and does not capture energy demand from data centres (Box 9.3). Over the period 1990-2019, the highest increase of energy demand from connected and small appliances, 4740%, was observed in Eastern Asia, followed by Southern Asia, 1358% while the lowest increase, 99%, occurred in Asia Pacific developed countries. The increase of energy demand from connected and small appliances is driven by the ownership increase of such appliances all over the world. The highest increase in ownership of connected appliances, 403%, was observed in Eastern Asia and the lowest increase in ownership of connected appliances was observed in North America, 94%. Future energy demand is expected to occur in the developing world given the projected rate of penetration of household appliances and devices (Wolfram et al. 2012). However, (Grubler et al. 2018) projects a lower energy demand from connected and small appliances by assuming an increase of shared appliances and multiple appliances and equipment will be integrated into units delivering multiple services.

START BOX 9.3 HERE

Box 9.3 Emerging energy demand trends in residential buildings

Literature assessed points to three major energy demand trends:

Cooling energy demand

In a warming world (IPCC 2021) with a growing population and expanding middle-class, the demand for cooling is likely to increase leading to increased emissions if cooling solutions implemented are carbon intensive (Kian Jon et al. 2021; Dreyfus et al. 2020b; Santamouris 2016; Sustainable Energy for All 2018; United Nations Environment Programme (UNEP) International Energy Agency (IEA) 2020). Sufficiency measures such as building design and forms, which allow balancing the size of openings, the volume, the wall and window area, the thermal properties, shading, and orientation are all non-cost solutions, which should be considered first to reduce cooling demand. Air conditioning systems using halocarbons are the most common solutions used to cool buildings. Up to 4 billion cooling appliances are already installed and this could increase to up 14 billion by 2050 (Peters 2018; Dreyfus et al. 2020b). Energy efficiency of air conditioning systems is of a paramount importance to ensuring that the increased demand for cooling will be satisfied without contributing to global warming through halocarbon emissions (Shah et al. 2019, 2015; Campbell 2018; United Nations Environment Programme (UNEP) International Energy Agency (IEA) 2020). The installation of highly efficient technological solutions with low Global Warming Potential (GWP), as part of the implementation of the Kigali amendment to the Montreal Protocol, is the second step towards reducing GHG emissions from cooling. Developing renewable energy solutions integrated to buildings is another track to follow to reduce GHG emissions from cooling.

Electricity energy demand

Building electricity demand was slightly above 43 EJ in 2019, which is equivalent to more than 18% of global electricity demand. Over the period 1990-2019, electricity demand increased by 161%. The increase of global electricity demand is driven by the combination of rising incomes, income distribution and the S-curve of ownership rates (Wolfram et al. 2012; Gertler et al. 2016). Electricity is used in buildings for plug-in appliances i.e., refrigerators, cleaning appliances, connected and small appliances, and lighting. An important emerging trend in electricity demand is the use of electricity for thermal energy services (cooking, water, and space heating). The increased penetration of heat pumps is the main driver of the use of electricity for heating. Heat pumps used either individually or in conjunction with heat networks can provide heating in cold days and cooling in hot ones. (Lowes et al. 2020) suggests electricity is expected to become an important energy vector to decarbonise heating. However, the use of heat pumps will increase halocarbon emissions (United Nations Environment Programme (UNEP) International Energy Agency (IEA) 2020). (Bloess et al. 2018; Barnes and Bhagavathy 2020; Connolly 2017) argue for electrification of heat as a cost-effective decarbonisation measure, if electricity is supplied by renewable energy sources (Ruhnau et al. 2020). The electrification of the heat supplied to buildings is likely to lead to an additional electricity demand and consequently additional investment in new power plants. (Thomaßen et al. 2021) identifies flexibility as a key enabler of larger heat electrification shares. Importantly, heat pumps work at their highest efficiency level in highly efficient buildings and their market uptake is likely to require incentives due to their high up-front cost (Hannon 2015; Heinen et al. 2017).

Digitalisation energy demand

Energy demand from digitalisation occurs in datacentres, which are dedicated buildings or part of buildings for accommodating large amount of information technologies equipment such as servers, data storage and communication devices, and network devices. Data-centres are responsible for about 2% of global electricity consumption (Diguet and Lopez 2019; Avgerinou et al. 2017). Energy demand from datacentres arises from the densely packed configuration of information technologies, which is up to 100 times higher than a standard office accommodation (Chu and Wang 2019). Chillers combined with air handling units are usually used to provide cooling in datacentres. Given the high cooling demand of datacentres, some additional cooling strategies, such as free cooling, liquid cooling, low-grade waste heat recovery, absorption cooling, etc., have been adopted. In addition, heat recovery can provide useful heat for industrial and building applications. More recently, datacentres are being investigated as a potential resource for demand response and load balancing (Zheng et al. 2020; Koronen et al. 2020). Supplying datacentres with renewable energy sources is increasing (Cook et al. 2014) and is expected to continue to increase (Koomey et al. 2011). Estimates of energy demand from digitalisation (connected and small appliances, data centres, and data networks) combined vary from 5% to 12% of global electricity use (Ferreboeuf 2019; Gelenbe and Caseau 2015; Malmodin and Lundén 2018; Diguet and Lopez 2019). According to (Ferreboeuf 2019) the annual increase of energy demand from digitalisation could be limited to 1.5% against the current 4% if sufficiency measures are adopted along the value chain.

Digitalisation occurs also at the construction stage. (European Union 2019; Witthoeft and Kosta 2017) identified seven digital technologies already in use in the building sector. These technologies include (i) Building Information Modelling/Management (BIM), (ii) additive manufacturing, also known as 3D printing, (iii) robots, (iv) drones, (v) 3D scanning, (vi) sensors, and (vii) Internet of Things (IoT). BIM supports decision making in the early design stage and allows assessing a variety of design options and their embodied emissions (Röck et al. 2018; Basbagill et al. 2013). 3D printing reduces material waste and the duration of the construction phase as well as labour accidents (Dixit 2019). Coupling 3D printing and robots allows for increasing productivity through fully automated prefabricated buildings. Drones allow for a better monitoring and inspection of construction projects through real-time comparison between planned and implemented solutions. Coupling drones with 3D scanning allows predicting building heights and energy consumption (Streltsov et al. 2020). Sensors offer a continuous data collection and monitoring of end-use services (i.e., heating, cooling, and lighting), thus allowing for preventive maintenance while providing more comfort to end-users. Coupling sensors with IoT, which connects to the internet household appliances and devices such as thermostats, enable demand-response, and flexibility to reduce peak loads (IEA 2017; Lyons 2019). Overall, connected appliances offer a variety of opportunities for end-users to optimise their energy demand by improving the responsiveness of energy services (Nakicenovic et al. 2019; [IEA] - International Energy Agency 2017) through the use of digital goods and services (Wilson et al., 2020) including peer-to-peer electricity trading (Morstyn et al. 2018).

END BOX 9.3 HERE

9.4 Mitigation technological options and strategies towards zero carbon buildings

Literature in this topic is extensive, but unfortunately, most studies and reviews do not relate themselves to climate change mitigation, therefore there is a clear gap in reporting the mitigation potential of the different technologies (Cabeza et al. 2020). It should be highlighted that when assessing the literature, it is clear that a lot of new research is focussed on the improvement of control systems, including the use of artificial intelligence or internet of things (IoT).

This section is organised as follow. First, the key points from AR5 and special reports are summarized, following with a summary of the technological developments since AR5, specially focussing on residential buildings.

9.4.1 Key points from AR5 and special reports

AR5 Chapter 9 on Buildings (Ürge-Vorsatz et al. 2014) presents mitigation technology options and practices to achieve large reductions in building energy use as well as a synthesis of documented examples of large reductions in energy use achieved in real, new, and retrofitted buildings in a variety of different climates and examples of costs at building level. A key point highlighted is the fact that the conventional process of designing and constructing buildings and its systems is largely linear, losing opportunities for the optimization of whole buildings. Several technologies are listed as being able to achieve significant performance improvements and cost potentials (daylighting and electric lighting, household appliances, insulation materials, heat pumps, indirect evaporative cooling, advances in digital building automation and control systems, and smart meters and grids to implement renewable electricity sources).

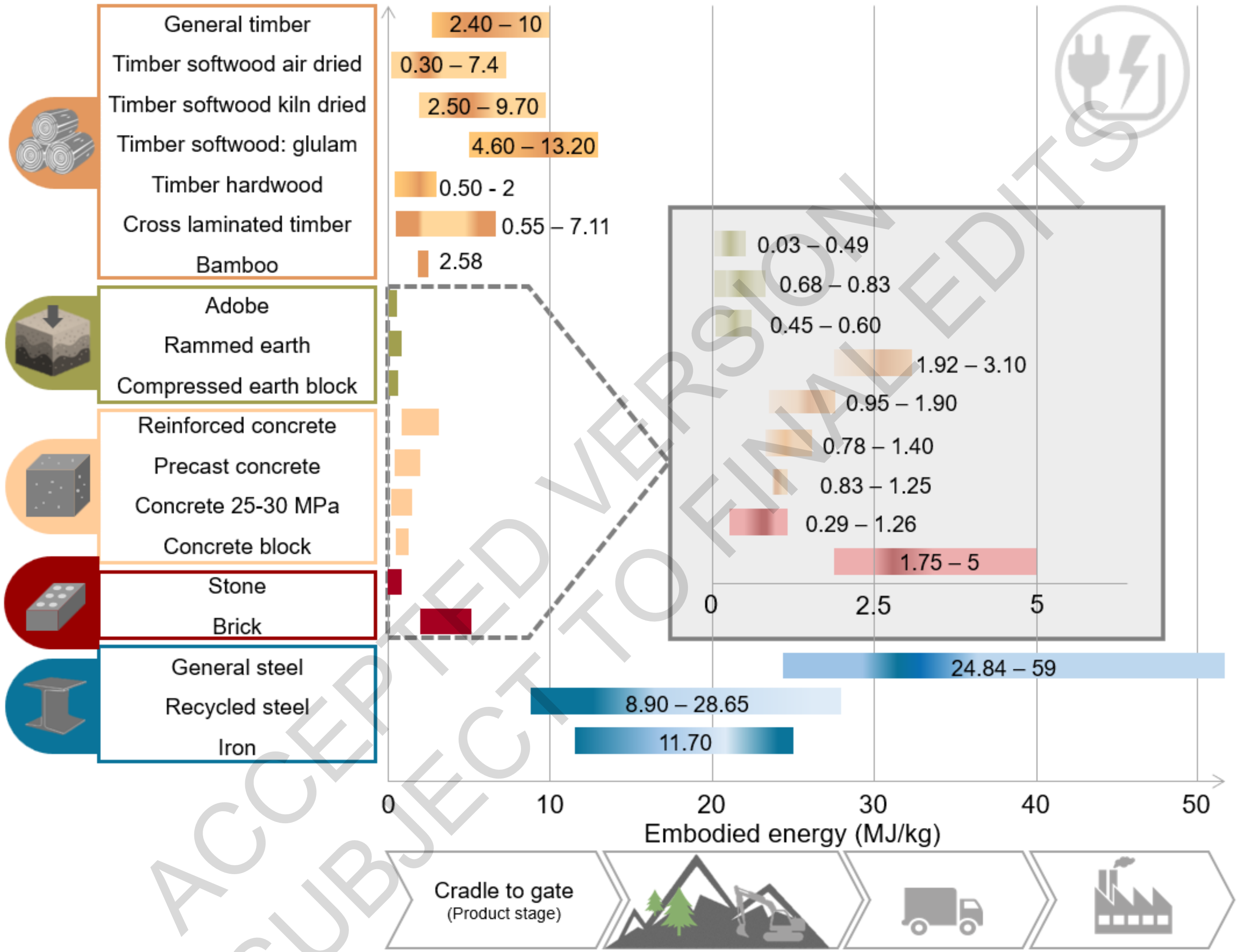
9.4.2 Embodied energy and embodied carbon

9.4.2.1 Embodied energy and embodied carbon in building materials

As building energy demand is decreased the importance of embodied energy and embodied carbon in building materials increases (Ürge-Vorsatz et al. 2020). Buildings are recognised as built following five building frames: concrete, wood, masonry, steel, and composite frames (International Energy Agency 2019a); but other building frames should be considered to include worldwide building construction practice, such as rammed earth and bamboo in vernacular design (Cabeza et al. 2021).

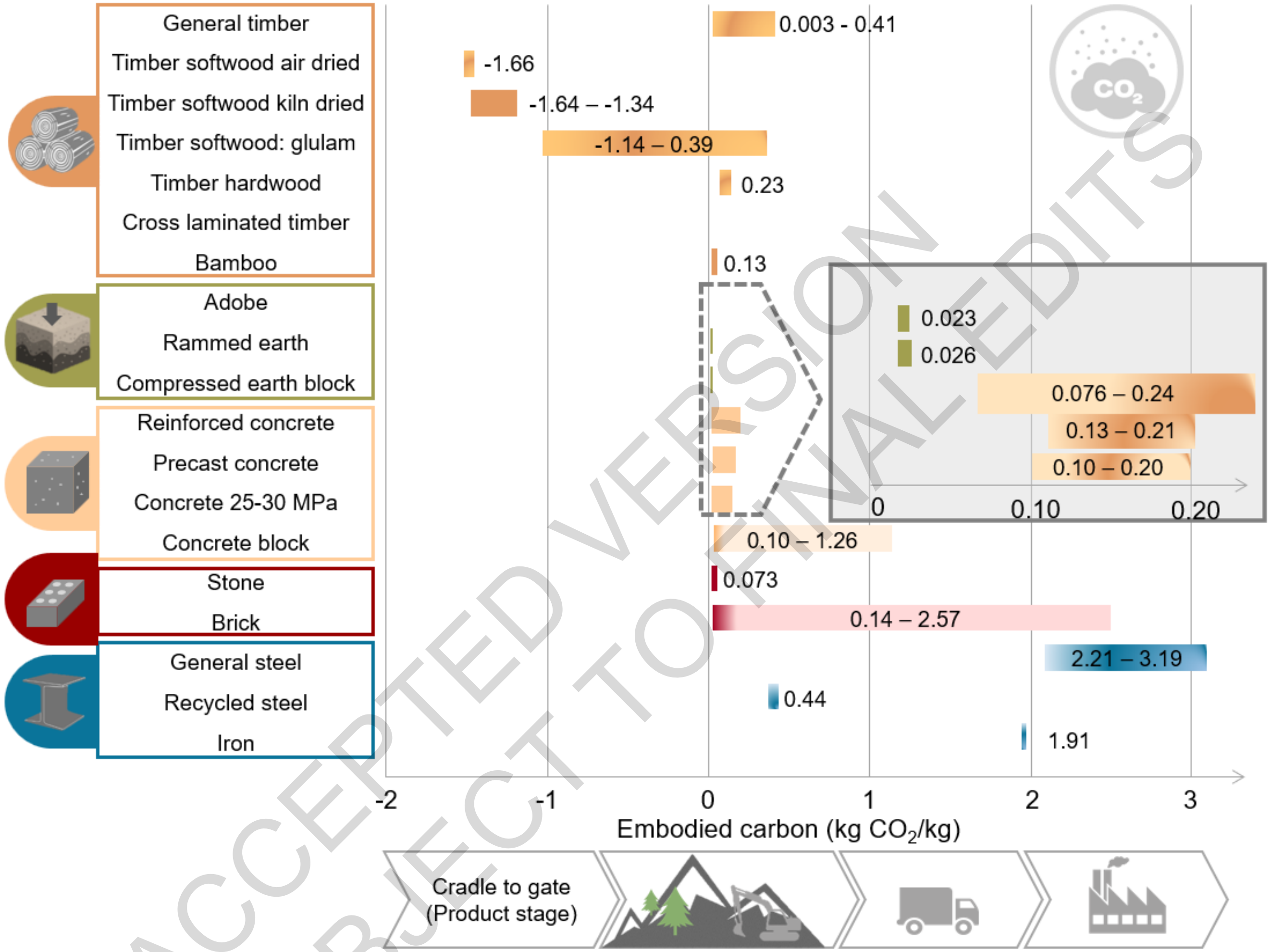
The most prominent materials used following these frames classifications are the following. Concrete, a man-made material, is the most widely used building material. Wood has been used for many centuries for the construction of buildings and other structures in the built environment; and it remains as an important construction material today. Steel is the strongest building material; it is mainly used in industrial facilities and in buildings with big glass envelopes. Masonry is a heterogeneous material using bricks, blocks, and others, including the traditional stone. Composite structures are those involving multiple dissimilar materials. Bamboo is a traditional building material throughout the world tropical and sub-tropical regions. Rammed earth can be considered to be included in masonry construction, but it is a structure very much used in developing countries and it is finding new interest in developed ones (Cabeza et al. 2021).

The literature evaluating the embodied energy in building materials is extensive, but that considering embodied carbon is much more scarce (Cabeza et al. 2021). Recently this evaluation is done using the methodology life cycle assessment (LCA), but since the boundaries used in those studies are different, varying for example, in the consideration of cradle to grave, cradle to gate, or cradle to cradle, the comparison is very difficult (Moncaster et al. 2019). A summary of the embodied energy and embodied carbon cradle to gate coefficients reported in the literature are found in Figure 9.9 (Alcorn and Wood 1998; Birgisdottir et al. 2017; Cabeza et al. 2013; De Wolf et al. 2016; Symons 2011; Moncaster and Song 2012; Omrany et al. 2020; Pomponi and Moncaster 2016, 2018; Crawford and Treolar 2010; Vukotic et al. 2010; Cabeza et al. 2021). Steel represents the materials with higher embodied energy, 32-35 $MJ \cdot kg^{-1}$; embodied energy in masonry is higher than in concrete and earth materials, but surprisingly, some type of wood have more embodied energy than expected; there are dispersion values in the literature depending of the ma. On the other hand, earth materials and wood have the lowest embodied carbon, with less than 0.01 kg CO_2 per kg of material (Cabeza et al. 2021). The concept of buildings as carbon sinks raise from the idea that wood stores considerable quantities of carbon with a relatively small ratio of carbon emissions to material volume and concrete has substantial embodied carbon emissions with minimal carbon storage capacity (Churkina et al. 2020; Sanjuán et al. 2019).


General timber
Timber softwood air dried
Timber softwood kiln dried
Timber softwood: glulam
Timber hardwood
Cross laminated timber
Bamboo
Adobe
Rammed earth
Compressed earth block
Reinforced concrete
Precast concrete
Concrete 25-30 MPa
Concrete block
Stone
Brick
General steel
Recycled steel
Iron
2.40 – 10
0.30 – 7.4
2.50 – 9.70
4.60 – 13.20
0.50 - 2
0.55 – 7.11
2.58
0.03 – 0.49
0.68 – 0.83
0.45 – 0.60
1.92 – 3.10
0.95 – 1.90
0.78 – 1.40
0.83 – 1.25
0.29 – 1.26
1.75 – 5
0
2.5
5
24.84 – 59
8.90 – 28.65
11.70
0
10
20
30
40
50
Embodied energy (MJ/kg)
Cradle to gate
(Product stage)

1

1



2 **Figure 9.9 Building materials (a) embodied energy and (b) embodied carbon** (Cabeza et al. 2021).

9.4.2.2 Embodied emissions

Embodied emissions from production of materials are an important component of building sector emissions, and their share is likely to increase as emissions from building energy demand decrease (Röck et al. 2020). Embodied emissions trajectories can be lowered by limiting the amount of new floor area required (Berrill and Hertwich 2021; Fishman et al. 2021), and reducing the quantity and GHG intensity of materials through material efficiency measures such as lightweighting and improved building design, material substitution to lower-carbon alternatives, higher fabrication yields and scrap recovery during material production, and re-use or lifetime extension of building components (Allwood et al. 2011; Pamenter and Myers 2021; Churkina et al. 2020; Heeren et al. 2015b; Pauliuk et al. 2021; Hertwich et al. 2019). Reducing the GHG intensity of energy supply to material production activities also has a large influence on reducing overall embodied emissions. Figure 9.10 shows projections of embodied emissions to 2050 from residential buildings in a baseline scenario (SSP2 Baseline) and a scenario incorporating multiple material efficiency measures and a much faster decarbonization of energy supply (LED and 2°C policy) (Pauliuk et al. 2021). Embodied emissions are projected to be 32% lower in 2050 than 2020 in a baseline scenario, primarily due to a lower growth rate of building floor area per population. This is because the global population growth rate slows over the coming decades, leading to less demand for new floor area relative to total population. Further baseline reductions in embodied emissions between 2020 and 2050 derive from improvements in material production and a gradual decline in GHG intensity of energy supply. In a LED + 2°C policy scenario, 2050 embodied emissions are 86% lower than the Baseline. This reduction of 2050 emissions comes from contributions of comparable magnitude from three sources; slower floor area growth leading to less floor area of new construction per capita (sufficiency), reductions in the mass of materials required for each unit of newly built floor area (material efficiency), and reduction in the GHG intensity of material production, from material substitution to lower carbon materials, and faster transition of energy supply.

The attribution of changes in embodied emissions to changes in the drivers of population, sufficiency, material efficiency, and GHG intensity of material production is calculated using additive log-mean divisia index decomposition analysis (Ang and Zhang 2000). The decomposition of emissions into four driving factors is shown in Eq. 9.3, where m^2_{NC} refers to floor area of new construction, kg_{Mat} refers to mass of materials used for new construction, and kg_{CO2e} refers to embodied GHG emissions in CO_{2e}. The allocation of changes in emissions between two cases *k* and *k-1* to changes in a single driving factor *D* is shown in Eq. 9.4. For instance, to calculate changes in emissions due to population growth, *D* will take on the value of population in the two cases being compared. The superscript *k* stands for the time period and scenario of the emissions, e.g., SSP2 Baseline scenario in 2050. When decomposing emissions between two cases *k* and *k-1*, either the time period or the scenario stays constant. The decomposition is done for every region at the highest regional resolution available, and aggregation (e.g., to global level) is then done by summing over regions. For changes in emissions within a scenario over time (e.g., SSP Baseline emissions in 2020 and 2050), the decomposition is made for every decade, and the total 2020-2050 decomposition is then produced by summing decompositions of changes in emissions each decade.

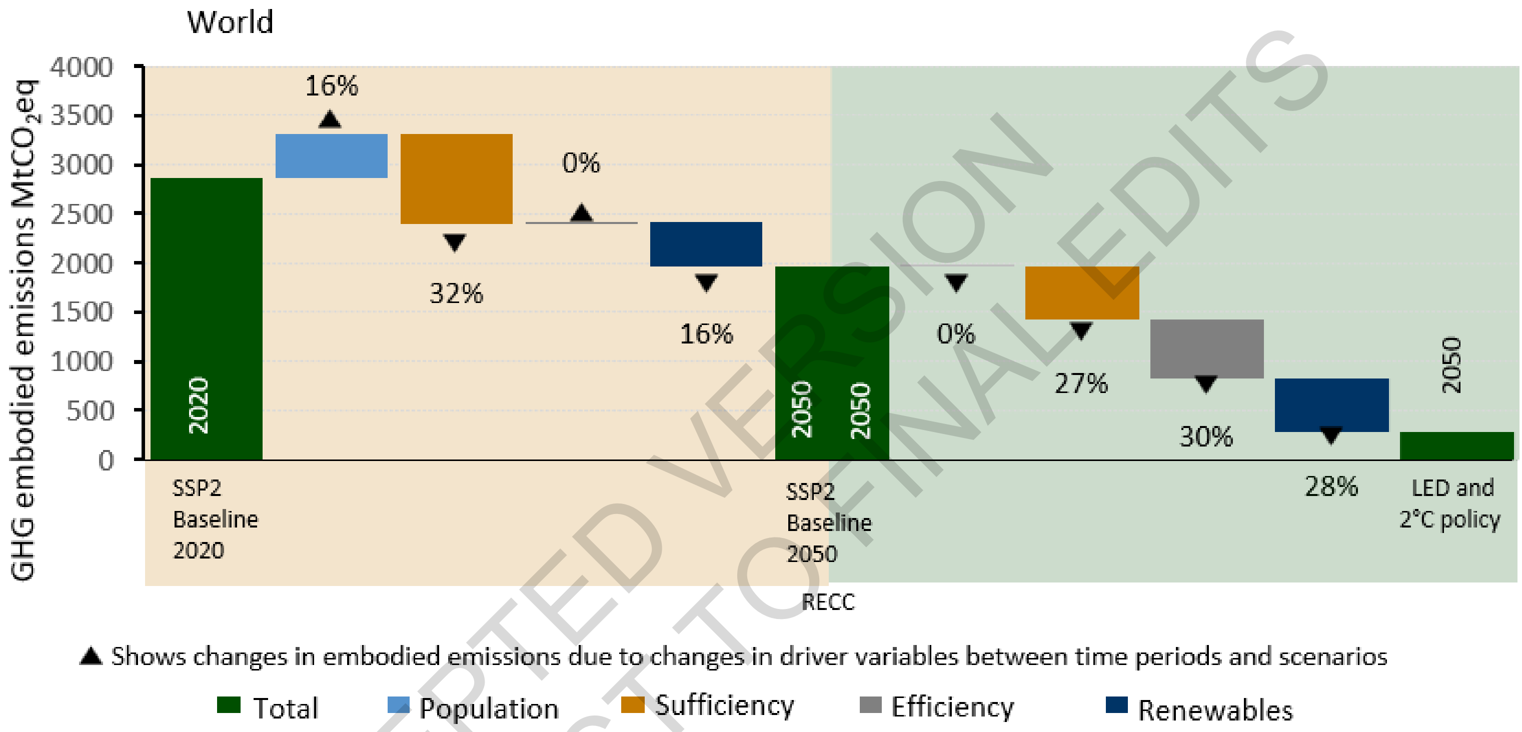
Equation 9.3

$$GHG^k_{emb} = Pop \times \frac{m^2_{NC}}{Pop} \times \frac{kg_{Mat}}{m^2_{NC}} \times \frac{kg_{CO2e}}{kg_{Mat}} = Pop \times Suff \times Eff \times Ren$$

Equation 9.4

$$\Delta GHG^{k,k-1}_{emb,D} = \frac{GHG^k_{emb} - GHG^{k-1}_{emb}}{ln(GHG^k_{emb}) - ln(GHG^{k-1}_{emb})} \times ln\left(\frac{D^k}{D^{k-1}}\right)$$

(a) Global



(b) Regional

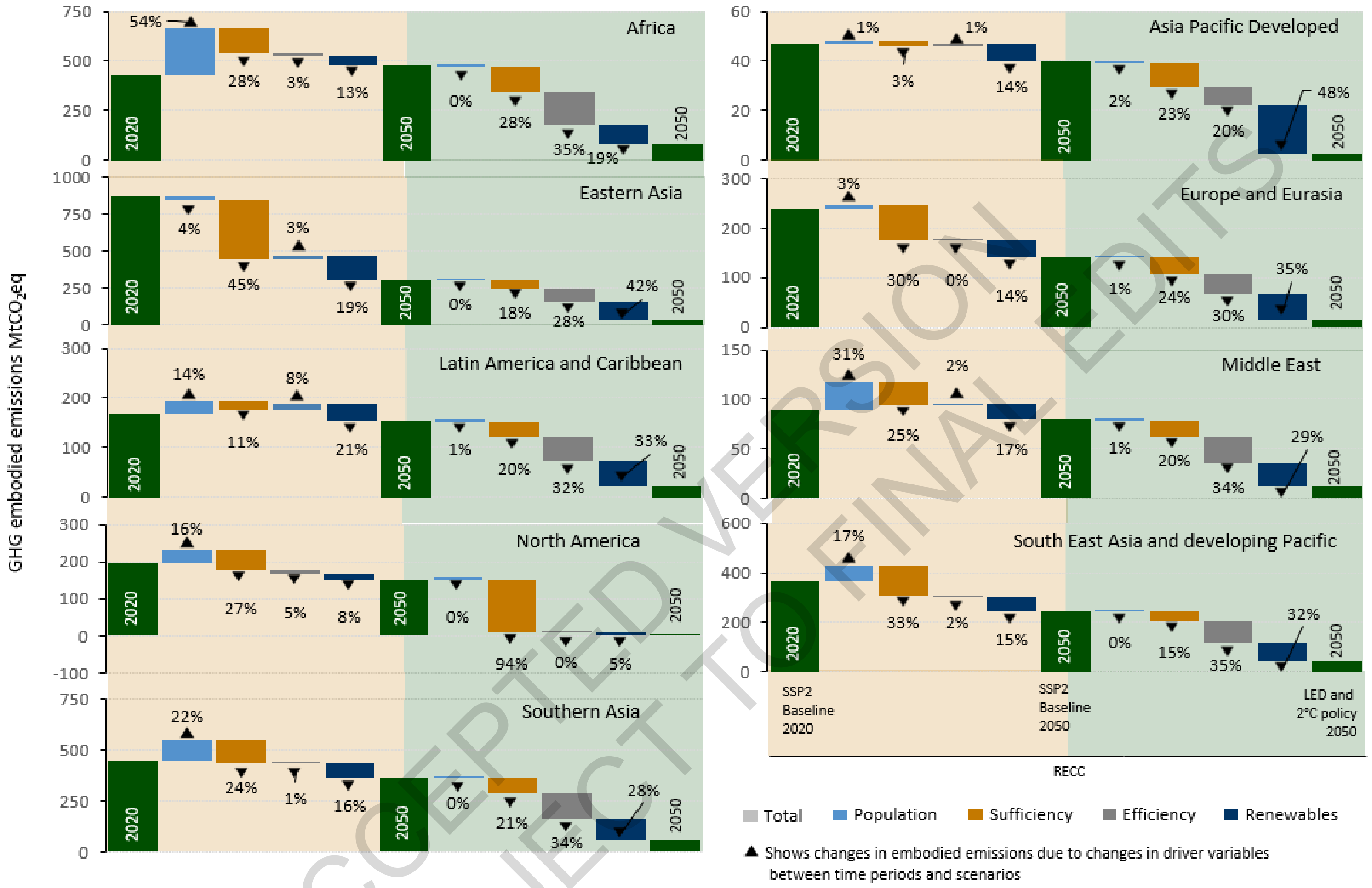


Figure 9.10 Decompositions of changes in residential embodied emissions projected by baseline scenarios for 2020-2050, and differences between scenarios in 2050 using two scenarios from the RECC model. (a) Global resolution, and (b) for nine world regions. Emissions are decomposed based on changes in driver variables of population, sufficiency (floor area of new construction per capita), material efficiency (material production per floor area), and renewables (GHG emissions per unit material production). 'Renewables' is a summary term describing changes in GHG intensity of energy supply. Emission projections to 2050, and differences between scenarios in 2050, demonstrate mitigation potentials from the dimensions of the SER framework realised in each model scenario.

9.4.3 Technological developments since AR5

9.4.3.1 Overview of technological developments

There are many technologies that can reduce energy use in buildings (Finnegan et al. 2018; Kockat et al. 2018a), and those have been extensively investigated. Other technologies that can contribute to achieving carbon zero buildings are less present in the literature. Common technologies available to achieve zero energy buildings were summarized in (Cabeza and Chàfer 2020) and are presented in Tables SM9.1 to SM9.3 in detail, where Figure 9.11 shows a summary.

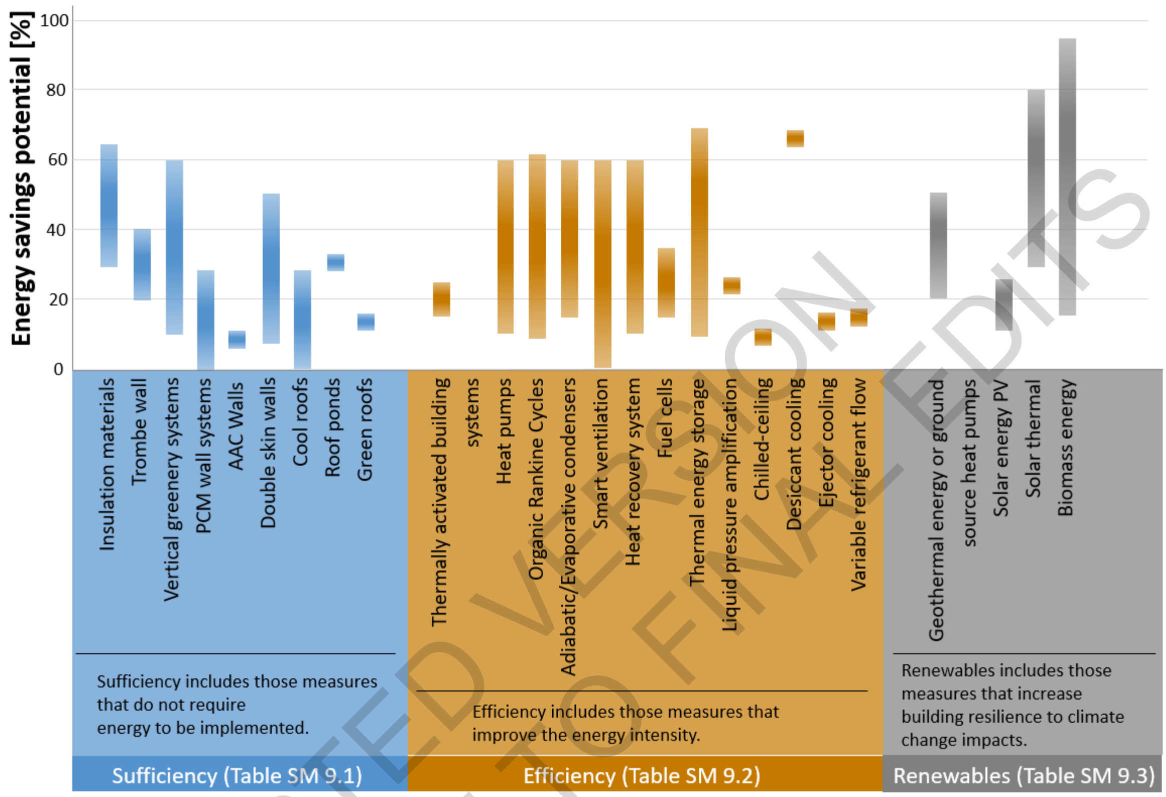


Figure 9.11 Energy savings potential of technology strategies for climate change mitigation in buildings.

Source: Adapted from (Bojić et al. 2014; Bevilacqua et al. 2019; Coma et al. 2017; Djedjig et al. 2015; Chen et al. 2013; Haggag et al. 2014; Khoshbakht et al. 2017; Saffari et al. 2017; Seong and Lim 2013; Radhi 2011; Pomponi et al. 2016; Andjelković et al. 2016; Rosado and Levinson 2019; Costanzo et al. 2016; Spanaki et al. 2014; Coma et al. 2016; Yang et al. 2015; Cabeza et al. 2010; Kameni Nematchoua et al. 2020; Annibaldi et al. 2020; Varela Luján et al. 2019; Jedidi and Benjeddou 2018; Capozzoli et al. 2013; Asdrubali et al. 2012; Irshad et al. 2019; Luo et al. 2017; Prívara et al. 2011; Sourbron et al. 2013; Ling et al. 2020; Peng et al. 2020; Zhang et al. 2020c; Dong et al. 2020; Harby et al. 2016; Liu et al. 2019; Vakiloroaya et al. 2014; Mahmoud et al. 2020; Romdhane and Louahlia-Gualous 2018; Gong et al. 2019; de Gracia et al. 2013; Navarro et al. 2016; Fallahi et al. 2010; Mujahid Rafique et al. 2015; Soltani et al. 2019; Imanari et al. 1999; Yu et al. 2020; Lee et al. 2018; Sarbu and Sebarchievici 2014; Hohne et al. 2019; Zhang et al. 2019; Omara and Abuelnour 2019; Alam et al. 2019; Langevin et al. 2019; Cabeza and Chàfer 2020)

Other opportunities exist, such as building light-weighting or more efficient material production, use and disposal (Hertwich et al. 2020), fast-growing biomass sources such as hemp, straw or flax as insulation in renovation processes (Pittau et al. 2019), bamboo-based construction systems as an alternative to conventional high-impact systems in tropical and subtropical climates (Zea Escamilla et al. 2018). Earth architecture is still limited to a niche (Morel and Charef 2019). See also Cross-Chapter Box 9 in Chapter 13 for carbon dioxide removal and its role in mitigation strategies.

9.4.3.2 Appliances and lighting

Electrical appliances have a significant contribution to household electricity consumption (Pothitou et al. 2017). Ownership of appliances, the use of appliances, and the power demand of the appliances are key contributors to domestic electricity consumption (Jones et al. 2015). The drivers in energy use of appliances are the appliance type (e.g., refrigerators), number of households, number of appliances per household, and energy used by each appliance (Cabeza et al. 2014)(Chu and Bowman 2006; Spiliotopoulos 2019). At the same time, household energy-related behaviours are also a driver of energy use of appliances (Khosla et al. 2019) (see Section 9.5). Although new technologies such as IoT linked to the appliances increase flexibility to reduce peak loads and reduce energy demand (Berkeley et al. 2020), trends show that appliances account for an increasing amount of building energy consumption (Figure 9.8). Appliances used in developed countries consume electricity and not fuels (fossil or renewable), which often have a relatively high carbon footprint. The rapid increase in appliance ownership (Cabeza et al. 2018b) can affect the electricity grid. Moreover, energy intensity improvement in appliances such as refrigerators, washing machines, TVs, and computers has counteracted the substantial increase in ownership and use since the year 2000 (International Energy Agency 2019b).

But appliances also are a significant opportunity for energy efficiency improvement. Research on energy efficiency for different appliances worldwide showed that this research focused in different time frames in different countries (Figure 9.12). This figure presents the number of occurrences of a term (the name of a studied appliance) appearing per year and per country, according to the references obtained from a Scopus search. The figure shows that most research carried out was after 2010. And again, this figure shows that research is mostly carried out for refrigerators and for brown appliances such as smart phones. Moreover, the research carried out worldwide is not only devoted to technological aspects, but also to behavioural aspects and quality of service (such as digital television or smart phones).

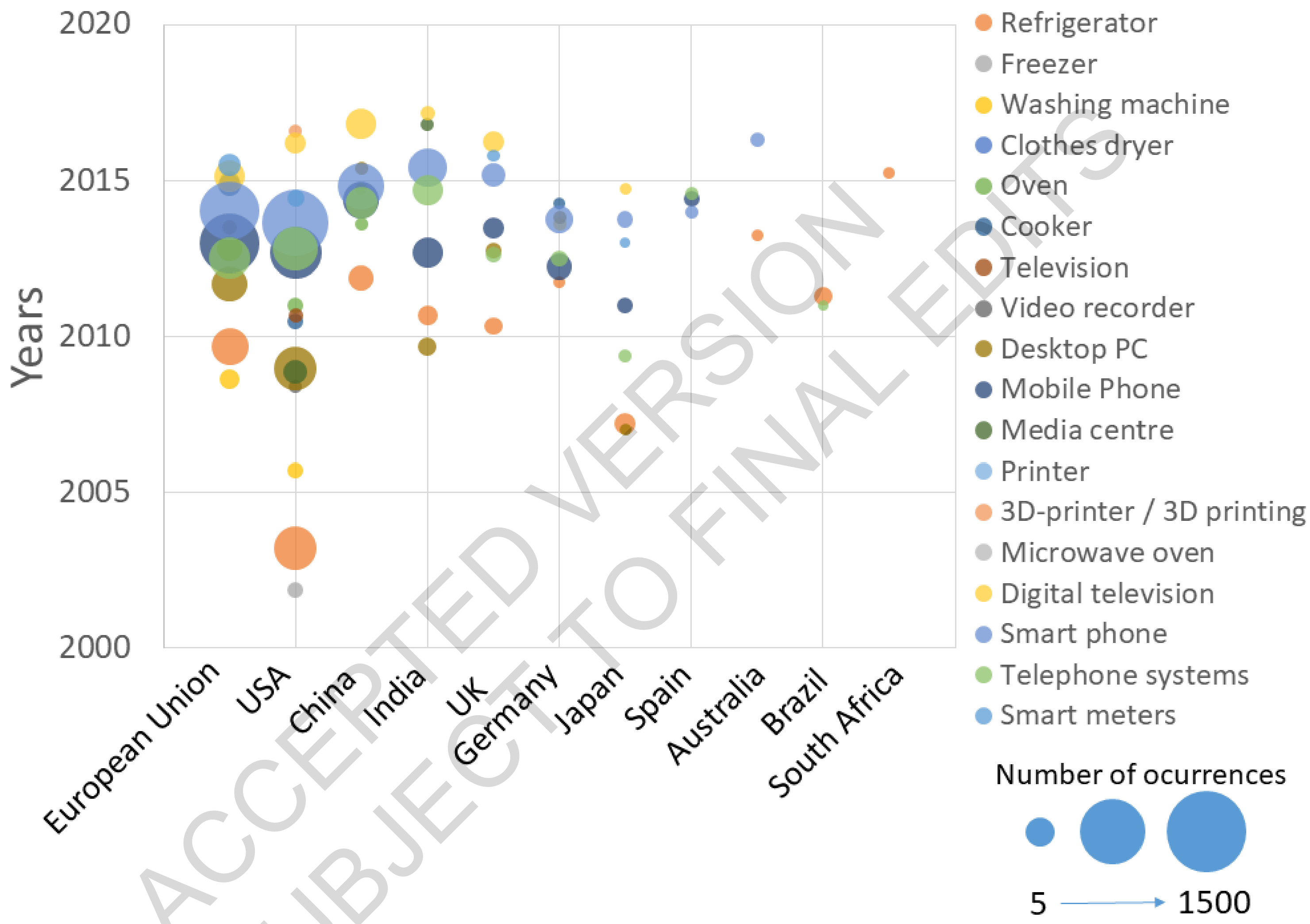


Figure 9.12 Energy efficiency in appliances research. Year and number of occurrences of different appliances in each studied country/territory.

Lighting energy accounts for around 19% of global electricity consumption (Attia et al. 2017; Enongene et al. 2017; Baloch et al. 2018). Many studies have reported the correlation between the decrease in energy consumption and the improvement of the energy efficiency of lighting appliances (Table 9.1). Today, the new standards recommend the phase out of incandescent light bulbs, linear fluorescent lamps, and halogen lamps and their substitution by more efficient technologies such as compact fluorescent lighting (CFL) and light-emitting diodes (LEDs) (Figure 9.8). Due to the complexity of these systems, simulation tools are used for the design and study of such systems, which can be summarized in Baloch et al. 2018 (Baloch et al. 2018).

Single-phase induction motors are extensively used in residential appliances and other building low-power applications. Conventional motors work with fixed speed regime directly fed from the grid, giving unsatisfactory performance (low efficiency, poor power factor, and poor torque pulsation). Variable speed control techniques improve the performance of such motors (Jannati et al. 2017).

Table 9.1 Types of domestic lighting devices and their characteristics (Adapted from (Attia et al. 2017)**)**

Type of lighting device	Code in plan	Lumens per watt [$lm \cdot W^{-1}$]	Colour temperature [K]	Life span [h]	Energy use [W]
Incandescent	InC	13.9	2700	1000	60
Candle incandescent	CnL	14.0	2700	1000	25
Halogen	Hal	20.0	3000	5000	60
Fluorescent TL 8	FluT8	80.0	3000-6500	20000	30-40
Compact fluorescent	CfL	66.0	2700-6500	10000	20
LED GLS	LeD	100.0	2700-5000	45000	10
LED spotlight	LeD Pin	83.8	2700-6500	45000	8
Fluorescent T5	FluT5	81.8	2700-6500	50000	22
LED DT8	LeDT8	111.0	2700-6500	50000	15

Within the control strategies to improve energy efficiency in appliances, energy monitoring for energy management has been extensively researched. Abubakar et al. 2017 (Abubakar et al. 2017) present a review of those methods. The paper distinguishes between intrusive load monitoring (ILM), with distributed sensing, and non-intrusive load monitoring (NILM), based on a single point sensing.

9.4.4 Case studies

9.4.4.1 Warehouses

Warehouses are major contributors to the rise of greenhouse gas emissions in supply chains (Bartolini et al. 2019). The expanding e-commerce sector and the growing demand for mass customization have even led to an increasing need for warehouse space and buildings, particularly for serving the uninterrupted customer demand in the business-to-consumer market. Although warehouses are not specifically designed to provide their inhabitants with comfort because they are mainly unoccupied, the impact of their activities in the global GHG emissions is remarkable. Warehousing activities contribute roughly 11% of the total GHG emissions generated by the logistics sector across the world. Following this global trend, increasing attention to green and sustainable warehousing processes has led to many new research results regarding management concepts, technologies, and equipment to reduce warehouses carbon footprint, i.e., the total emissions of GHG in carbon equivalents directly caused by warehouses activities.

9.4.4.2 Historical and heritage buildings

Historical buildings, defined as those built before 1945, are usually low-performance buildings by definition from the space heating point of view and represent almost 30–40% of the whole building stock in European countries (Cabeza et al. 2018a). Historical buildings often contribute to townscape character, they create the urban spaces that are enjoyed by residents and attract tourist visitors. They may be protected by law from alteration not only limited to their visual appearance preservation, but also concerning materials and construction techniques to be integrated into original architectures. On the other hand, a heritage building is a historical building which, for their immense value, is subject to legal preservation. The integration of renewable energy systems in such buildings is more challenging than in other buildings. The review carried out by (Cabeza et al. 2018a) different case studies are presented and discussed, where heat pumps, solar energy and geothermal energy systems are integrated in such buildings, after energy efficiency is considered.

9.4.4.3 Positive energy or energy plus buildings

The integration of energy generation on-site means further contribution of buildings towards decarbonisation (Ürge-Vorsatz et al. 2020). Integration of renewables in buildings should always come after maximising the reduction in the demand for energy services through sufficiency measures and maximising efficiency improvement to reduce energy consumption, but the inclusion of energy generation would mean a step forward to distributed energy systems with high contribution from buildings, becoming prosumers (Sánchez Ramos et al. 2019). Decrease price of technologies such as PV and the integration of energy storage (de Gracia and Cabeza 2015) are essential to achieve this objective. Other technologies that could be used are photovoltaic/thermal (Sultan and Ervina Efzan 2018), solar/biomass hybrid systems (Zhang et al. 2020b), solar thermoelectric (Sarbu and Dorca 2018), solar powered sorption systems for cooling (Shirazi et al. 2018), and on-site renewables with battery storage (Liu et al. 2021).

9.4.4.4 District energy networks

District heating networks have evolved from systems where heat was produced by coal or waste and storage was in the form of steam, to much higher energy efficiency networks with water or glycol as the energy carrier and fuelled by a wide range of renewable and low carbon fuels. Common low carbon fuels for district energy systems include biomass, other renewables (i.e., geothermal, PV, and large solar thermal), industry surplus heat or power-to-heat concepts, and heat storage including seasonal heat storage (Lund et al. 2018). District energy infrastructure opens opportunities for integration of several heat and power sources and is 'future proof' in the sense that the energy source can easily be converted or upgraded in the future, with heat distributed through the existing district energy network. Latest developments include the inclusion of smart control and AI (Revesz et al. 2020), and low temperature thermal energy districts. Authors show carbon emissions reduction up to 80% compared to the use of gas boilers.

9.4.5 Low- and net zero energy buildings – exemplary buildings

Nearly zero energy (NZE) buildings or low-energy buildings are possible in all world relevant climate zones (Mata et al. 2020b; Ürge-Vorsatz et al. 2020) (Figure 9.13). Moreover, they are possible both for new and retrofitted buildings. Different envelope design and technologies are needed, depending on the climate and the building shape and orientation. For example, using the Passive House standard an annual heating and cooling energy demand decrease between 75% and 95% compared to conventional values can be achieved. Table 9.2 lists several exemplary low- and NZE-buildings with some of their feature.

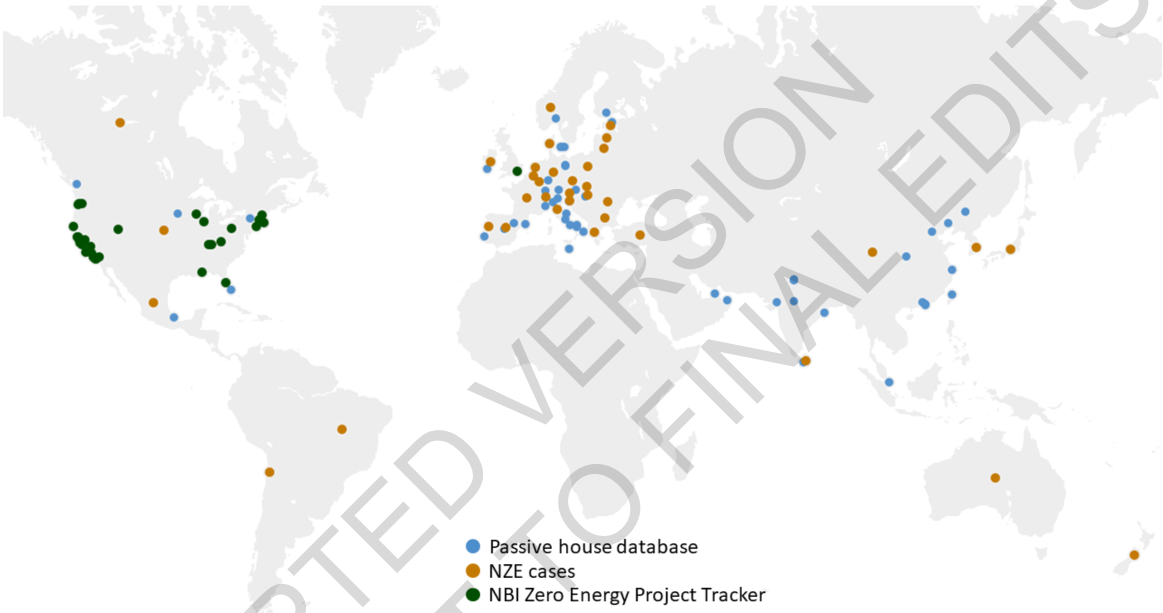


Figure 9.13 Regional distribution of documented low-energy buildings.

Source: New Building Institute 2019; Ürge-Vorsatz et al. 2020

Table 9.2 Selected exemplary low- and net zero- energy buildings worldwide (Adapted from (Mørck 2017; Schnieders et al. 2020; Ürge-Vorsatz et al. 2020)**)**

Building name and organization	Location	Building type	Energy efficiency and renewable energy features	Measured energy performance
SDB-10 at the software development company, Infosys	India	Software development block	• Hydronic cooling and a district cooling system with a chilled beam installation • Energy-efficient air conditioning and leveraged load diversity across categorized spaces: comfort air conditioning (workstations, rooms), critical load conditioning (server, hub, UPS, battery rooms), ventilated areas (restrooms, electrical, transformer rooms), and pressurized areas (staircases, lift wells, lobbies)	EPI of 74 $kWh{\cdot}m^{-2}$, with an HVAC peak load of 5.2 $W{\cdot}m^{-2}$ for a total office area of 47,340 m^2 and total conditioned area of 29,115 m^2

			• BMS to control and monitor the HVAC system, reduced face velocity across DOAS filters, and coils that allow for low pressure drop	
Y.S. Sun Green Building by an electronics manufacturing company Delta Electronics Inc.,	Taiwan, China	University research green building	• Low cost and high efficiency are achieved via passive designs, such as large roofs and protruded eaves which are typical shading designs in hot-humid climates and could block around 68% of incoming solar radiation annually • Porous and wind-channelling designs, such as multiple balconies, windowsills, railings, corridors, and make use of stack effect natural ventilation to remove warm indoor air • Passive cooling techniques that help reduce the annual air-conditioning load by 30%	EUI of the whole building is 29.53 kWh·m^{-2} (82% more energy-saving compared to the similar type of buildings)
BCA Academy Building	Singapore	Academy Building	• Passive design features such a green roof, green walls, daylighting, and stack effect ventilation • Active designs such as energy-efficient lighting, air-conditioning systems, building management system with sensors and solar panels • Well-insulated, thermal bridge free building envelope	First net zero energy retrofitted building in Southeast Asia
Energy-Plus Primary School	Germany	School	• Highly insulated Passive House standard • Hybrid (combination of natural and controlled ventilation) ventilation for thermal comfort, air quality, user acceptance and energy efficiency • Integrated photovoltaic plant and wood pellet driven combined heat and power generation • Classrooms are oriented to the south to enable efficient solar shading, natural lighting and passive solar heating • New and innovative building components including different types of innovative glazing, electro chromic glazing, LED lights, filters and control for the ventilation system	Off grid building with an EPI of 23 kWh m^{-2} yr^{-1}
NREL Research Support Facility	USA	Office and Research Facility	• The design maximizes passive architectural strategies such as building orientation, north and south glazing, daylighting which penetrates deep into the building, natural ventilation, and a structure which stores thermal energy • Radiant heating and cooling with radiant piping through all floors, using water as the cooling and heating medium in the majority of workspaces instead of forced air • Roof-mounted photovoltaic system and adjacent parking structures covered with PV panels	EPI of 110 kWh m^{-2} yr^{-1} with a project area of 20624.5 m^2 to become the then largest the largest commercial net zero energy building in the country
Mohammed Bin Rashid Space Centre (Schnieders et al. 2020)	United Arab Emirates, Dubai	Non-residential, offices	• Exterior walls U-value = 0.08 W m^{-2} K^{-1} • Roof U-value = 0.08 W m^{-2} K^{-1} • Floor slab U-value = 0.108 W m^{-2} K^{-1} • Windows UW = 0.89 W m^{-2} K^{-1} • PVC and aluminium frames, triple solar protective glazing with krypton filling • Ventilation = MVHR, 89% efficiency • Heat pump for cooling with recovery of the rejected heat for DHW and reheating coil	Cooling and dehumidification demand = 40 kWh m^{-2} yr^{-1} sensible cooling +10 kWh m^{-2} yr^{-1} latent cooling Primary energy demand = 143 kWh m^{-2} yr^{-1}

Sems Have (Mørck 2017)	Roskilde, Denmark	Multi-family residential (Retrofit)	• Pre-fabricated, light weight walls • Low-energy glazed windows, basement insulated with expanded clay clinkers under concrete • Balanced mechanical ventilation with heat recovery • PV	Final Energy Use: 24.54 $kWh{\cdot}m^{-2}$ Primary energy use: 16.17 $kWh{\cdot}m^{-2}$

9.5 Non-technological and behavioural mitigation options and strategies

Non-technological (NT) measures are key for low-carbon buildings, but still attract less attention than technological measures (Ruparathna et al. 2016; Vence and Pereira 2019; Cabeza et al, 2020; Creutzig et al. 2016; Mundaca et al. 2019; Mata et al. 2021b)(Creutzig et al. 2018). The section is set out to understand, over the buildings lifecycle, NT determinants of buildings' energy demand and emissions (Section 9.5.1); to present NT climate mitigation actions (Section 9.5.2); then, to understand how to get these actions implemented (Section 9.5.3). The latter is a starting point in the design of policies (Section 9.9).

9.5.1 Non-technological determinants of energy demand and carbon emissions

Buildings climate impact includes CO_2 emissions from operational energy use, carbon footprint, PM2.5 concentrations and embodied carbon, and is unequivocally driven by GDP, income, population, buildings floor area, energy price, climate, behaviour, and social and physical environment (Wolske et al. 2020; Mata et al. 2021d).

9.5.1.1 Climate and physical environment

Outdoor temperature, Heating and Cooling Degree Days, sunshine hours, rainfall, humidity and wind are highly determinant of energy demand (Harold et al. 2015; Rosenberg 2014; Lindberg et al. 2019; Risch and Salmon 2017)(Tol et al. 2012). Density, compacity, and spatial effects define the surrounding environment and urban microclimate. Urban residents usually have a relatively affluent lifestyle, but use less energy for heating (Huang 2015; Niu et al. 2012; Rafiee et al. 2019; Ayoub 2019; Oh and Kim 2019). Urbanization is discussed in Chapter 8.

Climate variability and extreme events may drastically increase peak and annual energy consumption (Mashhoodi et al. 2019; Cui et al. 2017; Hong et al. 2013). Climate change effects on future demand and emissions, are discussed in Section 9.7, and effects of temperature on health and productivity, in Section 9.8.

9.5.1.2 Characteristics of the building

Building typology and floor area (or e.g. number of bedrooms or lot size) are correlated to energy demand (Fosas et al. 2018; Morganti et al. 2019; Manzano-Agugliaro et al. 2015; Moura et al. 2015; Berrill et al. 2021). Affluence is embedded in these variables as higher-income households have larger homes and lots. Residential consumption increases with the number of occupants but consumption per capita decreases proportionally to it (Serrano et al. 2017). Construction or renovation year has a negative correlation as recently built buildings must comply with increasingly strict standards (Brounen et al. 2012; Kavousian et al. 2015; Österbring et al. 2016). Only for electricity consumption no significant correlation is observed to building age (Kavousian et al. 2013). Material choices, bioclimatic and circular design discussed in Section 9.4.2.

9.5.1.3 Socio-demographic factors

Income is positively correlated to energy demand (Singh et al. 2017; Bissiri et al. 2019; Sreekanth et al. 2011; Couture et al. 2012;Yu 2017; Moura et al. 2015; Mata et al. 2021b; Cayla et al. 2011). High-income households tend to use more efficient appliances and are likely to be more educated and environmentally sensitive, but their higher living standards require more energy (Hidalgo et al. 2018; Harold et al. 2015). Low-income households are in higher risk of fuel poverty (Section 9.8).

Mixed effects are found for household size, age, gender, ethnicity, education levels and tenancy status (Engvall et al. 2014; Arawomo 2019; Lévy and Belaïd 2018; Hansen 2016; Rafiee et al. 2019). Single-parent and elderly households consume more gas and electricity, and gender has no significant effect (Harold et al. 2015; Brounen et al. 2012; Huang 2015). Similarly, larger families use less electricity per capita (Bedir et al. 2013; Kavousian et al. 2013). Heating expenditure tends to be higher for owners than for renters, despite the formers tendency to have more efficient appliances (Gillingham et al. 2012; Davis, 2012; Kavousian et al. 2015).

9.5.1.4 Behaviour

Occupants presence and movement, interactions with the building, comfort-driven adaptations and cultural practices determine energy consumption (Li et al. 2019; Khosla et al. 2019; D'Oca et al. 2018; Hong et al. 2017; O'Brien et al. 2020; Yan et al. 2017). Households consume more on weekends and public holidays, and households with employed occupants consume less than self-employed occupants, probably because some of the latter jobs are in-house (Harold et al. 2015; Hidalgo et al. 2018). Understanding and accurate modelling of occupant behaviour is crucial to reduce the gap between design and energy performance (Gunay et al. 2013; Yan et al. 2017), especially for more efficient buildings, which rely on passive design features, human-centred technologies, and occupant engagement (Grove-Smith et al. 2018; Pitts 2017).

9.5.2 Insights from non-technological and behavioural interventions

A range of NT actions can substantially reduce buildings energy demand and emissions (Figure 9.14; see Supplementary Material SM9.2 for details). The subsections below present insights on the variations depending on the solution, subsector, and region.

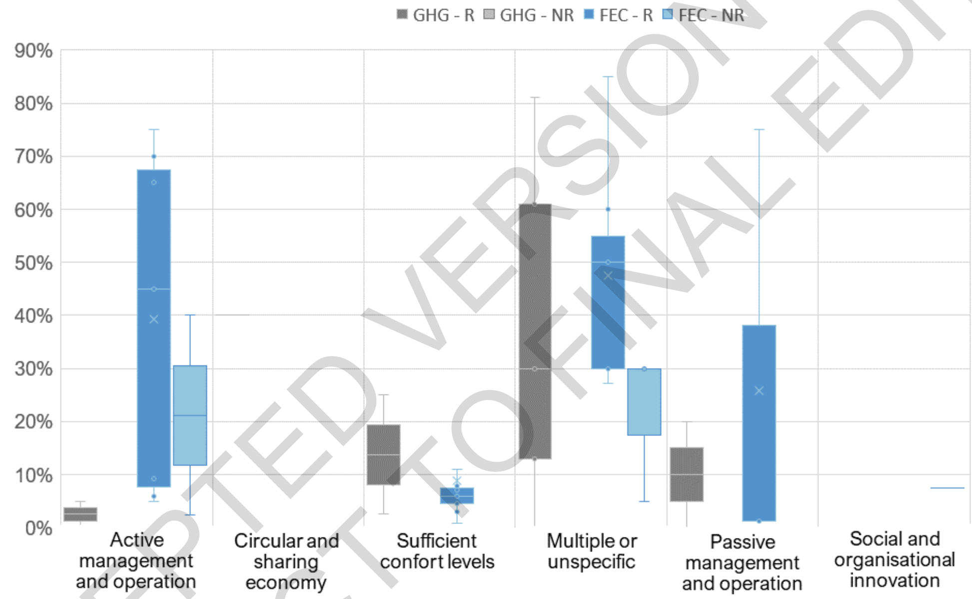


Figure 9.14 Energy saving and GHG mitigation potentials for categories of NT interventions for Residential (R) and Non-Residential (NR) buildings, from studies with worldwide coverage.

Sources: (Ruparathna et al. 2016b; Khosrowpour et al. 2016; Kaminska 2019; Creutzig et al. 2016; Wilson et al. 2020b; Derungs et al. 2019; Levesque et al. 2019a; Bierwirth and Thomas 2019b; Roussac and Bright 2012; Ohueri et al. 2018; Bavaresco et al. 2020; Ahl et al. 2019; Van Den Wymelenberg 2012; Cantzler et al. 2020; Ivanova and Büchs 2020b; Harris et al. 2021a; van Sluisveld et al. 2016;Rupp et al. 2015; Grover 2019).

9.5.2.1 Passive and active design, management, and operation

Bioclimatic design and passive strategies for natural heating, cooling and lighting, can greatly reduce buildings' climate impact, and avoid cooling in developing countries (Bienvenido-Huertas et al. 2021, 2020; Amirifard et al. 2019). Design can provide additional small savings, e.g., by placing refrigerator away from the oven, radiators or windows (Christidou et al. 2014). Passive management refers to adjustments in human behaviour such as adapted clothing, allocation of activities in the rooms of the building to minimize the energy use (Rafsanjani et al. 2015; Klein et al. 2012) or manual operation of the building envelope (Rijal et al. 2012; Volochovic et al. 2012). Quantitative modelling of such measures is most common for non-residential buildings, in which adaptive behaviours are affected by the office space distribution and interior design, amount of occupants, visual comfort, outdoor view, and ease to use control mechanisms (Talele et al. 2018; O'Brien and Gunay 2014). Socio demographic factors, personal characteristics and contextual factors also influence occupant behaviour and their interactions with buildings (D'Oca et al. 2018b; Hong et al. 2020).

Active management refers to human control of building energy systems. Efficient lighting practices can effectively reduce summer peak demand (Dixon et al. 2015; Taniguchi et al. 2016). On the contrary, the application of the Daylight-Saving Time in the US increases up to 7% lighting consumption (Rakha et al. 2018). Efficient cooking practices for cooking, appliance use (e.g. avoid stand-by regime, select eco-mode), or for hot water can save up to 25% (Teng et al. 2012; Berezan et al. 2013; Hsiao et al. 2014; Abrahamse and Steg 2013; Peschiera and Taylor 2012; Dixon et al. 2015; Reichert et al. 2016). High behavioural control is so far proven difficult to achieve (Ayoub et al. 2014) (Sköld et al. 2018). Automated controls and technical measures to trigger occupant operations are addressed in Section 9.4.

9.5.2.2 Limited demands for services

Adjustment in the set-point temperature in winter and summer results in savings between 5% and 25% (Ayoub et al. 2014)(Christidou et al. 2014; Sun and Hong 2017; Taniguchi et al. 2016). As introduced in 9.3, a series of recent works study a cap on the living area (Mata et al. 2021a) or an increase in household size (Berrill et al. 2021). These studies are promising but of limited complexity in terms of rebounds, interactions with other measures, and business models, thus require further investigation. Professional assistance and training on these issues is limited (Maxwell et al. 2018).

Willingness to adopt is found for certain measures (full load to laundry appliances, lid on while cooking, turning lights off, defer electricity usage and HVAC systems, adjust set-point temperature by 1°C) but not for others (appliances on standby, using more clothes, avoid leaving the TV on while doing other things, defer ovens, ironing or heating systems, adjust set-point temperature by 3°C, move to a low energy house or smaller apartment) (Brown et al. 2013; Sköld et al. 2018; Yohanis 2012; Li et al. 2017). A positive synergy with digitalization and smart home appliances is identified, driven by a combination of comfort requirements and economic interest, confirmed by a willingness to defer electricity usage in exchange for cost savings (Ferreira et al. 2018; Mata et al. 2020c).

9.5.2.3 Flexibility of demand and comfort requirements

In a flexible behaviour, the desired level of service is the same, but it can be shifted over time, typically allowing automated control, for the benefit of the electricity or district heating networks. There are substantial economic, technical, and behavioural benefits from implementing flexibility measures (Mata et al. 2020c), with unknown social impacts.

With demand side measures (DSM), such as shifting demand a few hours, peak net demand can be reduced up to 10-20% (Stötzer et al. 2015), a similar potential is available for short-term load shifting during evening hours (Aryandoust and Lilliestam 2017). Although different household types show different consumption patterns and thus an individual availability of DSM capacity during the day (Fischer et al. 2017), there is limited (Shivakumar et al. 2018) or inexistent (Nilsson et al. 2017; Drysdale et al. 2015) information of consumers response to Time of Use pricing, specifically among those living in apartments (Bartusch and Alvehag 2014). Behavioural benefits are identified in terms of increased level of energy awareness of the users (Rehm et al. 2018), measured deliberate attempts of the consumers to reduce and/or shift their electricity usage (Bradley et al. 2016). Real-time control and behavioural change influence 40% of the electricity use during operational life of non-residential buildings (Kamilaris et al. 2014).

9.5.2.4 Circular and sharing economy (CSE)

Non technological CSE solutions, based on the Regenerate, Share, Optimize, Loop, Virtualize, Exchange (ReSOLVE) framework (CE100 2016; ARUP 2018) include sharing, virtualizing and exchanging. These are less studied than circular materials, with notably less investigation of existing buildings and sharing solutions (Pomponi and Moncaster 2017; Høibye and Sand 2018; Kyrö 2020; European Commission 2020).

The sharing economy generates an increased utilization rate of products or systems by enabling or offering shared use, access or ownership of products and assets that have a low ownership or use rate. Measures include conditioned spaces (accommodation, facility rooms, offices) as well as tools and transfer of ownership (i.e., second-hand or donation) (Rademaekers et al. 2017; Harris et al. 2021; Mercado 2018; Hertwich et al. 2020; Cantzler et al. 2020; Mata et al. 2021c). The evidence on the link between user behaviour and net environmental impacts of sharing options is still limited (Laurenti et al. 2019; Mata et al. 2020a; Harris et al. 2021b) and even begins to be questioned, due to rebounds that partially or fully offset the benefits (Agrawal and Bellos 2017; Zink and Geyer 2017). E.g., the costs savings from reduced ownership can be allocated to activities with a higher carbon intensity, or result in increased mobility. Both reduced ownership and other circular consumption habits show no influence on material footprint, other than mildly positive influence in low-income households (Junnila et al. 2018; Ottelin et al. 2020).

9.5.2.5 Value-chain, social and institutional innovations

Cooperative efforts are necessary to improve buildings energy efficiency (Masuda and Claridge 2014; Kamilaris et al. 2014; Ruparathna et al. 2016). For instance, inter-disciplinary understanding of organizational culture, occupant behaviour, and technology adoption is required to set up occupancy/operation best practises (Janda 2014). Similarly, close collaboration of all actors along the value chain can reduce by 50% emissions from concrete use (Habert et al. 2020); such collaboration can be enhanced in a construction project by transforming the project organisation and delivery contract to reduce costs and environmental impact (Hall and Bonanomi 2021). Building commissioning helps to reduce energy consumption by streamlining the systems, but benefits may not persistent. Energy communities are discussed later in the chapter.

NT challenges include training and software costs (tailored learning programs, learning-by-doing, human capital mobilization), client and market demand (service specification, design and provision; market and financial analysis) and legal issues (volatile energy prices, meeting regulation); and partnership, governance and commercialization. These challenges are identified for Building Information Modelling (Rahman and Ayer 2019; Oduyemi et al. 2017), PV industry (Triana et al. 2018), Smart Living (Solaimani et al. 2015) or circular economy (Vence and Pereira 2019).

9.5.3 Adoption of climate mitigation solutions– reasons and willingness

Mixed effects are found for technical issues, attitudes, and values (Table 9.3). In spite of proven positive environmental attitudes and willingness to adopt mitigation solutions, these are outweighed by financial aspects all over the world (Mata et al. 2021b). Adopters in developed countries are more sensitive towards financial issues and comfort disruptions; whereas in other world regions techno-economic concerns prevail. Private consumers seem ready to support stronger governmental action, whereas non-private interventions are hindered by constraints in budgets and profits, institutional barriers and complexities (Curtis et al. 2017; Zuhaib et al. 2017; Tsoka et al. 2018; Kim et al. 2019).

A variety of interventions targeted to heterogeneous consumer groups and decision makers is needed to fulfil their diverse needs (Zhang et al. 2012; Liang et al. 2017; Soland et al. 2018; Marshall et al. 2015; Haines and Mitchell 2014; Gram-Hanssen 2014; Friege et al. 2016; Hache et al. 2017; Ketchman et al. 2018). Policy reviews for specific market segments and empirical studies investigating investment decisions would benefit from a multidisciplinary approach to energy consumption patterns and market maturity (Boyd 2016; Marzano et al. 2018; Heiskanen and Matschoss 2017; Baumhof et al. 2018; Wilson et al. 2018).

Table 9.3 Reasons for adoption of climate mitigation solutions. The sign represents if the effect is positive (+) or negative (-), and the number of signs represents confidence level (++, many references; +, few references) (Mata et al. 2021a)

	Climate mitigation solutions for buildings							
	Building envelope	**Efficient technical systems**	**On-site renewable energy**	**Behaviour**	**Performance standards**	**Low-carbon materials**	**Digitalization and flexibility**	**Circular and sharing econ.**
Economic:								
Subsidies/microloans*	+	++	++	+	++		+	
Low/high investment costs	-	+/--	++/--	+/-	+/--	+/-	-	-
Short payback period	+	+	+	+	+	+	+	
High potential savings	++	++	++	+	++		++	+
Market-driven demand		+	+		+		+	+
Higher resale value	+	+	+		+		+	
Operating/maintenance costs	+	++/-	++/-	+	+	+	+/-	
Split incentives	-	-	-	-	-		-	
Constrained budgets and profits	-	--	-		--	-	--	--
Price competitive (overall)		+	+		+	+	+	+
Information and support:								
Governmental support and capacity/lack of	+/-	+/-	++/-		++/-	+	+/-	-
Institutional barriers and complexities	-	-	-	-	--	-	-	-
Information and labeling/lack of	+/-	++/-	++/-	+	++/-		+/-	-
Smart metering		+	+	+			+	
Participative ownership		+	+	+	+	+		
Peer effects	+	+	++		+		+	
Professional advice/lack of	+/-	++/-	++/-	-	+/--	-	+/-	+/-
Social norm	+	+	+	+	+		+	+
Previous experience with solution/lack of	+/-	+/-	+/-	-	-	-	+/-	+/-
Technical:								
Condition of existing elements	+	+	+	+	+		+	
Natural resource availability	+	+	++	+		+		+
Performance and maintenance concerns*	-	-	--		--	-	-	-
Low level of control over appliances		-	-	-	-		-	
Limited alternatives available		-	-		-	-		
Not compatible with existing equipment	-	-	-	-			-	-
Attitudes and values:								
Appealing novel technology	+	+	++	+	+	+	++	+
Social and egalitarian world views	+		+	+	+		+	
Willingness to pay		+	++		+		+	
Heritage or aesthetic values	+/-	++/-	+/-		+/-		+/-	
Environmental values	+	+	++	+	++	+	++	+
Status and comfort / Lack of	++	++	++	+	++		+	
Discomfort during the retrofitting period	-	-	-		-		-	
Control, privacy, and security / Lack of*		+/-	+/-	-	-	-	+/--	
Risk aversion	-	-	-		-	-	-	
Social:								
Size factors (household, building)		+/-	++/-	+	+		+	
Status (education, income)	+/-	++/-	+/-	+/-	+/-	+	+/-	
Sociodemographic (age, gender, and ethnicity)	+/-	++/-	+/-	+/-	+/-		+/-	

9.5.3.1 *Building envelope*

In North America and Europe, personal attitudes, values, and existing information and support are the most and equally important reasons for improving the building envelope. Consumers have some economic concerns and little technical concerns, the later related to the performance and maintenance of the installed solutions (Mata el al, 2021c). In other world regions or per climate zone the literature is limited.

Motivations are often triggered by urgent comfort or replacement needs. Maintaining the aesthetic value may as well hinder the installation of insulation if no technical solutions are easily available (Haines and Mitchell 2014; Bright et al. 2019). Local professionals and practitioners can both encourage (Ozarisoy and Altan 2017; Friege 2016) and discourage the installation of insulation, according to their knowledge and training (Maxwell et al. 2018; Curtis et al. 2017; Zuhaib et al. 2017; Tsoka et al. 2018). If energy renovations of the buildings envelopes are not normative, cooperative ownership may be a barrier in apartment buildings (Miezis et al. 2016). Similarly, product information and labelling may be helpful or overwhelming (Ozarisoy and Altan 2017; Lilley et al. 2017; Bright et al. 2019). Decisions are correlated to governmental support (Tam et al. 2016; Swantje et al. 2015) and peer information (Friege et al. 2016; Friege 2016).

The intervention is required to be cost efficient, although value could be placed in the amount of energy saved (Mortensen et al. 2016; Howarth and Roberts 2018; Kim et al. 2019; Lilley et al. 2017) or the short payback period (Miezis et al. 2016). Subsidies have a positive effect (Swan et al. 2017).

9.5.3.2 Adoption of efficient HVAC systems and appliances

Mixed willingness is found to adopt efficient technologies. While developed countries are positive towards building envelope technologies, appliances such as A-rated equipment or condensing boilers are negatively perceived (Yohanis 2012). In contrast, adopters in Asia are positive towards energy saving appliances (Liao et al. 2020; Spandagos et al. 2020).

Comfort, economic and ecological aspects, as well as information influence the purchase of a heating system (Decker and Menrad 2015; Claudy et al. 2011). Information and support from different stakeholders are the most relevant aspects in different geographical contexts (Tumbaz and Moğulkoç 2018; Hernandez-Roman et al. 2017; Curtis et al. 2018; Bright et al. 2019; Chu and Wang 2019).

Among high-income countries, economy aspects have positive effects, specially reductions in energy bills and financial incentives or subsidies (Mortensen et al. 2016; Clancy et al. 2017; Christidou et al. 2014; Chun and Jiang 2013; Ketchman et al. 2018). Having complementary technologies already in place also has positively affects adoption (Zografakis et al. 2012; Clancy et al. 2017), but performance and maintenance concerns appear as barriers (Qiu et al. 2014). The solutions are positively perceived as high-technology innovative, to enhance status, and are supported by peers and own-environmental values (Ketchman et al. 2018; Mortensen et al. 2016; Heiskanen and Matschoss 2017).

9.5.3.3 Installation of renewable energy sources (RES)

Although consumers are willing to install distributed RES worldwide, and information has successfully supported their roll out, economic and governmental support is still necessary for their full deployment. Technical issues remain for either very novel technologies or for the integration of RES in the energy system (Mata et al. 2021c; Ürge-Vorsatz et al. 2020). Capacities are to be built by coordinated actions by all stakeholders (Musonye et al. 2020). To this aim, energy communities and demonstrative interventions at local scale are key to address technical, financial, regulatory and structural barriers and document long-term benefits (von Wirth et al. 2018; Shafique M Luo J 2020, Fouladvand et al. 2020).

Regarding solar technologies, heterogeneous decisions are formed by sociodemographic, economic and technical predictors interwoven with a variety of behavioural traits (Alipour M Salim RA Sahin, O 2020; Khan 2020). Studies on PV adoption confirm place-specific (various spatial and peer effects), multi-scalar cultural dynamics (Schaffer and Brun 2015; Bollinger and Gillingham 2012; Graziano and Gillingham 2015). Environmental concern and technophilia drive the earliest PV adopters , while later adopters value economic gains (Hampton and Eckermann 2013; Jager-Waldau et al. 2018; Abreu et al. 2019; Palm 2020). Previous experience with similar solutions increases adoption (Bach et al. 2020; K 2018; QURAISHI and AHMED 2019; Reindl and Palm 2020).

9.5.3.4 Low-carbon materials

Studies on low-carbon materials tend to focus on wood-based building systems and prefabricated housing construction, mostly in high-income countries, as many sustainable managed forestries and factories for prefabricated housing concentrated in such regions (Mata el al, 2021c). This uneven promotion of wood can lead to its overconsumption (Pomponi et al. 2020).

Although the solutions are not yet implemented at scale, examples include , the adoption of low carbon cement in Cuba motivated by the possibility of supplying the raising demand with low initial investment costs (Cancio Díaz et al. 2017) or adoption of bamboo based social houses in Philippines motivated by local job creation and Typhoon resistance (Zea Escamilla et al. 2016). More generally, low investment costs and high level decision-making, e.g. political will and environmental values of society, increase the adoption rate of low-carbon materials (Steinhardt and Manley 2016; Lien and Lolli 2019; Hertwich et al. 2020). In contrast, observed barriers include lobbying by traditional materials industries, short-term political decision making (Tozer 2019) and concerns over technical performance, risk of damage, and limited alternatives available (Thomas et al. 2014).

9.5.3.5 Digitalization and demand-supply flexibility

Demand-supply flexibility measures are experimentally being adopted in North America, Europe, and Asia-Pacific Developed regions. Changes in the current regulatory framework would facilitate participation based on trust and transparent communication (Wolsink 2012; Nyborg and Røpke 2013; Mata et al. 2020b). However, consumers expect governments and energy utilities to steer the transition (Seidl et al. 2019).

Economic challenges are observed, as unclear business models, disadvantageous market models and high costs of advanced smart metering. Technical challenges include constraints for HPs and seasonality of space heating demands. Social challenges relate to lack of awareness of real-time price information and inadequate technical understanding. Consumers lack acceptance towards comfort changes (noise, overnight heating) and increased automation (Sweetnam et al. 2019; Bradley et al. 2016; Drysdale et al. 2015). Risks identified include higher peaks and congestions in low price-hours, difficulties in designing electricity tariffs because of conflicts with CO_2 intensity, and potential instability in the entire electricity system caused by tariffs coupling to wholesale electricity pricing.

Emerging market players are changing customer utility relationships, as the grid is challenged with intermittent loads and integration needs for ICTs, interfering with consumers requirements of autonomy and privacy (Parag and Sovacool 2016; Wolsink 2012). Although most private PV owners would make their storage system available as balancing load for the grid operator, the acquisition of new batteries by a majority of consumers requires incentives (Gährs et al. 2015). For distributed energy hubs, social acceptance depends on the amount of local benefits in economic, environmental or social terms (Kalkbrenner and Roosen 2015), and increases around demonstration projects (von Wirth et al. 2018).

9.5.3.6 Circular and sharing economy

The circular and sharing economy begins to be perceived as organizational and technologically innovative, with the potential to provide superior customer value, response to societal trends and positive marketing (Mercado 2018; Cantzler et al. 2020; L.K et al. 2020). Although technical and regulatory challenges remain, there are key difficulties around the demonstration of a business case for both consumers and the supply chain (Pomponi and Moncaster 2017; Hart et al. 2019).

Government support is needed an initiator but also to reinforce building retrofit targets, promote more stringent energy and material standards for new constructions, and protect consumer interests (Hongping 2017; Fischer and Pascucci 2017; Patwa et al. 2020). Taxes clearly incentivize waste reduction and recycling (Ajayi et al. 2015; Rachel and Travis 2011; Volk et al. 2019). In developing countries, broader, international, market boundaries can allow for a more attractive business model (Mohit et al. 2020). Participative and new ownership models can favour the adoption of prefabricated buildings (Steinhardt and Manley 2016). Needs for improvements are observed, in terms of design for flexibility and deconstruction, procurement and prefabrication and off-site construction, standardization and dimensional coordination, with differences among solutions (Ajayi et al. 2017)(Schiller et al, 2015,2017; Osmani, 2012; Lu and Yuan, 2013; Cossu and Williams, 2015; Bakshan et al 2017; Coehlo et al 2013).

Although training is a basic requirement, attitude, past experience, and social pressure can also be highly relevant, as illustrated for waste management in a survey to construction site workers (Amal et al. 2017). Traditional community practices of reuse of building elements are observed to be replaced by a culture of waste (Hongping 2017; Ajayi et al. 2015).

9.6 Global and regional mitigation potentials and costs

9.6.1 Review of literature calculating potentials for different world countries

Section 9.4 provides an update on technological options and practices, which allow constructing and retrofitting individual buildings to produce very low emissions during their operation phase. Since AR5, the world has seen a growing number of such buildings in all populated continents, and a growing amount of literature calculates the mitigation potential for different countries if such technologies and practices penetrate at scale. Figure 9.15 synthesizes the results of sixty-seven bottom-up studies, which rely on the bottom-up technology-reach approach and assess the potential of such technologies and practices, aggregated to stock of corresponding products and/or buildings at national level.

The studies presented in Figure 9.15 rely on all, the combination, or either of the following mitigation strategies: the construction of new high energy-performance buildings taking the advantage of building design, forms, and passive construction methods; the thermal efficiency improvement of building envelopes of the existing stock; the installation of advanced HVAC systems, equipment and appliances; the exchange of lights, appliances, and office equipment, including ICT, water heating, and cooking with their efficient options; demand side management, most often controlling comfort requirements and demand-side flexibility and digitalization; as well as onsite production and use of renewable energy. Nearly all studies, which assess the technological potential assume such usage of space heating, cooling, water heating, and lighting that does not exceed health, living, and working standards, thus realizing at least a part of the non-technological potential, as presented in Figure 9.14. The results presented in Figure 9.15 relate to measures applied within the boundaries of the building sector, including the reduction in direct and indirect emissions. The results exclude the impact of decarbonisation measures applied within the boundaries of the energy supply sector, i.e., the decarbonisation of grid electricity and district heat.

The analysis of Figure 9.15 illustrates that there is a large body of literature attesting to mitigation potential in the countries of Europe and North America of up to 55-85% and in Asia-Pacific Developed of up to 45% in 2050, as compared to their sector baseline emissions, even though they sometimes decline. For developing countries, the literature estimates the potential of up to 40-80% in 2050, as compared to their sharply growing baselines. The interpretation of these estimates should be cautious because the studies rely on assumptions with uncertainties and feasibility constrains (see Sections 9.6.4, Figure 9.20 and Table SM9.6).

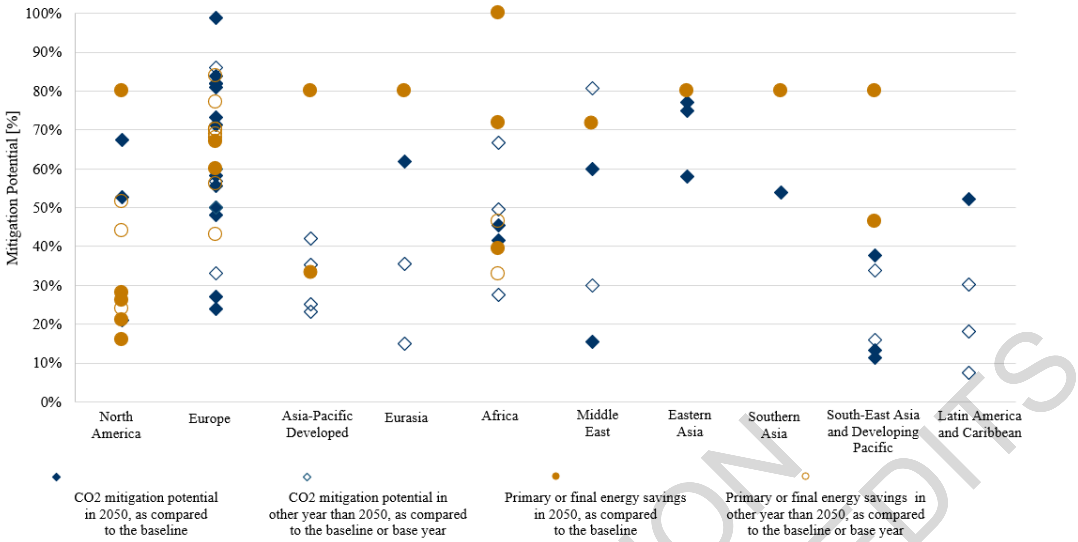


Figure 9.15 Potential GHG emission reduction in buildings of different world countries grouped by region, as reported by sixty-seven bottom-up studies

Sources: North America: Canada (Radpour et al. 2017; Subramanyam et al. 2017a,b; Trottier 2016; Zhang et al. 2020a), the Unites States of America (Gagnon, Peter, Margolis, Robert, Melius, Jennifer, Phillips, Saleb, Elmore 2016; Nadel 2016; Yeh et al. 2016; Zhang et al. 2020a; Wilson et al. 2017); Europe: Albania (Novikova et al. 2020, 2018c), Austria (Ploss et al. 2017), Bulgaria, the Czech Republic, Hungary (Csoknyai et al. 2016), France (Ostermeyer, Y.; Camarasa, C.; Saraf, S.; Naegeli, C.; Jakob, M.; Palacios, A, Catenazzi 2018), the European Union (Roscini et al. 2020; Brugger et al. 2021; Duscha et al. 2019), Germany (Markewitz et al. 2015; Bürger et al. 2019; Ostermeyer et al. 2019b), Greece (Mirasgedis et al. 2017), Italy (Calise et al. 2021; Filippi Oberegger et al. 2020), Lithuania (Toleikyte et al. 2018), Montenegro (Novikova et al. 2018c), Netherlands (Ostermeyer et al. 2018a), Norway (Sandberg et al. 2021), Serbia (Novikova et al. 2018a), Switzerland (Iten et al. 2017; Streicher et al. 2017), Poland (Ostermeyer et al. 2019a), the United Kingdom (Ostermeyer, Y.; Camarasa, C.; Naegeli, C.; Saraf, S.; Jakob, M.; Hamilton, I; Catenazzi 2018a); Eurasia: Armenia, Georgia (Timilsina et al. 2016); the Russian Federation (Bashmakov 2017; Zhang et al. 2020a); Asia-Pacific Developed: Australia (Butler et al. 2020; Energetics 2016; Zhang et al. 2020a), Japan (Zhang et al. 2020a; Momonoki et al. 2017; Wakiyama and Kuramochi 2017; Sugyiama et al. 2020; Minami et al. 2019); Africa: Egypt (Pedzi Makumbe, Manuela Mot, Marwa Moustafa Khalil 2017; Calise et al. 2021), Morocco (Merini et al. 2020), Nigeria (Dioha et al. 2019; Kwag et al. 2019; Onyenokporo and Ochedi 2019), Rwanda (Colenbrander et al. 2019), South Africa (Department of Environmental Affairs 2014), Uganda (de la Rue du Can et al. 2018), Algeria, Egypt, Libya, Morocco, Sudan, Tunisia (Krarti 2019); Middle East - Qatar (Krarti et al. 2017; Kamal et al. 2019), Saudi Arabia (Khan et al. 2017; Alaidroos and Krarti 2015), Bahrain, Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, State of Palestine, Syrian Arab Republic, United Arab Emirates, Yemen (Krarti 2019); Eastern Asia - China (Tan et al. 2018; Xing et al. 2021; Zhou et al. 2018; Zhang et al. 2020); Southern Asia: India (de la Rue du Can et al. 2019; Yu et al. 2018; Zhang et al. 2020); South-East Asia and Developing Pacific: Indonesia (Kusumadewi and Limmeechokchai 2015, 2017), Thailand (Kusumadewi and Limmeechokchai 2015, 2017; Chaichaloempreecha et al. 2017), Viet Nam (ADB 2017), respective countries from the Asia-Pacific Economic Cooperation (APEC) (Zhang et al. 2020a); Latin America and Caribbean: Brazil (de Melo and de Martino Jannuzzi 2015; González-Mahecha et al. 2019), Colombia (Prada-hernández et al. 2015), Mexico (Grande-acosta and Islas-samperio 2020; Rosas-Flores and Rosas-Flores 2020).

The novelty since AR5 is emerging bottom-up literature, which attempts to account for potential at national and global level from applying the sufficiency approach (see Box 9.1 in Section 9.1and decomposition analysis in Section 9.3.2). In spite of the reducing energy use per unit of floor area at an average rate of 1.3% per year, the growth of floor area at an average rate of 3% per year causes rising energy demand and GHG emissions because each new square meter must be served with thermal comfort and/or other amenities (International Energy Agency 2017; Ellsworth-Krebs 2020). Nearly all studies reviewed in Figure 9.15 assume the further growth of floor area per capita until 2050, with many studies of developing countries targeting today per capita floor area as in Europe.

Table 9.4 reviews the bottom-up literature, which quantifies the potential from reorganization of human activities, efficient design, planning, and use of building space, higher density of building and settlement inhabitancy, redefining and downsizing goods and equipment, limiting their use to health, living, and working standards, and their sharing, recognizing the number of square meters and devices as a determinant of GHG emissions that could be impacted via policies and measures. Nearly all national or regional studies originate from Europe and North America recognizing challenges, developed countries face toward decarbonisation. Thus, (Goldstein et al. 2020) suggested prioritizing the reduction in floor space of wealthier population and more efficient space planning because grid decarbonisation is not enough to meet the U.S. target by 2050 whereas affluent suburbs may have 15 times higher emission footprints than nearby neighbourhoods. (Cabrera Serrenho et al. 2019) argue that reducing the UK floor area is a low cost mitigation option given a low building replacement rate and unreasonably high retrofit costs of existing buildings. (Lorek and Spangenberg 2019) discusses the opportunity of reducing building emissions in Germany fitting better the structure of the dwelling stock to the declined average household size, as most dwellings have 3–4 rooms while most households have only one person.

Whereas these studies suggest sufficiency as an important option for developed countries, global studies argue that it is also important for the developing world. This is because it provides the means to address inequality, poverty reduction and social inclusion, ensuring the provision of acceptable living standards for the entire global population given the planetary boundaries. As Figure 9.6 illustrates, the largest share of current construction occurs in developing countries, while these countries follow a similar demographic track of declining household sizes versus increasing dwelling areas. This trajectory translates into the importance of their awareness of the likely similar forthcoming challenges, and the need in early efficient planning of infrastructure and buildings with a focus on space usage and density.

Table 9.4 Potential GHG emission reduction in the building sector offered by the introduction of sufficiency as a main or additional measure, as reported by bottom-up (or hybrid) literature

Region	Reference	Scenario and its result	Sufficiency for floor space
Globe	(Grubler et al. 2018)	The Low Energy Demand Scenario halves the final energy demand of buildings by 2050, as compared the WEO Current Policy (International Energy Agency 2019c) by modelling the changes in quantity, types, and energy intensity of services.	The scenario assumed a reduction in the residential and non-residential building floor area to 29 and 11 $m^2 \cdot cap^{-1}$ respectively.
Globe	(Millward-Hopkins et al. 2020)	With the changes in structural and technological intensity, the Decent Living Energy scenario achieved the decent living standard for all whilst reducing the final energy consumption of buildings by factor three, as compared to the WEO Current Policy Scenario (International Energy Agency 2019c).	The scenario assumed a reduction in floor area to 15 $m^2 \cdot cap^{-1}$ across the world.
Globe	(Levesque et al. 2019)	Realizing both the technological and sufficiency potential, the Low Demand Scenario and the Very Low Demand Scenario calculated a reduction in global building energy demand by 32% and 45% in 2050, as compared to the business-as-usual baseline.	The Low Scenario limited the residential and non-residential floor area to 70 and 23 $m^2 \cdot cap^{-1}$; the Very Low Scenario - to 45 and 15 $m^2 \cdot cap^{-1}$.
EU	(Bierwirth and Thomas 2019b)	For the EU residential sector, the authors calculated potential energy savings of 17% and 29% from setting the per capita floor area limits.	A reduction of the residential floor area to 30 $m^2 \cdot cap^{-1}$ and 35 $m^2 \cdot cap^{-1}$., respectively.
EU	(Roscini et al. 2020)	With help of technological and non-technological measures, the Responsible Policy Scenario for the EU buildings allows achieving the emission reduction by 60% in 2030, as compared to 2015.	The scenario assumed 6% decrease in the residential per capita floor area (to max. 44.8 $m^2 \cdot cap^{-1}$).
Canada, UK,	(Hertwich et al. 2020)	The potential reduction in GHG emissions from the production of building materials is 56%-58% in 2050, as compared to these	Via the efficient use of living space, the scenario assumed its 20%

France, Italy, Japan, USA, Germany		baseline emissions. The reduction in heating and cooling energy demand is 9%-10% in 2050, as compared to its baseline.	reduction, as compared to its baseline development
UK	(Cabrera Serrenho et al. 2019)	The scenario found that the sufficiency measures allowed mitigating 30% of baseline emissions of the English building sector in 2050, without other additional measures.	The scenario assumed a 10% reduction in the current floor area per capita by 2050.
USA	(Goldstein et al. 2020)	The scenario calculated 16% GHG mitigation potential in 2050, as compared to the baseline, on the top of two other scenarios assuming building retrofits and grid decarbonization already delivering a 42% emission reduction.	The scenario assumed a 10% reduction in per capita floor area and higher penetration of onsite renewable energy.
Switzerland	(Roca-Puigròs et al. 2020)	The Green Lifestyle scenario allows achieving 48% energy savings by 2050, as compared to the baseline, due to sufficiency in the floor area among other measures.	The scenario assumed a reduction in residential floor area. from 47 to 41 $m^2 \cdot cap^{-1}$.
France	(Negawatt 2017)	The Negawatt scenario assumes that sufficiency behaviour becomes a mainstream across all sectors. In 2050, the final energy savings are 21% and 28% for the residential and tertiary sectors respectively, as compared to their baselines.	The scenario assumes a limit of the residential floor at 42 $m^2 \cdot cap^{-1}$ due to apartment sharing and compact urban planning.
France	(Virage-Energie Nord-Pas-de-Calais. 2016)	The authors assessed sufficiency opportunities across all sectors for the Nord-Pas-de-Calais Region of France. Depending on the level of implementation, sufficiency could reduce the energy consumption of residential and tertiary buildings by 13-30% in 2050, as compared to the baseline.	The scenario assumed sharing spaces, downsizing spaces and sharing equipment from a 'soft' to 'radical' degree.

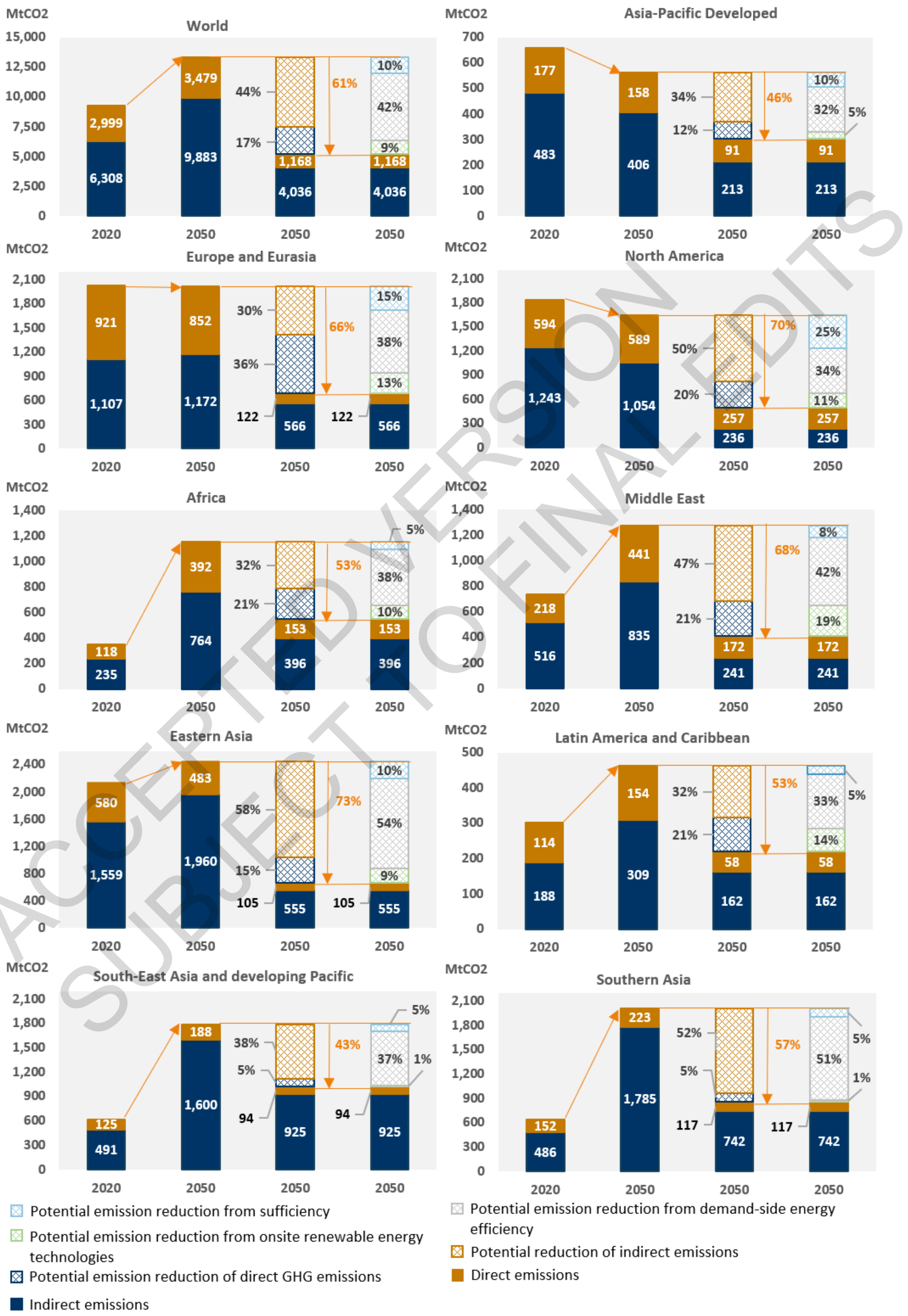
9.6.2 Assessment of the potentials at regional and global level

This section presents an aggregation of bottom-up potential estimates for different countries into regional and then global figures for 2050, based on literature presented in Section 9.6.1. First, national potential estimates reported as a share of baseline emissions in 2050 were aggregated into regional potential estimates. Second, the latter were multiplied with regional baseline emissions to calculate the regional potential in absolute numbers. Third, the global potential in absolute numbers was calculated as a sum of regional absolute potentials. When several bottom-studies were identified for a region, either a rounded average or a rounded median figure was taken, giving the preference to the one that was closest to the potential estimates of countries with very large contribution to regional baseline emissions in 2050 (i.e., to China in Eastern Asia). Furthermore, we preferred studies, which assessed the whole or a large share of sector emissions and considered a comprehensive set of measures. The regional baseline emissions, refer the WEO Current Policy Scenario (International Energy Agency 2019c). The sector mitigation potential reported in Chapter 12 for the year 2030 was estimated in the same manner.

Figure 9.16 presents the mitigation potential in the building sector for the world and each region in 2050, estimated as a result of this aggregation exercise. The potentials presented in the figure are different from those reported in Section 9.3.3, where they are estimated by IEA and IMAGE hybrid model. The figure provides two breakdowns of the potential, into the reduction of direct and indirect emissions as well as into the reduction of emissions from introducing sufficiency, energy efficiency, and renewable energy measures. The potential estimates rely on the incremental stepwise approach, assembling the measures according to the SER framework (see Box 9.1) and correcting the amount of the potential at each step for the interaction of measures. The sequence of energy efficiency and renewable energy measures follow the conclusion of the IPCC Global warming of 1.5°C Report (Rogelj et al. 2018) that lower energy demand allows more choice of low-carbon energy supply options, and therefore such sequencing is more beneficial and cost-effective.

Figure 9.16 argues that it is possible to mitigate 8.2 $GtCO_2$ or 61% of global building emissions in 2050, as compared to their baseline. At least 1.4 $GtCO_2$ or 10% of baseline emissions could be avoided introducing the sufficiency approaches. Further 5.6 $GtCO_2$ or 42% of baseline emissions could be mitigated with the help of energy efficiency technologies and practices. Finally, at least 1.1 $GtCO_2$ or 9% of baseline emissions could be reduced through the production and use of onsite renewable energy.

Out of the total potential, the largest share of 5.4 $GtCO_2$ will be available in developing countries; these countries will be able to reduce 59% of their baseline emissions. Developed countries will be able to mitigate 2.7 $GtCO_2$ or 65% of their baseline emissions. Only few potential studies, often with only few mitigation options assessed, were available for the countries of South-East Asia and Developing Pacific, Africa, and Latin America and Caribbean; therefore, the potential estimates represent low estimates, and the real potentials are likely be higher.



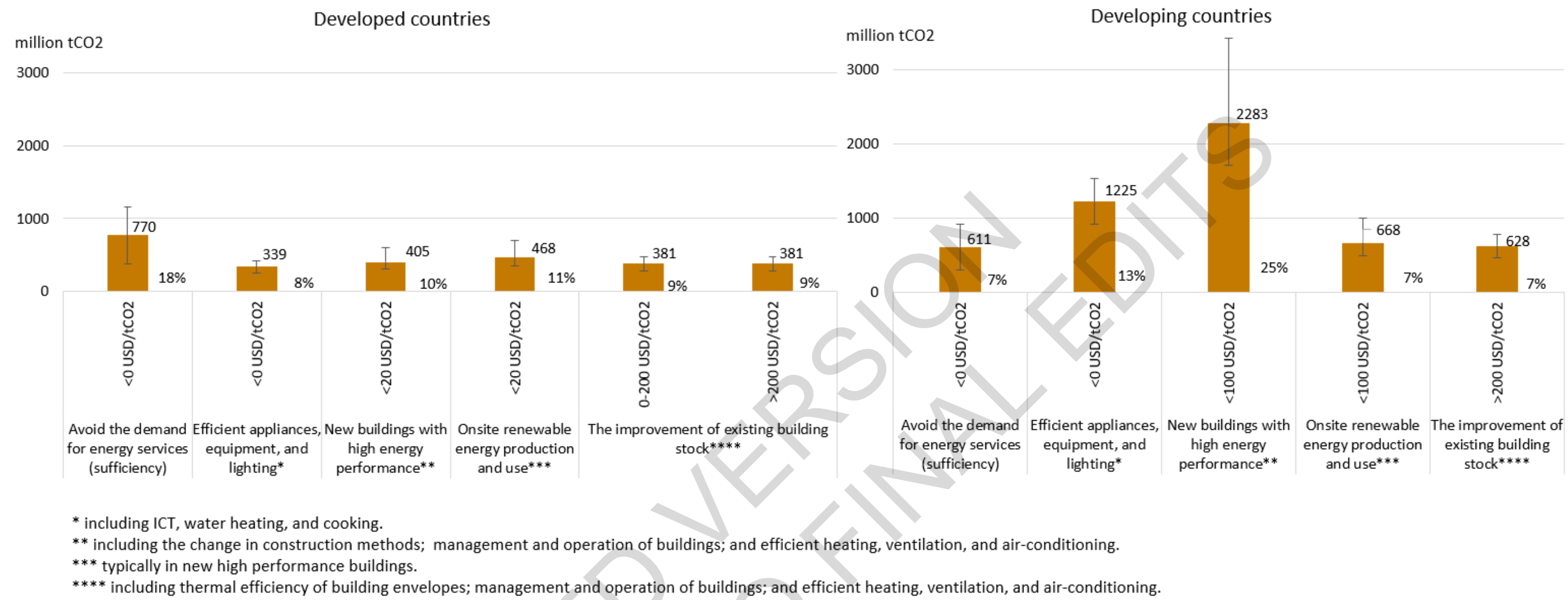
Note: the baseline refers to the WEO Current Policy Scenario (International Energy Agency 2019c). It may differ from other chapters.

Figure 9.16 Global and regional estimates of GHG emissions in the building sector in 2020 and 2050, and their potential reduction in 2050 broken down by measure (sufficiency / energy efficiency / renewable energy) and by emission source (direct / indirect)

9.6.3 Assessment of the potential costs

The novelty since AR5 is that a growing number of bottom-up studies considers the measures as an integrated package recognising their technological complementarity and interdependence, rather than the linear process of designing and constructing buildings and their systems, or incremental improvements of individual building components and energy-using devices during building retrofits, losing opportunities for the optimisation of whole buildings. Therefore, integrated measures rather than the individual measures are considered for the estimates of costs and potentials. Figure 9.17 presents the indicative breakdown of the potential reported in Figure 9.16 by measure and cost, to the extent that it was possible to disaggregate and align to common characteristics. Whereas the breakdown per measure was solely based on the literature reviewed in Section 9.6.1, the cost estimates additionally relied on the literature presented in this section, Figure 9.20, and Table SM9.6. The literature reviewed reports fragmented and sometimes contradicting cost-effectiveness information. Despite a large number of exemplary buildings achieving very high performance in all parts of the world, there is a lack of mainstream literature or official studies assessing the costs of these buildings at scale (Lovins 2018; Ürge-Vorsatz et al. 2020).

Figure 9.17 indicates that a very large share of the potential in developed countries could be realized through the introduction of sufficiency measures (at least 18% of their baseline emissions). Literature identifies many opportunities, which may help operationalize it. These are reorganization of human activities, teleworking, coworking, more efficient space design, planning and use, higher density of building and settlement inhabitancy, flexible space, housing swaps, shared homes and facilities, space and room renting, and others (Bierwirth and Thomas 2019a; Ivanova and Büchs 2020; Ellsworth-Krebs 2020). Whereas literature does not provide a robust cost assessment of the sufficiency potential, it indicates that these measures are likely to be at no or very little cost (Cabrera Serrenho et al. 2019).



Notes: 1. The baseline refers to the WEO Current Policy Scenario (International Energy Agency 2019c). It may differ from other chapters. 2. The figure merged the results of Eurasia into those of developed countries.

Figure 9.17 Indicative breakdown of GHG emission reduction potential of the buildings sector in developed and developing countries into measure and costs in 2050, in absolute figures with uncertainty ranges and as a share of their baseline emissions

The exchange of lights, appliances, and office equipment, including ICT, water heating, and cooking technologies could reduce more than 8% and 13% of the total sector baseline emissions in developed and developing countries respectively, typically at negative cost (González-Mahecha et al. 2019; Grande-Acosta and Islas-Samperio 2020; de Melo and de Martino Jannuzzi 2015; Prada-hernández et al. 2015; Subramanyam et al. 2017a,b; Department of Environmental Affairs 2014). This cost-effectiveness is however often reduced by a larger size of appliances and advanced features, which offset a share of positive economic effects (Molenbroek et al. 2015).

Advanced HVAC technologies backed-up with demand side management, and onsite integrated renewables backed-up with demand-side flexibility and digitalization measures are typically a part of the retrofit or construction strategy. Among HVAC technologies, heat pumps are very often modelled to become a central heating and cooling technology supplied with renewable electricity. The estimates of HVAC cost-effectiveness, including heat pumps, varies in modelling results from very cost-effective to medium (Hirvonen et al. 2020; Akander et al. 2017; Prada-hernández et al. 2015; Department of Environmental Affairs 2014). Among demand side management, demand-side flexibility and digitalization options, various sensors, controls, and energy consumption feedback devices have typically negative costs, whereas advanced smart management systems as well as thermal and electric storages linked to fluctuating renewables are not yet cost-effective (Uchman 2021; Duman et al. 2021; Nguyen et al. 2015; Huang et al. 2019; Sharda et al. 2021; Rashid et al. 2021; Prada-hernández et al. 2015). Several developed countries achieved to make onsite renewable energy production and use profitable for at least a part of the building stock (Fina et al. 2020; Vimpari and Junnila 2019; Akander et al. 2017; Horváth et al. 2016), but this is not yet the case for developing countries (Cruz et al. 2020; Grande-acosta and Islas-samperio 2020; Kwag et al. 2019). Due to characteristics and parameters of different building types, accommodating the cost-optimal renewables at large scale is especially difficult in non-residential buildings and in urban areas, as compared to residential buildings and rural areas (Fina et al. 2020; Horváth et al. 2016).

Literature agrees that new advanced buildings, using design, form, and passive building construction equipped with demand side measures, and advanced HVAC technologies can reduce the sector total baseline emissions in developed and developing countries by at least 10% and 25% in 2050, respectively, and renewable energy technologies backed-up with demand-side flexibility and digitalization measures typically installed in new buildings could further reduce these emissions by at least 11% and 7% (see also Cross-Chapter Box 12 in Chapter 16). The literature however provides different and sometimes conflicting information of their cost-effectiveness. (Esser et al. 2019) reported that by 2016, the perceived share of buildings similar or close to nZEB in the new construction was just above 20% across the EU. In this region, additional investment costs were no higher than 15%, as reported for Germany, Italy, Denmark, and Slovenia (Erhorn-Kluttig et al. 2019). Still the European market experiences challenges which relate to capacity and readiness, as revealed by (Architects' Council of Europe (ACE) 2019) recording a decline in the share of architects who are designing buildings to nZEB standards to more than 50% of their time, from 14% in 2016 to 11% in 2018. In contrast, the APEC countries reported additional investment costs of 67% on average (Xu and Zhang 2017) that makes them a key barrier to the nZEB penetration in developing countries as of today (Feng et al. 2019). This calls for additional R&D policies and financial incentives to reduce the nZEB costs (Xu and Zhang 2017; Kwag et al. 2019).

Thermal efficiency retrofits of existing envelopes followed up by the exchange of HVAC backed up with demand side measures could reduce the sector total baseline emissions in developed and developing countries by at least 18% and 7% respectively in 2050. There have been many individual examples of deep building retrofits, which incremental costs are not significantly higher than those of shallow retrofits. However, literature tends to agree that cost-effective or low cost deep retrofits are not universally applicable for all cases, especially in historic urban areas, indicating a large share of the potential in the high-cost category (Mata et al. 2019; Semprini et al. 2017; Paduos and Corrado 2017; Subramanyam et al. 2017b; Department of Environmental Affairs 2014; Streicher et al. 2017; Akander et al. 2017). Achieving deep retrofits assumes additional measures on the top of business-as-usual retrofits, therefore high rate of deep retrofits at acceptable costs are not possible in case of low business-as-usual rates (Streicher et al. 2020).

For a few studies, which conducted an assessment of the sector transformation aiming at emission reduction of 50–80% in 2050 versus their baseline, the incremental investment need over the modelling period is estimated at 0.4–3.3% of the country annual GDP of the scenario first year (Kotzur et al. 2020; Novikova et al. 2018c; Bashmakov 2017; Markewitz et al. 2015). These estimates represent strictly the incremental share of capital expenditure and sometimes installation costs. Therefore, these figures are not comparable with investment tracked against the regional or national sustainable finance taxonomies, as recently developed in the EU (European Parliament and the Council 2020), Russia (Government of Russian Federation 2021), South Africa (National Treasury of Republic of South Africa 2021), and others, or the growing literature on calculating the recent finance flows (Macquarie et al. 2020; Hainaut et al. 2021; Novikova et al. 2019; Valentova et al. 2019; Kamenders et al. 2019), because they are measured against other methodologies, which are not comparable with the methodologies used to derive the incremental costs by integrated assessment models and bottom-up studies. Therefore, the gap between the investment need and recent investment flows is likely to be higher, than often reported.

9.6.4 Determinants of the potentials and costs

That fact that the largest share of the global flow area is still to be built offers a large potential for emission reduction that is however only feasible if ambitious building energy codes will be applied to this new stock (see Section 9.9.3 on building codes). The highest demand for additional floor area will occur in developing countries; the building replacement is also the highest in developing countries because their building lifetime could be as short as 30 years (Lixuan et al. 2016; Alaidroos and Krarti 2015). Whereas as of 2018, 73 countries had already had building codes or were developing them, only 41 had mandatory residential codes and 51 had mandatory non-residential codes (Global Alliance for Buildings and Construction 2019). Therefore, the feasibility of capturing this potential is a subject to greater coverage, adoption, and strength of building codes.

Low rates of building retrofits are the major feasibility constrain of building decarbonization in developed countries. Long building lifetime and their slow replacement caused a lock-in of low energy performance in old buildings of developed countries, especially in urban areas. A few studies of developing countries, mostly medium and high-income, also considered building retrofits (Yu et al. 2018b; Zhou et al. 2018; Krarti 2019; Kamal et al. 2019; Prada-hernández et al. 2015). The studies in developed countries tend to rely on either of the strategies: very “deep” envelope retrofits followed by the exchange of HVAC with various advanced alternatives (Novikova et al. 2018c,b; Csoknyai et al. 2016; Filippi Oberegger et al. 2020; Duscha et al. 2019) or more shallow retrofits followed by switching to low-carbon district heating or by the exchange of current HVAC with heat pumps linked to onsite renewables backed up energy storages (Kotzur et al. 2020; Hirvonen et al. 2020; Yeh et al. 2016). The factors, which impact the feasibility of these strategies therefore are the building retrofit rates and replacement rates of building systems. To achieve the building stock decarbonization by 2050, most studies reviewed in Figure 9.16 assume “deep” retrofit rates between 2.5% and 5%, and even 10% per annum. (Esser et al. 2019) reported that the annual renovation rate in EU28 is around 0.2%, with relatively small variation across individual EU member states. (Sandberg et al. 2016) simulated retrofit rates in eleven European countries and concluded that only minor future increases in the renovation rates of 0.6–1.6% could be expected. Therefore, without strong policies supporting these renovations, the feasibility to achieve such high “deep” retrofit rates is low.

Among key factors affecting the costs-effectiveness of achieving high-performance buildings remain low energy prices in many countries worldwide (Alaidroos and Krarti 2015; Akander et al. 2017) and high discount rates reflecting low access to capital and high barriers. (Copiello et al. 2017) found that the discount rate affects the economic results of retrofits four times higher than the energy price, and therefore the reduction in upfront costs and working out barriers are the feasibility enablers.

The good news is that literature expects a significant cost reduction for many technologies, which are relevant for the construction of high energy-performance buildings and deep retrofits. Applying a technology learning curve to the data available for Europe and reviewing dozens of studies available, (Köhler et al. 2018) estimated the cost reduction potential of biomass boilers, heat pumps, ventilation, air-conditioning, thermal storages, electricity storages, solar PVs and solar thermal systems of 14%, 20%, 46–52%, 29%, 29%, 65%, 57%, and 43% respectively in 2050; no significant cost reduction potential was found however for established and wide-spread insulation technologies. More investment into RDD to reduce the technology costs and more financial incentives to encourage uptake of the technologies would allow moving along this learning curve.

Furthermore, some literature argues that the key to cost-effectiveness is not necessarily a reduction in costs of technologies, but a know-how and skills of their choosing, combining, sequencing, and timing to take the most benefits of their interdependence, complementarity, and synergy as illustrated by many examples (Lovins 2018; Ürge-Vorsatz et al. 2020). However, the scenarios reviewed lack such approaches in their cost assessments. Few indicative examples of cost reduction at scale were provided though not by the scenario literature, but case studies of the application of One-Stop Shop (OSS) approach at scale (see Section 9.9.4). In 2013, the Dutch Energiesprong network brokered a deal between Dutch building contractors and housing associations to reduce the average retrofit costs from EUR 130,000 down to 65,000 for 111,000 homes with building prefabrication systems and project delivery models while targeting energy savings of 45–80% (Ürge-Vorsatz et al. 2020); out of which 10,000 retrofits have been realized by 2020. The French Observatory of Low Energy Buildings reported to achieve the cost-effective deep renovations of 818 dwellings and 27 detached houses in France setting a cap for absolute primary energy consumption to achieve after renovation and a cap for the budget to deliver it; the cost-effectiveness was however calculated with grants and public subsidies (Saheb 2018).

Literature emphasizes the critical role of the time between in 2020 and 2030 for the building sector decarbonisation (IEA 2020a; Roscini et al. 2020). To set the sector at the pathway to realize its whole mitigation potential, it is critical to exponentially accelerate the learning of this know-how and skills to reduce the costs and remove feasibility constrains to enable the penetration of advanced technologies at speed that the world has not seen before. The World Energy Outlook (IEA 2020a) portraited in the Net Zero Emissions by 2050 Scenario (see Box 9.2) the challenges and commitments the sector will have to address by 2030. These include bringing new buildings and existing buildings to near zero, with a half of existing buildings in developed countries and a third of existing buildings in developing countries being retrofitted by 2030. These also mean banning the sale of new fossil fuel-fired boilers, as well as making heat pumps and very efficient appliances standard technologies. The Net Zero Emissions by 2050 Scenario achieves almost fully to decarbonize the sector by 2050, with such commitments reflected neither in the planning and modelling efforts (Section 9.9) nor in policies and commitments (Section 9.9) of most world countries, with the countries of South-East Asia and Developing Pacific, Southern Asia, Africa, and Latin America and Caribbean having the least research.

As discussed in Section 9.6.1, the alternative and low-cost opportunity to reduce the sector emissions in the countries with high floor area per capita and the low stock turnover is offered by the introduction of the sufficiency approach. Section 9.9.3.1 discusses a range of policy instruments, which could support the realization of the sufficiency potential. As the approach is new, the literature does not yet report experiences of these measures. In the framework of project OptiWohn, the German cities of Göttingen, Köln und Tübingen just started testing the sufficiency approach and policy measures for sufficiency (Stadt Göttingen 2020). Therefore, the feasibility of realizing the sufficiency potential depends on its recognition by the energy and climate policy and the introduction of supporting measures

(Samadi et al. 2017; Ellsworth-Krebs 2020; Goldstein et al. 2020). More research is needed to understand which measures will work and which will not.

Similar to buildings, the energy consumption and associated emissions of appliances and equipment is driven by the replacement of old appliances and the additional stock due to the increase in penetration and saturation of appliances. The feasibility of appliance stock replacement with efficient options is higher than the feasibility of building stock replacement or retrofit due to their smaller size, shorter lifetime, and cheaper costs (Chu and Bowman 2006; Spiliotopoulos 2019). Some literature argues that once appliances achieve a particular level of efficiency their exchange does not bring benefits from the resource efficiency point of view (Hertwich et al. 2019). Even through the data records a permanent energy efficiency improvement of individual devices (Figure 9.12), their growing offsets energy savings delivered by this improvement. The emerging literature suggests addressing the growing number of energy services and devices as a part of climate and energy policy (Bierwirth and Thomas 2019b). Sections 9.5.2.2 describes measures for limiting demand for these services and Section 9.5.3.6 addresses reducing the number of technologies through their ownership and use patterns. (Grubler et al. 2018) also suggested redefining energy services and aggregating appliances, illustrating the reduction of energy demand by factor 30 to substitute over 15 different end-use devices with one integrated digital platform. More research is needed to understand opportunities to realize this sufficiency potential for appliances, and more research is needed to understand policies which may support these opportunities (Bierwirth and Thomas 2019a).

The difference between baselines is among the main reason for difference between the potential estimates in 2030 reported by Chapter 6 on buildings of AR4 (Levine et al. 2017) and the current section of AR6. For developed countries, the sector direct and indirect baseline emissions in AR6 are 43% and 28% lower than those in AR4 respectively. For developing countries, the sector direct baseline emissions in AR6 are 47% lower than those in AR4, and the sector indirect baseline emissions are 3% higher than those in AR4. As AR6 is closer to 2030 than AR4 and thus more precise, the likely reason for the difference (besides the fact that some potential was realized) is that AR4 overall overestimated the future baseline emissions, and it underestimated how quickly the fuel switch to electricity from other energy carriers has been happening, especially in developing countries. As illustrated, the baseline is one of determinant of the potential size and hence, all reported estimates shall only be interpreted together with the baseline developments.

The potential is a dynamic value, increasing with the technological progress. Most potential studies reviewed in Section 9.6.1 consider today mature commercialised or near to commercialisation technologies with demonstrated characteristics "freezing them" in the potential estimates until the study target year. Until 2050, many of these technologies will further improve, and furthermore new advanced technologies may emerge. Therefore, the potential estimates are likely to be low estimates of the real potential volumes. Furthermore, models apply many other assumptions and they cannot always capture right emerging societal or innovation trends; these trends may also significantly impact the potential size into both directions (Brugger et al. 2021).

With the declining amount of emissions during the building operation stage, the share of building embodied emissions in their lifetime emissions will grow, also due to additional building material (Peñaloza et al. 2018; Cabeza et al. 2021). Reviewing 650 life cycle assessment case studies, (Röck et al. 2020) estimated the contribution of embodied emissions to building lifetime emissions up to 45–50% for highly efficient buildings, surpassing 90% in extreme cases.

Recently, a significant body of research has been dedicated to studying the impacts of using bio-based solutions (especially timber) for building construction instead of conventional materials, such as concrete and steel, because more carbon is stored in bio-based construction materials than released during their manufacturing. Assuming the aggressive use of timber in mid-rise urban buildings, Churkina et al. (2020) estimated the associated mitigation potential between 0.04-3.7 $GtCO_2$ per year depending on how fast countries adopt new building practices and floor area per capita. Based on a simplified timber supply-demand model for timber-based new floor area globally by 2050, Pomponi et al. (2020) showed that the global supply of timber can only be 36% of the global demand for it between 2020 and 2050; especially much more forest areas will be required in Asian countries, such as China and India and American countries, such as the USA, Mexico, and Argentina. Goswein et al. (2021) conducted a similar detailed analysis for Europe and concluded that current European forest areas and wheat plantations are sufficient to provide timber and straw for the domestic construction sector.

The increased use of timber and other bio-based materials in buildings brings not only benefits, but also risks. The increased use of timber can accelerate degradation through poor management and the pressure for deforestation, as already recorded in the Amazon and Siberia forests, and the competition for land and resources (Brancalion et al. 2018; Carrasco et al. 2017; Hart and Pomponi 2020; Pomponi et al. 2020). Churkina et al. (2020) emphasized that promoting the use of more timber in buildings requires the parallel strengthening of legislation for sustainable forest management, forest certification instruments, and care for the people and social organizations that live in forests. In tropical and subtropical countries, the use of bamboo and other fibres brings more benefits and less risks than the use of timber (ibid). One of the main barriers associated with the use of bio-based materials in buildings is fire safety, although there is extensive research on this topic (Audebert et al. 2019; Östman et al. 2017). This is a particularly important criterion for the design of medium and high-rise buildings, which tend to be the most adequate typologies for denser and more compact cities. Overall, more robust models are needed to assess the interlinkages between the enhanced use of bio-based materials in the building stock and economic and social implications of their larger supply, as well as the associated competition between forest and land-use activities (for food), and ecological aspects. Furthermore, more research is required on how to change forest and building legislation and design a combination of policy instruments for the specific political, economic and cultural county characteristics (Hildebrandt et al. 2017). Benefits and risks of enhanced use of wood products in buildings are also discussed in Chapter 7, Section 7.4.5.3.

9.7 Links to adaptation

Buildings are capital-intensive and long-lasting assets designed to perform under a wide range of climate conditions (Hallegatte 2009; Pyke et al. 2012). Their long life span means that the building stock will be exposed to future climate (de Wilde and Coley 2012; Wan et al. 2012; Hallegatte 2009) and, as such, adaptation measures will be necessary.

The impacts of climate change on buildings can affect building structures, building construction, building material properties, indoor climate and building energy use (Andrić et al. 2019). Many of those impacts and their respective adaptation strategies interact with GHG mitigation in different ways.

9.7.1 Climate change impacts and adaptation in buildings

A large body of literature on climate impacts on buildings focuses on the impacts of climate change on heating and cooling needs (de Wilde and Coley 2012; Wan et al. 2012; Andrić et al. 2019). The associated impacts on energy consumption are expected to be higher in hot summer and warm winter climates, where cooling needs are more relevant (Li et al. 2012; Wan et al. 2012; Andrić et al. 2019). If not met, this higher demand for thermal comfort can impact health, sleep quality and work productivity, having disproportionate effects on vulnerable populations and exacerbating energy poverty (Falchetta and Mistry 2021; Biardeau et al. 2020; Sun et al. 2020) (see Section 9.8).

Increasing temperatures can lead to higher cooling needs and, therefore, energy consumption (Schaeffer et al. 2012; Clarke et al. 2018; International Energy Agency 2018; Wan et al. 2012; Li et al. 2012; Andrić et al. 2019). Higher temperatures increase the number of days/hours in which cooling is required and as outdoor temperatures increase, the cooling load to maintain the same indoor temperature will be higher (Andrić et al. 2019). These two effects are often measured by cooling degree-days[1] (CDD) and there is a vast literature on studies at the global (Atalla et al. 2018; Mistry 2019; Isaac and van Vuuren 2009; Biardeau et al. 2020; Clarke et al. 2018) and regional level (Bezerra et al. 2021; Zhou et al. 2014; Falchetta and Mistry 2021). Other studies use statistical econometric analyses to capture the empirical relationship between climate variables and energy consumption (Auffhammer and Mansur 2014; van Ruijven et al. 2019). A third effect is that higher summer temperatures can incentivize the purchase of space cooling equipment (Auffhammer 2014; De Cian et al. 2019; Biardeau et al. 2020), especially in developing countries (Pavanello et al. 2021).

The impacts of increased energy demand for cooling can have systemic repercussions (Ralston Fonseca et al. 2019; Ciscar and Dowling 2014), which in turn can affect the provision of other energy services. Space cooling can be an important determinant of peak demand, especially in periods of extreme heat (International Energy Agency 2018). Warmer climates and higher frequency and intensity of heat waves can lead to higher loads (Dirks et al. 2015; Auffhammer et al. 2017), increasing the risk of grid failure and supply interruptions.

Although heating demand in cold climate regions can be expected to decrease with climate change and, to a certain extent, outweigh the increase in cooling demand, the effects on total primary energy requirements are uncertain (Wan et al. 2012; Li et al. 2012). Studies have found that increases in buildings energy expenditures for cooling more than compensate the savings from lower heating demands in most regions (Clarke et al. 2018). In addition, climate change may affect the economic feasibility of district heating systems (Andrić et al. 2019).

In cold climates, a warming climate can potentially increase the risk of overheating in high-performance buildings with increased insulation and airtightness to reduce heat losses (Gupta and Gregg 2012). In such situations, the need for active cooling technologies may arise, along with higher energy consumption and GHG emissions (Gupta et al. 2015).

Changes in cloud formation can affect global solar irradiation and, therefore, the output of solar photovoltaic panels, possibly affecting on-site renewable energy production (Burnett et al. 2014). The efficiency of solar photovoltaic panels and their electrical components decreases with higher temperatures (Simioni and Schaeffer 2019) (Bahaidarah et al. 2013). However, studies have found that such effect can be relatively small (Totschnig et al. 2017), making solar PV a robust option to adapt to climate change (Shen and Lior 2016; Santos and Lucena 2021) (see Section 9.4).

Climate change can also affect the performance, durability and safety of buildings and their elements (facades, structure, etc.) through changes in temperature, humidity, wind, and chloride and CO_2 concentrations (Bastidas-Arteaga et al. 2010; Bauer et al. 2018; Rodríguez-Rosales et al. 2021; Chen et al. 2021). Historical buildings and coastal areas tend to be more vulnerable to these changes (Huijbregts et al. 2012; Mosoarca et al. 2019; Cavalagli et al. 2019; Rodríguez-Rosales et al. 2021).

Temperature variations affect the building envelope, e.g. with cracks and detachment of coatings (Bauer et al. 2016, 2018). Higher humidity (caused by wind-driven rain, snow or floods) hastens deterioration of bio-based materials such as wood and bamboo (Brambilla and Gasparri 2020), also deteriorating indoor air quality and users health (Grynning et al. 2017; Lee et al. 2020; Huijbregts et al. 2012).

Climate change can accelerate the degradation of reinforced concrete structures due to the increase of chloride ingress (Bastidas-Arteaga et al. 2010) and the concentration of CO_2, which increase the corrosion of the embedded steel (Stewart et al. 2012; Peng and Stewart 2016; Chen et al. 2021).

FOOTNOTE[1] CDD can be generally defined as the monthly or annual sum of the difference between an indoor set point temperature and outdoor air temperature whenever the latter is higher than a given threshold temperature (Mistry 2019).

Corrosion rates are higher in places with higher humidity and humidity fluctuations (Guo et al. 2019), and degradation could be faster with combined effects of higher temperatures and more frequent and intense precipitations (Bastidas-Arteaga et al. 2010; Chen et al. 2021).

Higher frequency and intensity of hurricanes, storm surges and coastal and non-coastal flooding can escalate economic losses to civil infrastructure, especially when associated with population growth and urbanization in hazardous areas (Bjarnadottir et al. 2011; Lee and Ellingwood 2017; Li et al. 2016). Climate change should increase the risk and exposure to damage from flood (de Ruig et al. 2019), sea level rise (Bove et al. 2020; Zanetti et al. 2016; Bosello and De Cian 2014) and more frequent wildfires (Craig et al. 2020; Barkhordarian et al. 2018).

9.7.2 Links between mitigation and adaptation in buildings

Adaptation options interacts with mitigation efforts because measures to cope with climate change impacts can increase energy and material consumption, which may lead to higher GHG emissions (Kalvelage et al. 2014; Davide et al. 2019; Sharifi 2020). Energy consumption is required to adapt to climate change. Mitigation measures, in turn, influence the degree of vulnerability of buildings to future climate and, thus, the adaptation required.

Studies have assessed the increases in energy demand to meet indoor thermal comfort under future climate (de Wilde and Coley 2012; Li et al. 2012; Andrić et al. 2019; Clarke et al. 2018). Higher cooling needs may induce increases in energy demand (Wan et al. 2012; Li et al. 2012), which could lead to higher emissions, when electricity is fossil-based (International Energy Agency 2018; Biardeau et al. 2020), and generate higher loads and stress on power systems (Auffhammer et al. 2017; Dirks et al. 2015). In this regard, increasing energy efficiency of space cooling appliances and adopting dynamic cooling setpoint temperatures, can reduce the energy needs for cooling and limit additional emissions and pressures on power systems (Davide et al. 2019; Bezerra et al. 2021) (Bienvenido-Huertas et al. 2020) (see Section 9.4, Figure 9.11 and Tables SM9.1 to SM9.3). This can also be achieved with on-site renewable energy production, especially solar PV for which there can be a timely correlation between power supply and cooling demand, improving load matching (Salom et al. 2014; Grove-Smith et al. 2018).

Mitigation alternatives through passive approaches may increase resilience to climate change impacts on thermal comfort and reduce active cooling needs (González Mahecha et al. 2020; Rosse Caldas et al. 2020; van Hooff et al. 2016; Wan et al. 2012; Andrić et al. 2019). Combining passive measures can help counteracting climate change driven increases in energy consumption for achieving thermal comfort (Huang and Hwang 2016).

Studies raise the concern that measures aimed at building envelope may increase the risk of overheating in a warming climate (Dodoo and Gustavsson 2016; Fosas et al. 2018) (see Section 9.4). If this is the case, there may be a conflict between mitigation through energy efficiency building regulations and climate change adaptation (Fosas et al. 2018). However, while overheating may occur as a result of poor insulation design, better insulation may actually reduce overheating when properly projected and the overheating risk can be overcome by clever designs (Fosas et al. 2018).

Strengthening building structures to increase resilience and reduce exposure to the risk of extreme events, such as draughts, torrential floods, hurricanes and storms, can be partially achieved by improving building standards and retrofitting existing buildings (Bjarnadottir et al. 2011). However, future climate is not yet considered in parameters of existing building energy codes (Steenbergen et al. 2012). While enhancing structural resilience would lead to GHG emissions (Liu and Cui 2018), so would disaster recovery and re-building. This adaptation-mitigation trade-off needs to be further assessed.

Since adaptation of the existing building stock may be more expensive and require building retrofit, climate change must be considered in the design of new buildings to ensure performance robustness in both current and future climates, which can have implications for construction costs (de Rubeis et al. 2020; Picard et al. 2020; Hallegatte 2009; Pyke et al. 2012; de Wilde and Coley 2012) and emissions (Liu and Cui 2018). Building energy codes and regulations are usually based on cost-effectiveness and historical climate data, which can lead to the poor design of thermal comfort in future climate (Hallegatte 2009; Pyke et al. 2012; de Wilde and Coley 2012) and non-efficient active adaptive measures based on mechanical air conditioning (De Cian et al. 2019) (see Section 9.4, Figure 9.11 and Tables SM9.1 to SM9.3). However, uncertainty about future climate change creates difficulties for projecting parameters for the design of new buildings (Hallegatte 2009; de Wilde and Coley 2012). This can be especially relevant for social housing programs (Rubio-Bellido et al. 2017; González Mahecha et al. 2020; Triana et al. 2018) in developing countries.

The impacts on buildings can lead to higher maintenance needs and the consequent embodied environmental impacts related to materials production, transportation and end-of-life, which account for a relevant share of GHG emissions in buildings life cycle (Rasmussen et al. 2018). Climate change induced biodegradation is especially important for bio-based materials such as wood and bamboo (Brambilla and Gasparri 2020) which are important options for reducing emissions imbued in buildings' construction materials (Peñaloza et al. 2016; Churkina et al. 2020; Rosse Caldas et al. 2020).

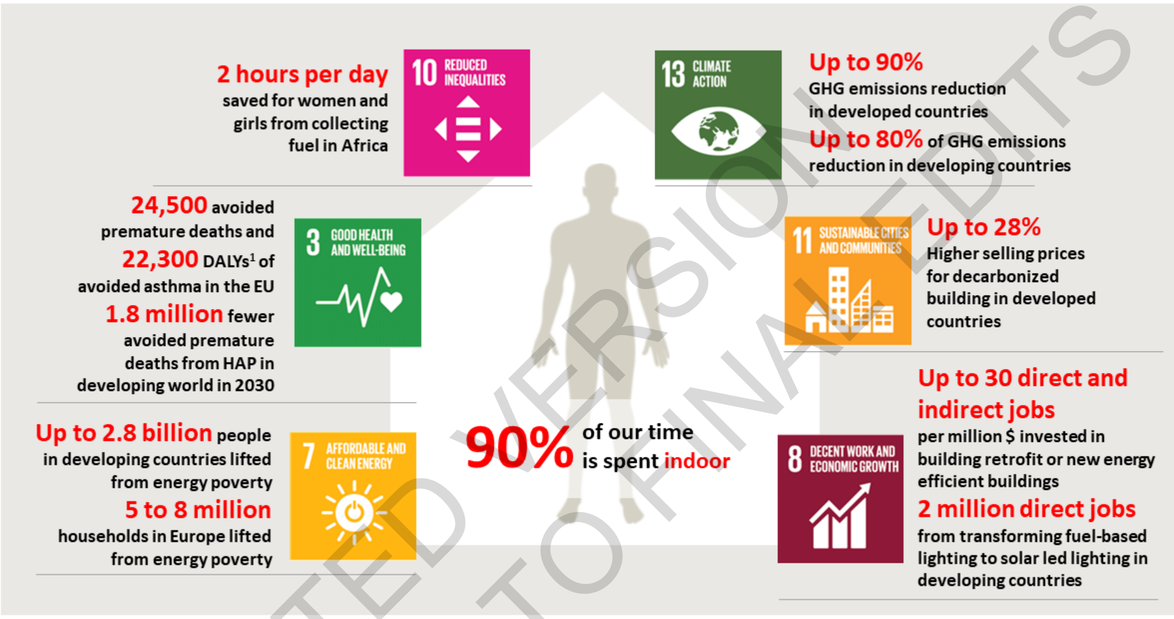
Although there can potentially be conflicts between climate change mitigation and adaptation, these can be dealt with proper planning, actions, and policies. The challenge is to develop multifunctional solutions, technologies and materials that can mitigate GHG emissions while improving buildings adaptive capacity. Solutions and technologies should reduce not only buildings' operational emissions, but also embodied emissions from manufacturing and processing of building materials (Röck et al. 2020). For instance, some building materials, such as bio-concrete, can reduce life cycle emissions of buildings and bring benefits in terms of building thermal comfort in tropical and subtropical climates. Also, energy efficiency, sufficiency and on-site renewable energy production can help to increase building resilience to climate change impacts and reduce pressure on the energy system.

9.8 Links to sustainable development

9.8.1 Overview of contribution of mitigation options to sustainable development

A growing body of research acknowledges that mitigation actions in buildings may have substantial social and economic value beyond their direct impact of reducing energy consumption and/or GHG emissions (Ürge-Vorsatz et al. 2016; Deng et al. 2017; Reuter et al. 2017; IEA 2014; US EPA 2018; Kamal et al. 2019; Bleyl et al. 2019) (see also Cross-Chapter Box 6 in Chapter 7). In other words, the implementation of these actions in the residential and non-residential sector holds numerous multiple impacts (co-benefits, adverse side-effects, trade-offs, risks, etc.) for the economy, society and end-users, in both developed and developing economies, which can be categorized into the following types (Nikas et al. 2020; Thema et al. 2017; Ferreira et al. 2017; Reuter et al. 2017; IEA 2014; US EPA 2018; Ürge-Vorsatz et al. 2016): (i) health impacts due to better indoor conditions, energy/fuel poverty alleviation, better ambient air quality and reduction of the heat island effect; (ii) environmental benefits such as reduced local air pollution and the associated impact on ecosystems (acidification, eutrophication, etc.) and infrastructures, reduced sewage production, etc.; (iii) improved resource management including water and energy; (iv) impact on social well-being, including changes in disposable income due to decreased energy expenditures and/or distributional costs of new policies, fuel poverty alleviation and improved access to energy sources, rebound effects, increased productive time for women and children, etc.; (v) microeconomic effects (e.g., productivity gains in non-residential buildings, enhanced asset values of green buildings, fostering innovation); (vi) macroeconomic effects, including impact on GDP driven by energy savings and energy availability, creation of new jobs, decreased employment in the fossil energy sector, long-term reductions in energy prices and possible increases in electricity prices in the medium run, possible impacts on public budgets, etc.; and (vii) energy security implications (e.g., access to modern energy resources, reduced import dependency, increase of supplier diversity, smaller reserve requirements, increased sovereignty and resilience).

Well-designed and effectively implemented mitigation actions in the sector of buildings have significant potential for achieving the United Nations (UN) Sustainable Development Goals (SDGs). Specifically, the multiple impacts of mitigation policies and measures go far beyond the goal of climate action (SDG13) and contribute to further activating a great variety of other SDGs (Figure 9.18 presents some indicative examples). Table 9.4 reviews and updates the analysis carried out in the context of the Special Report on Global Warming of 1.5°C (Roy et al. 2018) demonstrating that the main categories of GHG emission reduction interventions in buildings, namely the implementation of energy sufficiency and efficiency improvements as well as improved access and fuel switch to modern low carbon energy, contribute to achieving 16 out of a total of 17 SDGs.

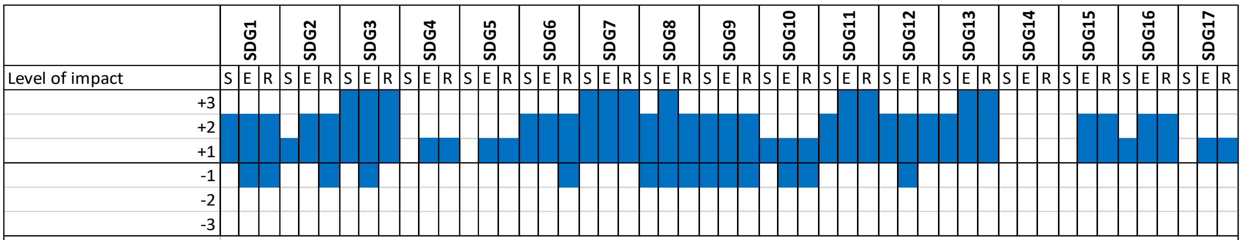


Key point: Achieving SDG targets requires implementation of ambitious climate mitigation policies which include sufficiency measures to align building design, size and use with SDGs, efficiency measures to ensure high penetration of best available technologies and supplying the remaining energy needs with renewable energy sources

Figure 9.18 Contribution of mitigation policies of the building sector to meeting sustainable development goals.

Source: Based on information from (IEA et al. 2020b; IEA 2020b; Mills 2016; European Commission 2016; Rafaj et al. 2018; Mzavanadze 2018a; World Health Organization 2016) and literature review presented in Section 9.8.5.2.

Table 9.4 Aspects of mitigation actions in buildings and their contributions to the 2030 Sustainable Development Goals. S: enhancement of energy sufficiency; E: energy efficiency improvements; R: improved access and fuel switch to lower carbon and renewable energy.



	SDG1	SDG2	SDG3	SDG4	SDG5	SDG6	SDG7	SDG8	SDG9	SDG10	SDG11	SDG12	SDG13	SDG14	SDG15	SDG16	SDG17
	Dimensions of mitigation actions that impact SDGs																
Health impact	X		X	X	X												
Environmental impact		X				X		X			X				X		
Resource efficienvy	X	X				X	X		X		X	X					
Impact on social well-being	X	X	X	X	X	X	X	X		X	X				X	X	
Microeconomic effects					X			X	X		X	X					
Macroeconomic effects								X		X	X						
Energy security							X		X								

Notes: The strength of interaction between mitigation actions and SDGs is described with a seven-point scale (Nilsson et al., 2016) Also, the symbol X shows the interactions between co-benefits/risk associated with mitigation actions and the SDGs. **SDG1**: Sufficiency and efficiency measures result in reduced energy expenditures and other financial savings that further lead to poverty reduction. Access to modern energy forms will largely help alleviate poverty in developing countries as the productive time of women and children will increase, new activities can be developed, etc. The distributional costs of some mitigation policies promoting energy efficiency and lower carbon energy may reduce the disposable income of the poor. **SDG2**: Energy sufficiency and efficiency measures result in lower energy bills and avoiding the "heat or eat" dilemma. Improved cook-stoves provide better food security and reduces the danger of fuel shortages in developing countries; under real-world conditions these impacts may be limited as the households use these stoves irregularly and inappropriately. Green roofs can support food production. Improving energy access enhances agricultural productivity and improves food security; on the other hand, increased bioenergy production may restrict the available land for food production. **SDG3**: All categories of mitigation action result in health benefits through better indoor air quality, energy/fuel poverty alleviation, better ambient air quality, and reduction of the heat island effect. Efficiency measures with inadequate ventilation may lead to the sick building syndrome symptoms. **SDG4**: Energy efficiency measures result in reduced school absenteeism due to better indoor environmental conditions. Also, fuel poverty alleviation increases the available space at home for reading. Improved access to electricity and clean fuels enables people living in poor developing countries to read, while it is also associated with greater school attendance by children. **SDG5**: Efficient cook-stoves and improved access to electricity and clean fuels in developing countries will result in substantial time savings for women and children, thus increasing the time for rest, communication, education and productive activities. **SDG6**: Reduced energy demand due to sufficiency and efficiency measures as well as an upscaling of RES can lead to reduced water demand for thermal cooling at energy production facilities. Also, water savings result through improved conditions and lower space of dwellings. Improved access to electricity is necessary to treat water at homes. In some situations, the switch to bioenergy could increase water use compared to existing conditions. **SDG7**: All categories of mitigation action result in energy/fuel poverty alleviation in both developed and developing countries as well as in improving the security of energy supply. **SDG8**: Positive and negative direct and indirect macroeconomic effects (GDP, employment, public budgets) associated with lower energy prices due to the reduced energy demand, energy efficiency and RES investments, improved energy access and fostering innovation. Also, energy efficient buildings with adequate ventilation, result in productivity gains and improve the competitiveness of the economy. **SDG9**: Adoption of distributed generation and smart grids helps in infrastructure improvement and expansion. Also, the development of "green buildings" can foster innovation. Reduced energy demand due to sufficiency and efficiency measures as well as an upscaling of RES can lead to early retirement of fossil energy infrastructure. **SDG10**: Efficient cook-stoves as well as improved access to electricity and clean fuels in developing countries will result in substantial time savings for women and children, thus enhancing education and the development of productive activities. Sufficiency and efficiency measures lead to lower energy expenditures, thus reducing income inequalities. The distributional costs of some mitigation policies promoting energy efficiency and lower carbon energy as well as the need for purchasing more expensive equipment and appliances may reduce the disposable income of the poor and increase inequalities. **SDG11**: Sufficiency and efficiency measures as well as fuel switching to RES and improvements in energy access would eliminate major sources (both direct and indirect) of poor air quality (indoor and outdoor). Helpful if in-situ production of RES combined with charging electric two, three and four wheelers at home. Buildings with high energy efficiency and/or green features are sold/rented at higher prices than conventional, low energy efficient houses. **SDG12**: Energy sufficiency and efficiency measures as well as deployment of RES result in reduced consumption of natural resources, namely fossil fuels, metal ores, minerals, water, etc. Negative impacts on natural resources could be arisen from increased penetration of new efficient appliances and equipment. **SDG13**: See sections 9.4-9.6. **SDG15**: Efficient cookstoves and improved access to electricity and clean fuels in developing countries will result in halting deforestation. **SDG16**: Building retrofits are associated with lower crime. Improved access to electric lighting can improve safety (particularly for women and children). Institutions that are effective, accountable and transparent are needed at all levels of government for providing energy access and promoting modern renewables as well as boosting sufficiency and efficiency. **SDG17**: The development of zero energy buildings requires among others capacity building, citizen participation as well as monitoring of the achievements.

Sources: (Balaban and Puppim de Oliveira 2017; Marmolejo-Duarte and Chen 2019; Barnes and Samad 2018; Bailis et al. 2015; Baimel et al. 2016; Berrueta et al. 2017; Bleyl et al. 2019; Boermans et al. 2015; Brounen and Kok 2011; Burney et al. 2017; Cajias et al. 2019; Camarinha-Matos 2016; Cameron et al. 2016; Cedeño-Laurent et al. 2018; De Ayala et al. 2016; Deng et al. 2012; Fuerst et al. 2015, 2016; Fricko et al. 2016; Galán-Marín et al. 2015; Goldemberg et al. 2018; Hanna et al. 2016; Hasegawa et al. 2015; Hejazi et al. 2015; Högberg 2013; Holland et al. 2015; Hyland et al. 2013; Jensen et al. 2016; Jeuland et al. 2018; Kahn and Kok 2014; Koirala et al. 2014; Levy et al. 2016; Liddell and Guiney 2015; Maidment et al. 2014; Markovska et al. 2016; Alawneh et al. 2019; Mastrucci et al. 2019; Mattioli and Moulinos 2015; McCollum et al. 2018; Mehetre et al. 2017; Mirasgedis et al. 2014; Mofidi and Akbari 2017; Mzavanadze 2018a; Niemelä et al. 2017; Ortiz et al. 2017; Payne et al. 2015; Rao et al. 2016; Rao and Pachauri 2017; Rosenthal et al. 2018; Saheb et al. 2018b,a; Scott et al. 2014; Smith et al. 2016; Steenland et al. 2018; Tajani et al. 2018; Teubler et al. 2020; Thomson et al. 2017a; Tonn et al. 2018; Torero 2015; Van de Ven et al. 2020; Venugopal et al. 2018; Wierzbicka et al. 2018; Willand et al. 2015a; Winter et al. 2015; Zheng et al. 2012; Liu et al. 2015a; Sola et al. 2016; Song et al. 2016; Zhao et al. 2017; Grubler et al. 2018; Thema et al. 2017; Ürge-Vorsatz et al. 2016; Nikas et al. 2020) (Blair et al. 2021; Batchelor et al. 2019; ESMAP et al. 2020; Walters and Midden 2018) (European Commission 2016) (MacNaughton et al. 2018)

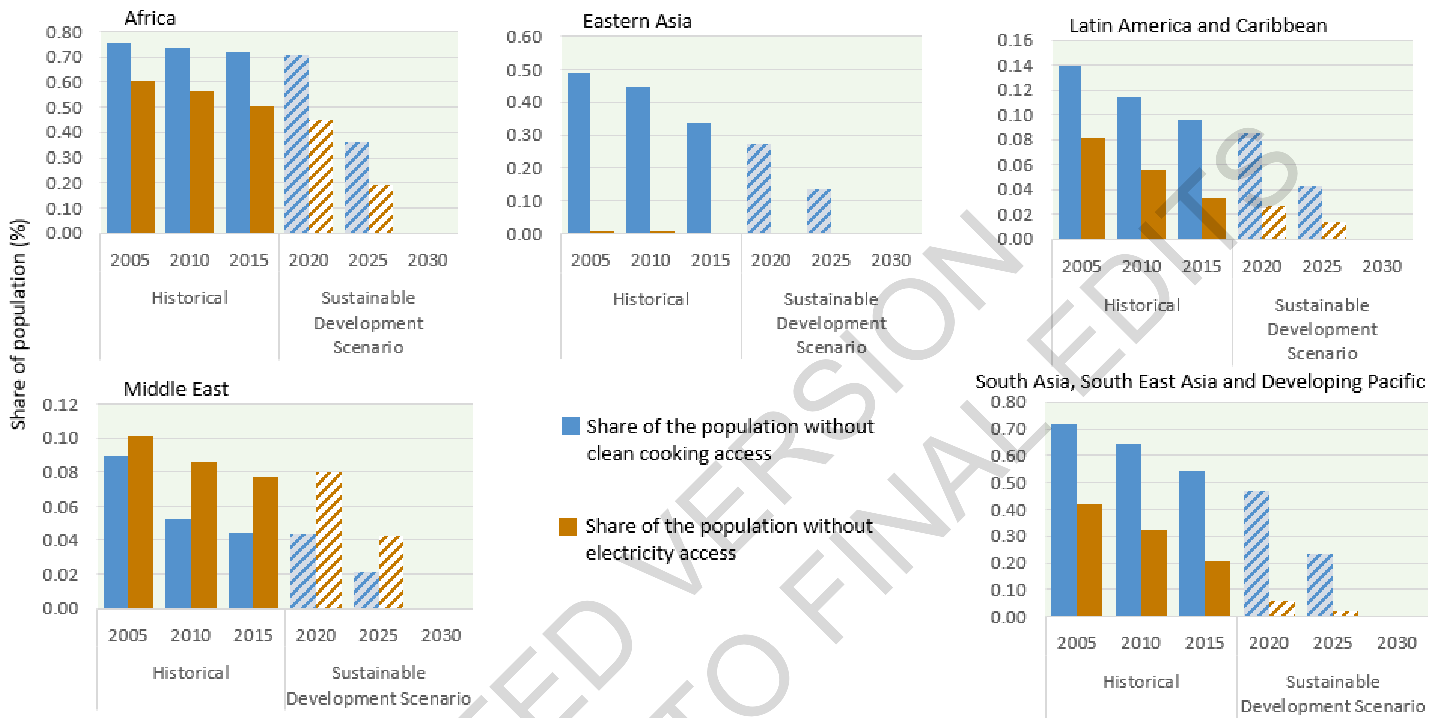
A review of a relatively limited number of studies made by (Ürge-Vorsatz et al. 2016) and (Payne et al. 2015) showed that the size of multiple benefits of mitigation actions in the sector of buildings may range from 22% up to 7,400% of the corresponding energy cost savings. In 7 out of 11 case studies reviewed, the value of the multiple impacts of mitigation actions was equal or greater than the value of energy savings. Even in these studies, several effects have not been measured and consequently the size of multiple benefits of mitigation actions may be even higher. Quantifying and if possible, monetizing, these wider impacts of climate action would facilitate their inclusion in cost-benefit analysis, strengthen the adoption of ambitious emissions reduction targets, and improve coordination across policy areas reducing costs (Thema et al. 2017) (Smith et al. 2016).

9.8.2 Climate mitigation actions in buildings and health impacts

9.8.2.1 Lack of access to clean energy

In 2018, approximately 2.8 billion people worldwide, most of whom live in Asia and Africa, still use polluting fuels, such as fuelwood, charcoal, dried crops, cow dung, etc., in low-efficiency stoves for cooking and heating, generating household air pollution (HAP), which adversely affects the health of the occupants of the dwellings, especially children and women (World Health Organization 2016; Quinn et al. 2018; Rahut et al. 2017; Mehetre et al. 2017; Rosenthal et al. 2018; Das et al. 2018; Xin et al. 2018; Liu et al. 2018) (IEA et al. 2020b). Exposure to HAP from burning these fuels is estimated to have caused 3.8 million deaths from heart diseases, strokes, cancers, acute lower respiratory infections in 2016 (World Health Organization 2018). It is acknowledged that integrated policies are needed to address simultaneously universal energy access, limiting climate change and reducing air pollution (World Health Organization 2016). (Rafaj et al. 2018) showed that a scenario achieving these SDGs in 2030 will imply in 2040 two million fewer premature deaths from HAP compared to current levels, and 1.5 million fewer premature deaths in relation to a reference scenario, which assumes the continuation of existing and planned policies. The level of incremental investment needed in developing countries to achieve universal access to modern energy was estimated at around USD0.8 trillion cumulatively to 2040 in the scenarios examined (Rafaj et al. 2018).

At the core of these policies is the promotion of improved cook-stoves and other modern energy-efficient appliances to cook (for the health benefits of improved cook-stoves see for example (García-Frapolli et al. 2010; Aunan et al. 2013) (Jeuland et al. 2018; Malla et al. 2011)), as well as the use of non-solid fuels by poor households in developing countries (Figure 9.19). Most studies agree that the use of non-solid energy options such as LPG, ethanol, biogas, piped natural gas, and electricity is more effective in reducing the health impacts of HAP compared to improved biomass stoves (see for example (Larsen 2016; Rosenthal et al. 2018; Steenland et al. 2018; Goldemberg et al. 2018). On the other hand, climate change mitigation policies (e.g., carbon pricing) may increase the costs of some of these clean fuels (e.g., LPG, electricity), slowing down their penetration in the poor segment of the population and restricting the associated health benefits (Cameron et al. 2016). In this case, appropriate access policies should be designed to efficiently shield poor households from the burden of carbon taxation (Cameron et al. 2016). The evaluation of the improved biomass burning cook-stoves under real-world conditions has shown that they have lower than expected, and in many cases limited, long-run health and environmental impacts, as the households use these stoves irregularly and inappropriately, fail to maintain them, and their usage decline over time (Wathore et al. 2017; Patange et al. 2015; Aung et al. 2016; Hanna et al. 2016). In this context, the various improved cook-stoves programs should consider the mid- and long-term needs of maintenance, repair, or replacement to support their sustained use (Schilmann et al. 2019; Shankar et al. 2014).



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2 **Figure 9.19 Trends on energy access: historical based on IEA statistics data and scenarios based on IEA WEO data.**

Electrification of households in rural or remote areas results also to significant health benefits. For example, in El Salvador, rural electrification of households leads to reduced overnight air pollutants concentration by 63% due to the substitution of kerosene as a lighting source, and 34-44% less acute respiratory infections among children under six (Torero 2015). In addition, the connection of the health centres to the grid leads to improvements in the quality of health care provided (Lenz et al. 2017).

9.8.2.2 Energy/fuel poverty, indoor environmental quality and health

Living in fuel poverty, and particularly in cold and damp housing is related to excess winter mortality and increased morbidity rates due to respiratory and cardiovascular diseases, arthritic and rheumatic illnesses, asthma, etc. (Camprubí et al. 2016; Wilson et al. 2016; Lacroix and Chaton 2015; Ormandy and Ezratty 2016; Payne et al. 2015; Thema et al. 2017). In addition, lack of affordable warmth can generate stress related to chronic discomfort and high bills, fear of falling into debt, and a sense of lacking control, which are potential drivers of further negative mental health outcomes, such as depression (Howden-Chapman et al. 2012; Payne et al. 2015; Wilson et al. 2016; Liddell and Guiney 2015). Health risks from exposure to cold and inadequate indoor environmental quality may be higher for low-income, energy-poor households, and in particular for those with elderly, young children, and members with existing respiratory illness (Payne et al. 2015; Thomson et al. 2017b; Nunes 2019). High temperatures during summer can also be dangerous for people living in buildings with inadequate thermal insulation and inappropriate ventilation (Sanchez-Guevara et al. 2019; Thomson et al. 2019; Ormandy and Ezratty 2016). Summer fuel poverty (or summer overheating risk) may increase significantly in the coming decades under a warming climate (see also Section 9.7), with the poorest, who cannot afford to install air conditioning, and the elderly (Nunes 2020) being the most vulnerable.

Improved energy efficiency in buildings contributes in fuel poverty alleviation and brings health gains through improved indoor temperatures and comfort as well as reduced fuel consumption and associated financial stress (Thomson and Thomas 2015; Curl et al. 2015; Poortinga et al. 2018; Lacroix and Chaton 2015; Liddell and Guiney 2015) (Willand et al. 2015). On the other hand, households suffering most from fuel poverty experience more barriers for undertaking building retrofits (Camprubí et al. 2016) (Charlier et al. 2018; Braubach and Ferrand 2013), moderating the potential health gains associated with implemented energy efficiency programs. This can be avoided if implemented policies to tackle fuel poverty target the most socially vulnerable households (Lacroix and Chaton 2015; Camprubí et al. 2016). (Mzavanadze 2018a) estimated that in EU-28 accelerated energy efficiency policies, reducing the energy demand in residential sector by 333 TWh in 2030 compared to a reference scenario, coupled with strong social policies targeting the most vulnerable households, could deliver additional co-benefits in the year of 2030 of around 24,500 avoided premature deaths due to indoor cold and around 22,300 DALYs of avoided asthma due to indoor dampness. The health benefits of these policies amount to €4.8 billion in 2030. The impacts on inhabitants in developing countries would be much greater than those in EU-28 owing to the much higher prevalence of impoverished household.

Apart from thermal comfort, the internal environment of buildings impacts public health through a variety of pathways including inadequate ventilation, poor indoor air quality, chemical contaminants from indoor or outdoor sources, outdoor noise, or poor lighting. The implementation of interventions aiming to improve thermal insulation of buildings combined with inadequate ventilation may increase the risk of mould and moisture problems due to reduced air flow rates, leading to indoor environments that are unhealthy, with the occupants suffering from the sick building syndrome symptoms (Wierzbicka et al. 2018; Cedeño-Laurent et al. 2018) (Willand et al. 2015). On the other hand, if the implementation of energy efficiency interventions or the construction of green buildings is accompanied by adequate ventilation, the indoor environmental conditions are improved through less moisture, mould, pollutant concentrations, and allergens, which result in fewer asthma symptoms, respiratory risks, chronic obstructive pulmonary diseases, heart disease risks, headaches, cancer risks, etc. (Cowell 2016; Allen et al. 2015; Doll et al. 2016; Wilson et al. 2016; Thomson and Thomas 2015) (Hamilton et al. 2015; Militello-Hourigan and Miller 2018; Underhill et al. 2018; Cedeño-Laurent et al. 2018). (Fisk 2018) showed that increased ventilation rates in residential buildings results in health benefits ranging from 20% to several-fold improvements; however, these benefits do not occur consistently, and ventilation should be combined with other exposure control measures. As adequate ventilation imposes additional costs, the sick building syndrome symptoms are more likely to be seen in low income households (Shrubsole et al. 2016).

The health benefits of residents due to mitigation actions in buildings are significant (for a review see (Maidment et al. 2014; Fisk et al. 2020; Thomson and Thomas 2015)), and are higher among low income households and/or vulnerable groups, including children, the elderly and those with pre-existing illnesses (Maidment et al. 2014; IEA 2014; Ortiz et al. 2019). (Tonn et al. 2018) estimated that the health-related benefits attributed to the two weatherization programs implemented in the US in 2008 and 2010 exceeds by a factor of 3 the corresponding energy cost savings yield. (IEA 2014) also found that the health benefits attributed to energy efficiency retrofit programs may outweigh their costs by up to a factor of 3. (Ortiz et al. 2019) estimated that the energy retrofit of vulnerable households in Spain requires an investment of around EUR 10.9-12.3 thousands per dwelling and would generate an average saving to the healthcare system of EUR 372 per year and dwelling (due to only better thermal comfort conditions in winter).

9.8.2.3 Outdoor air pollution

According to (World Health Organization 2018) around 4.2 million premature deaths worldwide (in both cities and rural areas) are attributed to outdoor air pollution. Only in China, the premature mortalities attributed to $PM_{2.5}$ and O_3 emissions exceeded 1.1 million in 2010 (Gu et al. 2018). Mitigation actions in residential and non-residential sectors decrease the amount of fossil fuels burnt either directly in buildings (for heating, cooking, etc.) or indirectly for electricity generation and thereby reduce air pollution (e.g., PM, O_3, SO_2, NO_x), improve ambient air quality and generate significant health benefits through avoiding premature deaths, lung cancers, ischemic heart diseases, hospital admissions, asthma exacerbations, respiratory symptoms, etc. (Karlsson et al. 2020; Balaban and Puppim de Oliveira 2017; MacNaughton et al. 2018; Levy et al. 2016). Several studies have monetized the health benefits attributed to reduced outdoor air pollution due to the implementation of mitigation actions in buildings, and their magnitude expressed as a ratio to the value of energy savings resulting from the implemented interventions in each case, are in the range of 0.08 in EU, 0.18 in Germany, 0.26-0.40 in US, 0.34 in Brazil, 0.47 in Mexico, 0.74 in Turkey, 8.28 in China and 11.67 in India (Diaz-Mendez et al. 2018; Joyce et al. 2013; MacNaughton et al. 2018; Levy et al. 2016). In developed economies, the estimated co-benefits are relatively low due to the fact that the planned interventions influence a quite clean energy source mix (Tuomisto et al. 2015; MacNaughton et al. 2018). On the other hand, the health co-benefits in question are substantially higher in countries and regions with greater dependency on coal for electricity generation and higher baseline morbidity and mortality rates (Kheirbek et al. 2014; MacNaughton et al. 2018).

9.8.3 Other environmental benefits of mitigation actions

Apart from the health benefits mentioned above, mitigation actions in the buildings sector are also associated with environmental benefits to ecosystems and crops, by avoiding acidification and eutrophication, biodiversity through green roofs and walls, building environment through reduced corrosion of materials, etc. (Mzavanadze 2018b; Thema et al. 2017) (Knapp et al. 2019; Mayrand and Clergeau 2018), while some negative effects cannot be excluded (Dylewski and Adamczyk 2016).

Also, very important are the effects of mitigation actions in buildings on the reduction of consumption of natural resources, namely fossil fuels, metal ores, minerals, etc. These comprise savings from the resulting reduced consumption of fuels, electricity and heat and the lifecycle-wide resource demand for their utilities, as well as potential net savings from the substitution of energy technologies used in buildings (production phase extraction) (Thema et al. 2017) (European Commission 2016). (Teubler et al. 2020) found that the implementation of an energy efficiency scenario in European buildings will result in resource savings (considering only those associated with the generation of final energy products) of 406 kg per MWh lower final energy demand in the residential sector, while the corresponding figure for non-residential buildings was estimated at 706 kg per MWh of reduced energy demand. On the other hand, (Smith et al. 2016) claim that a switch to more efficient appliances could result in negative impacts from increased resource use, which can be mitigated by avoiding premature replacement and maximizing recycling of old appliances.

Mitigation actions aiming to reduce the embodied energy of buildings through using local and sustainable building materials can be used to leverage new supply chains (e.g., for forestry products), which in turn bring further environmental and social benefits to local communities (Hashemi et al. 2015; Cheong C and Storey D 2019). Furthermore, improved insulation and the installation of double- or triple-glazed windows result in reduced noise levels. It is worth mentioning that for every 1 dB decrease in excess noise, academic performance in schools and productivity of employees in office buildings increases by 0.7% and 0.3% respectively (Kockat et al. 2018b). (Smith et al. 2016) estimated that in the UK the annual noise benefits associated with energy renovations in residential buildings may reach £400 million in 2030 outweighing the benefits of reduced air pollution.

9.8.4 Social well-being

9.8.4.1 Energy/fuel poverty alleviation

In 2018 almost 0.79 billion people in developing countries did not have access to electricity, while approximately 2.8 billion people relied on polluting fuels and technologies for cooking (IEA et al. 2020b). Only in sub-Saharan Africa, about 548 million people (i.e., more than 50% of the population) live without electricity. In developed economies, the EU Energy Poverty Observatory estimated that in EU-28 44.5 million people were unable to keep their homes warm in 2016, 41.5 million had arrears on their utility bills the same year, 16.3% of households faced disproportionately high energy expenditure in 2010, and 19.2% of households reported being uncomfortably hot during summer in 2012 (Thomson and Bouzarovski 2018). (Okushima 2016) using the "expenditure approach" estimated that fuel poverty rates in Japan reached 8.4% in 2013. In the US, in 2015, 17 million households (14.4% of the total) received an energy disconnect/delivery stop notice and 25 million households (21.2% of the total) had to forgo food and medicine to pay energy bills (Bednar and Reames 2020).

The implementation of well-designed climate mitigation measures in buildings can help to reduce energy/fuel poverty and improve living conditions with significant benefits for health (see Section 9.8.2) and well-being (Smith et al. 2016; Payne et al. 2015; Tonn et al. 2018). The social implications of energy poverty alleviation for the people in low- and middle-income developing countries with no access to clean energy fuels are further discussed in Section 9.8.4.2. In other developing countries and in developed economies as well, the implementation of mitigation measures can improve the ability of households to affordably heat/cool a larger area of the home, thus increasing the space available to a family and providing more private and comfortable spaces for several activities like homework (Payne et al. 2015). By reducing energy expenditures and making energy bills more affordable for households, a "heat or eat" dilemma can be avoided resulting in better nutrition and reductions in the number of low birthweight babies (Payne et al. 2015; Tonn et al. 2018). Also, renovated buildings and the resulting better indoor conditions, can enable residents to avoid social isolation, improve social cohesion, lower crime, etc. (Payne et al. 2015). (European Commission 2016) found that under an ambitious recast of Energy Performance Buildings Directive (EPBD), the number of households that may be lifted from fuel poverty across the EU lies between 5.17 and 8.26 million. To capture these benefits, mitigation policies and particularly energy renovation programmes should target the most vulnerable among the energy-poor households, which very often are ignored by the policy makers. In this context, it is recognized that fuel poverty should be analysed as a multidimensional social problem (Mashhoodi et al. 2019; Thomson et al. 2017b) (Charlier and Legendre 2019; Baker et al. 2018), as it is related to energy efficiency, household composition, age and health status of its members, social conditions (single parent families, existence of unemployed and retired people, etc.), energy prices, disposable income, etc. In addition, the geographical dimension can have a significant impact on the levels of fuel poverty and should be taken into account when formulating response policies (Besagni and Borgarello 2019; Mashhoodi et al. 2019).

9.8.4.2 Improved access to energy sources, gender equality and time savings

In most low- and middle-income developing countries women and children (particularly girls) spend a significant amount of their time for gathering fuels for cooking and heating (World Health Organization 2016; Rosenthal et al. 2018). For example, in Africa more than 70% of the children living in households that primarily cook with polluting fuels spend at least 15 hours and, in some countries, more than 30 hours per week in collecting wood or water, facing significant safety risks and constraints on their available time for education and rest (World Health Organization 2016; Mehetre et al. 2017). Also, in several developing countries (e.g., in most African countries but also in India, in rural areas in Latin America and elsewhere) women spend several hours to collect fuel wood and cook, thus limiting their potential for productive activities for income generation or rest (García-Frapolli et al. 2010; Mehetre et al. 2017; World Health Organization 2016). Expanding access to clean household energy for cooking, heating and lighting will largely help alleviate these burdens (Lewis et al. 2017; World Health Organization 2016; Rosenthal et al. 2018) (Malla et al. 2011). (Jeuland et al. 2018) found that the time savings associated with the adoption of cleaner and more fuel-efficient stoves by low-income households in developing countries are amount to USD 1.3-1.9 per household per month, constituting the 23-43% of the total social benefits attributed to the promotion of clean stoves.

Electrification of remote rural areas and other regions that do not have access to electricity enables people living in poor developing countries to read, socialize, and be more productive during the evening, while it is also associated with greater school attendance by children (Torero 2015; Rao et al. 2016; Barnes and Samad 2018). (Chakravorty et al. 2014) found that a grid connection can increase non-agricultural incomes of rural households in India from 9% up to 28.6% (assuming a higher quality of electricity). On the other hand, some studies clearly show that electricity consumption for connected households is extremely low, with limited penetration of electrical appliances (e.g., (Lee et al. 2017; Cameron et al. 2016) and low quality of electricity (Chakravorty et al. 2014). The implementation of appropriate policies to overcome bureaucratic red tape, low reliability, and credit constraints, is necessary for maximizing the social benefits of electrification.

9.8.5 Economic implications of mitigation actions

9.8.5.1 Buildings-related labour productivity

Low-carbon buildings, and particularly well-designed, operated and maintained high-performance buildings with adequate ventilation, may result in productivity gains and improve the competitiveness of the economy through three different pathways (Bleyl et al. 2019; Thema et al. 2017; Niemelä et al. 2017; Mofidi and Akbari 2017; MacNaughton et al. 2015) (European Commission 2016): (i) increasing the amount of active time available for productive work by reducing the absenteeism from work due to illness, the presenteeism (i.e., working with illness or working despite being ill), and the inability to work due to chronic diseases caused by the poor indoor environment; (ii) improving the indoor air quality and thermal comfort of non-residential buildings, which can result in better mental well-being of the employees and increased workforce performance; and (iii) reducing the school absenteeism due to better indoor environmental conditions, which may enhance the future earnings ability of the students and restrict the parents absenteeism due to care-taking of sick children.

Productivity gains due to increased amount of active time for work is directly related to acute and chronic health benefits attributed to climate mitigation actions in buildings (see Section 9.8.2.2). The bulk of studies quantifying the impact of energy efficiency on productivity focus on acute health effects. Proper ventilation in buildings is of particular importance and can reduce absenteeism due to sick days by 0.6–1.9 days per person per year (MacNaughton et al. 2015)(Ben-David et al. 2017; Thema et al. 2017). In a pan-European study, (Chatterjee and Ürge-Vorsatz 2018) showed that deep energy retrofits in residential buildings may increase the number of active days by 1.78-5.27 (with an average of 3.09) per year and person who has actually shifted to a deep retrofitted building. Similarly, the interventions in the non-residential buildings result in increased active days between 0.79 and 2.43 (with an average of 1.4) per year and person shifted to deeply retrofitted non-residential buildings.

As regards improvements in workforce performance due to improved indoor conditions (i.e., air quality, thermal comfort, etc.), (Kozusznik et al. 2019) conducted a systematic review on whether the implementation of energy efficient interventions in office buildings influence well-being and job performance of employees. Among the 34 studies included in this review, 31 found neutral to positive effects of green buildings on productivity and only 3 studies indicated detrimental outcomes for office occupants in terms of job performance. Particularly longitudinal studies, which observe and compare the office users' reactions over time in conventional and green buildings, show that green buildings have neutral to positive effects on occupants well-being and work performance (Thatcher and Milner 2016; Candido et al. 2019; Kozusznik et al. 2019). (Bleyl et al. 2019) estimated that deep energy retrofits in office buildings in Belgium would generate a workforce performance increase of 10.4 to 20.8 EUR·m^{-2} renovated. In Europe every 1°C reduction in overheating during the summer period increases students learning performance by 2.3% and workers performance in office buildings by 3.6% (Kockat et al. 2018b). Considering the latter indicator, it was estimated that by reducing overheating across Europe, the overall performance of the workers in office buildings can increase by 7-12% (Kockat et al. 2018b).

9.8.5.2 Enhanced asset values of energy efficient buildings

A significant number of studies confirm that homes with high energy efficiency and/or green features are sold at higher prices than conventional, low energy efficient houses. A review of 15 studies from 12 different countries showed that energy efficient dwellings have a price premium ranging between 1.5% and 28%, with a median estimated at 7.8%, for the highest energy efficient category examined in each case study compared to reference houses with the same characteristics but lower energy efficiency (the detailed results of this review are presented in Table SM9.55 included in the Supplementary Material). In a given real estate market, the higher the energy efficiency of dwellings compared to conventional housing, the higher their selling prices. However, a number of studies show that this premium is largely realized during resale transactions and is smaller or even negative in some cases immediately after the completion of the construction (Deng and Wu 2014; Yoshida and Sugiura 2015). A relatively lower number of studies (also included in Table SM9.5 of Supplementary Material) show that energy efficiency and green features have also a positive effect on rental prices of dwellings (Cajias et al. 2019; Hyland et al. 2013), but this is weaker compared to sales prices, and in a developing country even negative as green buildings, which incorporate new technologies such as central air conditioning, are associated with higher electricity consumption (Zheng et al. 2012).

Regarding non-residential buildings, (European Commission 2016) reviewed a number of studies showing that buildings with high energy efficiency or certified with green certificates present higher sales prices by 5.2-35%, and higher rents by 2.5-11.8%. More recent studies in relation to those included in the review confirm these results (e.g., (Mangialardo et al. 2018; Ott and Hahn 2018)) or project even higher premiums (e.g., (Chegut et al. 2014)) found that green certification in the London office market results in a premium of 19.7% for rents). On the other hand, in Australia, a review study showed mixed evidence regarding price differentials emerged as a function of energy performance of office buildings (Acil Allen Consulting 2015). Other studies have shown that energy efficiency and green certifications have been associated with lower default rates for commercial mortgages (An and Pivo 2020; Wallace et al. 2018; Mathew et al. 2021).

More generally, (Giraudet 2020) based on a meta-analysis of several studies, showed that the capitalization of energy efficiency is observed in building sales and rental (even in the absence of energy performance certificates), but the resulting market equilibrium can be considered inefficient as rented dwellings are less energy efficient than owner-occupied ones.

9.8.5.3 Macroeconomic effects

Investments required for the implementation of mitigation actions, create, mainly in the short-run, increase in the economic output and employment in sectors delivering energy efficiency services and products, which are partially counterbalanced by less investments and lower production in other parts of the economy (Thema et al. 2017; US EPA 2018; Yushchenko and Patel 2016) (European Commission 2016) (see also Cross-Working Group Box 1 in Chapter 3). The magnitude of these impacts depends on the structure of the economy, the extent to which energy saving technologies are produced domestically or imported from abroad, but also from the growth cycle of the economy with the benefits being maximized when the related investments are realized in periods of economic recession (Mirasgedis et al. 2014; Thema et al. 2017; Yushchenko and Patel 2016). Particularly in developing countries if the mitigation measures and other interventions to improve energy access (Figure 9.19) are carried out by locals, the impact on economy, employment and social well-being will be substantial (Mills 2016; Lehr et al. 2016). As many of these programs are carried out with foreign assistance funds, it is essential that the funds be spent in-country to the full extent possible, while some portion of these funds would need to be devoted to institution building and especially training. (Mills 2016) estimated that a market transformation from inefficient and polluting fuel-based lighting to solar-

LED systems to fully serve the 112 million households that currently lack electricity access will create directly 2 million new jobs in these developing countries, while the indirect effects could be even greater. (IEA 2020b) estimated that 9-30 jobs would be generated for every million dollars invested in building retrofits or in construction of new energy efficient buildings (gross direct and indirect employment), with the highest employment intensity rates occurring in developing countries. Correspondingly, 7-16 jobs would be created for every million dollars spent in purchasing highly efficient and connected appliances, while expanding clean cooking through LPG could create 16-75 direct local jobs per million dollars invested. Increases in product and employment attributed to energy efficiency investments also affect public budgets by increasing income and business taxation, reducing unemployment benefits, etc. (Thema et al. 2017), thus mitigating the impact on public deficit of subsidizing energy saving measures (Mikulić et al. 2016).

Furthermore, energy savings due to the implementation of mitigation actions will result, mainly in the long-run, in increased disposable income for households, which in turn may be spent to buy other goods and services, resulting in economic development, creation of new permanent employment and positive public budget implications (IEA 2014; US EPA 2018; Thema et al. 2017). According to (Anderson et al. 2014), the production of these other goods and services is usually more labour-intensive compared to energy production, resulting in net employment benefits of about 8 jobs per million dollars of consumer bill savings in the US. These effects may again have a positive impact on public budgets. Furthermore, reduced energy consumption on a large scale is likely to have an impact on lower energy prices and hence on reducing the cost of production of various products, improving the productivity of the economy and enhancing security of energy supply (IEA 2014; Thema et al. 2017).

9.8.5.4 Energy security

GHG emission reduction actions in the sector of buildings affect energy systems by: (i) reducing the overall consumption of energy resources, especially fossil fuels; (ii) promoting the electrification of thermal energy uses; and (iii) enhancing distributed generation through the incorporation of RES and other clean and smart technologies in buildings. Increasing sufficiency, energy efficiency and penetration of RES result in improving the primary energy intensity of the economy and reducing dependence on fossil fuels, which for many countries are imported energy resources (Markovska et al. 2016; Thema et al. 2017; Boermans et al. 2015). The electrification of thermal energy uses is expected to increase the demand for electricity in buildings, which in most cases can be reversed (at national or regional level) by promoting nearly zero energy new buildings and a deep renovation of the existing building stock (Couder and Verbruggen 2017; Boermans et al. 2015). In addition, highly efficient buildings can keep the desired room temperature stable over a longer period and consequently they have the capability to shift heating and cooling operation in time (Boermans et al. 2015). These result in reduced peak demand, lower system losses and avoided generation and grid infrastructure investments. As a significant proportion of the global population, particularly in rural and remote locations, still lack access to modern energy sources, renewables can be used to power distributed generation or micro-grid systems that enable peer-to-peer energy exchange, constituting a crucial component to improve energy security for rural populations (Leibrand et al. 2019; Kirchhoff and Strunz 2019). For successful development of peer-to-peer micro-grids, financial incentives to asset owners are critical for ensuring their willingness to share their energy resources, while support measures should be adopted to ensure that also non-asset holders can contribute to investments in energy generation and storage equipment and have the ability to sell electricity to others (Kirchhoff and Strunz 2019).

9.9 Sectoral barriers and policies

9.9.1 Barriers, feasibility, and acceptance

Understanding the reasons why cost-effective investment in building energy efficiency are not taking place as expected by rational economic behaviour is critical to design effective policies for decarbonize the buildings (Cattaneo 2019; Cattano et al. 2013). Barriers depend from the actors (owner, tenant, utility, regulators, manufacturers, etc.), their role in energy efficiency project and the market, technology, financial economic, social, legal, institutional, regulatory and policy structures (Reddy 1991; Weber 1997; Sorrell et al. 2000; Reddy 2002; Sorrell et al. 2011: Cagno et al. 2012; Bardhan et al., 2014; Bagaini et al. 2020; Vogel et al. 2015; Khosla et al. 2017; Gupta et al. 2017). Barriers identified for the refurbishment of exiting building or construction of new efficient buildings includes: lack of high-performance products, construction methods, monitoring capacity, investment risks, policies intermittency, information gaps, principal agent problems (both tenant and landlord face disincentives to invest in energy efficiency), skills of the installers, lack of a trained and ready workforce, governance arrangements in collectively owned properties and behavioural anomalies. (Do et al. 2020; Dutt 2020; Gillingham and Palmer 2014;Yang et al., 2019; Song et al. 2020; Buessler et al. 2017)). A better understanding of behavioural barriers (Frederiks et al. 2015) is essential to design effective policies to decarbonise the building sector. Energy efficiency in buildings faces one additional problem: the sector is highly heterogeneous, with many different building types, sizes and operational uses. Energy efficiency investments do not take place in isolation but in competition with other priorities and as part of a complex, protracted investment process (Cooremans 2011). Therefore, a focus on overcoming barriers is not enough for effective policy. Organisational context is important because the same barrier might have very different organisational effects and require very different policy responses (Mallaburn 2018). Cross-Chapter Box 2 in Chapter 2 presents a summary of methodologies for estimating the macro-level impact of policies on indices of GHG mitigation.

Reaching deep decarbonisation levels throughout the life cycle of buildings depend on multidimensional criteria for assessing the feasibility of mitigation measures, including criteria related to geophysical, environmental-ecological, technological, economic, socio-cultural and institutional dimensions. An assessment of 16 feasibility criteria for mitigation measures in the buildings sector indicates whether a specific factor, within broader dimensions, acts as a barrier or helps enabling such mitigation measures (Figure 9.20, Supplementary material Table SM9.6, Annex II.11). Although mitigation measures are aggregated in the assessment of Figure 9.20 and feasibility results can differ for more specific measures, generally speaking, the barriers to mitigation measures in buildings are few, sometimes including technological and socio-cultural challenges. However, many co-benefits could help enable mitigation in the buildings sector. For instance, many measures can have positive effects on the environment, health and well-being, and distributional potential, all of which can boost their feasibility. The feasibility of mitigation measures varies significantly according to socio-economic differences across and within countries.

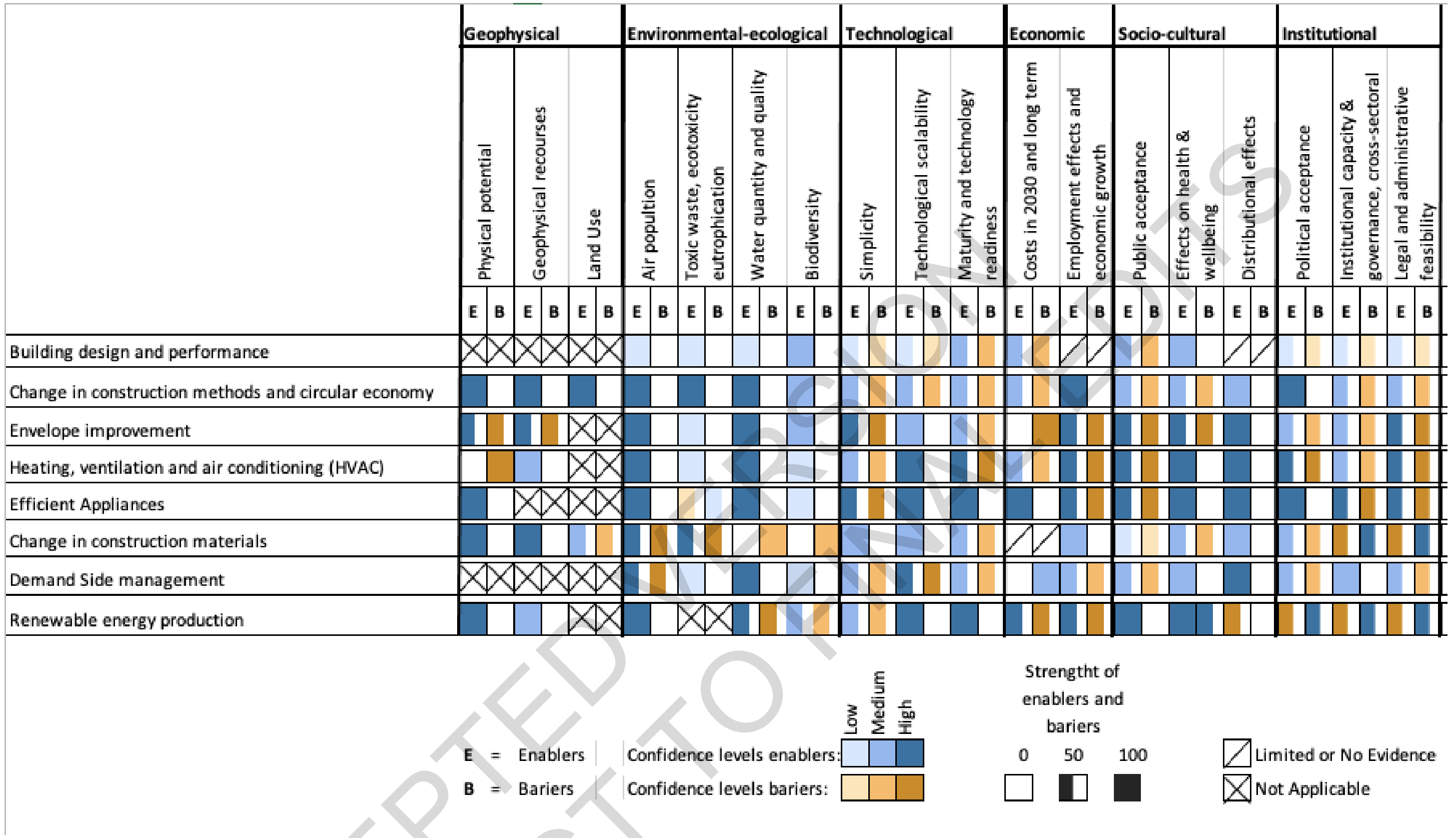


Figure 9.20 Summary of the extent to which different factors would enable or inhibit the deployment of mitigation options in buildings.

Blue bars indicate the extent to which the indicator enables the implementation of the option (E) and orange bars indicate the extent to which an indicator is a barrier (B) to the deployment of the option, relative to the maximum possible barriers and enablers assessed. A X signifies the indicator is not applicable or does not affect the feasibility of the option, while a forward slash / indicates that there is no or limited evidence whether the indicator affects the feasibility of the option. The shading indicates the level of confidence, with darker shading signifying higher levels of confidence. Table SM9.6 provides an overview of the extent to which the feasibility of options may differ across context (e.g., region), time (e.g., 2030 versus 2050), and scale (e.g., small versus large), and includes a line of sight on which the assessment is based. The assessment method is explained in Annex II.11.

9.9.2 Rebound effects

In the buildings sector energy efficiency improvements and promotion of cleaner fuels can lead to all types of rebound effects, while sufficiency measures lead only to indirect and secondary effects (Chitnis et al. 2013). The consideration of the rebound effects as a behavioural economic response of the consumers to cheaper energy services can only partially explain the gap between the expected and actual energy savings (Galvin and Sunikka-Blank 2017). The prebound effect, a term used to describe the situation where there is a significant difference between expected and observed energy consumption of non-refurbished buildings, is usually implicated in high rebound effects upon retrofitting (Teli et al. 2016; Calì et al. 2016; Galvin and Sunikka-Blank 2017). The access for all to modern energy services such as heating and cooling is one of the wellbeing objectives governments aim for. However, ensuring this access leads to an increase of energy demand which is considered as a rebound effect by (Berger and Höltl 2019; Poon 2015; Seebauer 2018; Sorrell et al. 2018; Orea et al. 2015; Teli et al. 2016; Chitnis et al. 2013). (Aydin et al. 2017) found that in the Netherlands the rebound effect for the lowest wealth quantile is double compared to the highest wealth quantile. Similar, energy access in developing countries leads to an increase consumption compared to very low baselines which is considered by some authors as rebound (Copiello 2017). On the other hand, in households whose members have a higher level of education and/or strong environmental values, the rebound is lower (Seebauer 2018).

Rebound effects in the building sector could be a co-benefit, in cases where the mechanisms involved provide faster access to affordable energy and/or contribute to improved social well-being, or a trade-off, to the extent that the external costs of the increased energy consumption exceed the welfare benefits of the increased energy service consumption (Galvin and Sunikka-Blank 2017; Sorrell et al. 2018) (Chan and Gillingham 2015; Borenstein 2015). In cases where rebound effects are undesirable, appropriate policies could be implemented for their mitigation.

There is great variation in estimates of the direct and indirect rebound effects, which stems from the end-uses included in the analysis, differences in definitions and methods used to estimate the rebound effects, the quality of the data utilized, the period of analysis and the geographical area in consideration (Gillingham et al. 2016; International Risk Governance Council 2013; Galvin 2014). Several studies examined in the context of this assessment (see Table SM9.7) showed that direct rebound effects for residential energy consumption, which includes heating, are significant and range between -9% and 91%, with a median at 35% in Europe, 0-30% with a median at 20% in the US, and 72-127%, with a median at 89% in China. The direct rebound effects for energy services other than heating may be lower (Chen et al. 2018; Sorrell et al. 2018). The rebound effects may be reduced with the time as the occupants learn how to optimally use the systems installed in energy renovated buildings (Calì et al. 2016) and seem to be lower in the case of major renovations leading to nZEB (Corrado et al. 2016). The combined direct and indirect or the indirect only rebound effects were found to range between -2% and 80%, with a median at 12% (see Table SM9.7). In non-residential buildings the rebound effects may be smaller, as the commercial sector is characterized by lower price elasticities of energy demand, while the comfort level in commercial buildings before renovation is likely to be better compared to residential buildings (Qiu 2014).

9.9.3 Policy packages for the decarbonisation of buildings

There is no single energy efficiency policy (Wiese et al. 2018) able to decarbonise the building sector, but a range of polices are needed, often included in a policy package (Kern et al., 2017; Rosenow et al. 2017) to enhance robustness against risks and uncertainties in both short and long-term and addressing the different stakeholder perspectives (Forouli et al. 2019; Nikas et al. 2020; Doukas and Nikas 2020). This is due to: the many barriers; the different types of buildings (residential, non-residential, etc.); the different socio-economic groups of the population (social housing, informal settlement, etc.); the country development status; the local climate (cooling and/or heating), ownership structure (tenant or owner), the age of buildings. Effective policy packages include mandatory standards, codes, the provision of information, carbon pricing, financing, and technical assistance for end-users. Important element related to policy packages is whether the policies reinforce each other or diminish the impact of individual policies, due to policy "overcrowding". Examples are the EU policy package for efficiency in buildings (Rosenow and Bayer 2017; Economidou et al, 2020; BPIE, 2020) and China goal of 10 million m^2 NZEB during the 13th Five-Year Plan, presented in the Supplementary Material (Section SM9.4). See also Cross-Chapter Box 10 in Chapter 14 for integrated policymaking for sector transitions.

Revisions in tenant and condominium law are necessary for reducing disincentives between landlord and tenant or between multiple owners, these acts alone cannot incentivise them to uptake an energy efficiency upgrade in a property (Economidou and Serrenho, 2019). A package addressing split incentives include regulatory measures, information measures, labels, individual metering rules and financial models designed to distribute costs and benefits to tenants and owners in a transparent and fair way (Bird and Hernández 2012; Economidou and Bertoldi 2015; Castellazi et al. 2017). A more active engagement of building occupants in energy saving practices, the development of agreements benefitting all involved actors, acknowledgement of real energy consumption and establishment of cost recovery models attached to the property instead of the owner are useful measures to address misalignments between actors.

In developed countries policy packages are targeted to increase the number and depth of renovations of existing building, while for developing countries policies focus on new construction, including regulatory measures and incentives, while carbon pricing would be more problematic unless there is a strong recycling of the revenues. Building energy codes and labels could be based on LCA emissions, rather than energy consumption during the use phase of buildings, as it is the case in Switzerland and Finland (Kuittinen and Häkkinen 2020).

Policy packages should also combine sufficiency, efficiency, and renewable energy instruments for buildings, for example some national building energy codes already include minimum requirements for the use of renewable energy in buildings.

9.9.3.1 Sufficiency and efficiency policies

Recently the concept of sufficiency complementary to energy efficiency has been introduced in policy making (Saheb 2021; Bertoldi 2020; Hewitt 2018; Brischke et al. 2015; Thomas et al. 2019), see Box 9.1. Lorek and Spangenberg (2019b) investigated the limitations of the theories of planned behaviour and social practice and proposed an approach combining both theories resulting in a heuristic sufficiency policy tool. Lorek and Spangenberg (2019b) showed that increased living area per person counteracts efficiency gains in buildings and called for sufficiency policy instruments to efficiency by limit building size. This could be achieved via mandatory and prescriptive measures, e.g., progressive building energy codes (IEA, 2013), or financial penalties in the form of property taxation (e.g., non-linear and progressive taxation), or with mandatory limits on building size per capita. Heindl and Kanschik (2016) suggested that voluntary policies promoting sufficiency and proposed that sufficiency should be "integrated in a more comprehensive normative framework related to welfare and social justice". Alcott highlighted that in sufficiency there is a loss of utility or welfare (Alcott, 2008), Thomas et al. (2019) described some of the possible policies, some based on the sharing economy principles, for examples co-sharing space, public authorities facilitating the exchange house between young and expanding families with elderly people, with reduce need for space. Policies for sufficiency include land-use and urban planning policies. Berril et al, (2021) proposed removing policies, which support supply of larger home typologies, e.g., single-family home or local land-use regulations restricting construction of multifamily buildings. In non-residential building, sufficiency could be implemented through the sharing economy, for example with flexible offices space with hot-desking.

Scholars have identified the "energy efficiency gap" (Hirst and Brown 1990; Jaffe and Stavins 1994; Stadelmann 2017; Gillingham and Palmer 2014; Alcott and Greenstone 2012) and policies to overcome it. (Markandya et al. 2015) and Shen et al. (2016) have classified energy efficiency policies in three broad categories: the command and control (e.g. mandatory building energy codes; mandatory appliances standards, etc.); price instruments (e.g. taxes, subsides, tax deductions, credits, permits and tradable obligations, etc.); and information instruments (e.g. labels, energy audits, smart meters and feed-back, etc.). Based on the EU Energy Efficiency Directive, the MURE and the IEA energy efficiency policy databases (Bertoldi and Mosconi 2020), Bertoldi (2020) proposed six policy categories: regulatory, financial and fiscal; information and awareness; qualification, training and quality assurance; market-based instruments: voluntary action. The categorization of energy efficiency policies used in this chapter is aligned with the taxonomy used in Chapter 13, sub-section 13.5.1 (economic or market-based instruments, regulatory instruments, and other policies). However, the classification used here is more granular in order to capture the complexity of end-use energy efficiency and buildings.

1. *Regulatory instruments*

Building energy codes

Several scholars highlighted the key role of mandatory building energy codes and minimum energy performance requirements for buildings (Enker and Morrison 2017). Wang et al. (2019) finds that "Building energy efficiency standards (BEES) are one of the most effective policies to reduce building energy consumption, especially in the case of the rapid urbanization content in China". Ex-post policy evaluation shows that stringent buildings codes reduce energy consumption in buildings and CO2 emissions and are cost-effective (Scott et al. 2015; Aydin and Brounen 2019; (Yu et al. 2017; Yu et al. 2018)(Aroonruengsawat 2012; Levinson 2016; Kotchen 2017; Jacobsen and Kotchen 2013). Progressive building energy codes include requirements on efficiency improvement but also on sufficiency and share of renewables (Rosenberg at al., 2017; Clune at al. 2012) and on embodied emissions (Schwarz et al. 2020), for example the 2022 ASHRAE Standard 90.1 includes prescriptive on-site renewable energy requirements for non-residential building. Evans et al. (2017; 2018) calls for strengthen the compliance checks with efficiency requirements or codes when buildings are in operation and highlighted the need for enforcement of building energy codes to achieve the estimate energy and carbon savings recommending actions to improve enforcements, including institutional capacity and adequate resources.

Evans et al. (2017; 2018) identified strengthening the compliance checks with codes when buildings are in operation and the need for enforcement of building energy codes in order to achieve the estimate energy and carbon savings, recommending actions to improve enforcements, including institutional capacity and adequate resources. Another important issue to be addressed by policies is the 'Energy Performance Gap' (EPG), i.e., the gap between design and policy intent and actual outcomes. Regulatory and market support regimes are based on predictive models (Cohen and Bordass 2015) with general assumptions about building types, the way they are used and are not covering all energy consumption. In the perspective of moving towards net zero carbon, it is important that policy capture and address the actual in-use performance of buildings (Gupta and Kotopouleas 2018; Gupta et al. 2015). Outcome-based codes are increasingly important because overcome some limitations of prescriptive building energy codes, which typically do not regulate all building energy uses or do not regulate measured operational energy use in buildings. Regulating all loads, especially plug and process loads, is important because they account for an increasingly large percentage of total energy use as building envelope and space-conditioning equipment are becoming more efficient (Denniston et al., 2011; Colker, 2012; Enker and Morrison, 2020).

Building codes could also foster the usage of wood and timber as a construction in particular for multi-storey buildings and in the long term penalise carbon intensive building materials (Ludwig 2019) with policies based on environmental performance assessment of buildings and the "wood first" principle (Ludwig, 2019; Ramage et al., 2017).

Retro-commissioning is a cost-effective process to periodically check the energy performance of existing building and assure energy savings are maintained overtime (Ssembatya et al., 2021)(Kong et al. 2019).

In countries with low rate of new construction, it is important to consider mandatory building energy codes for existing buildings, but this may also be relevant for countries with high new construction, as they will have soon a large existing building stock. The EU has requirements already in place when building undergo a major renovation (Economidou et. al, 2020). Countries considering mandatory regulations for existing buildings include Canada, the U.S. (specific cities), China, Singapore. Policies include mandating energy retrofits for low performances existing buildings, when sold or rented. In countries with increasing building stock, in particular in developing countries, policies are more effective when targeting new buildings (Kamal et al. 2019).

NZEBs definitions are proposed by (Marszal et al. 2011; Deng and Wu 2014; Zhang and Zhou 2015; Wells et al. 2018; Williams et al. 2016);), covering different geographical areas, developing and developed countries, and both existing buildings and new buildings. In 2019, China issued the national standard Technical Standard for Nearly Zero Energy Building (MoHURD, 2019). California has also adopted a building energy code mandating for NZEBs for new residential buildings in 2020 and 2030 for commercial buildings (Feng et al. 2019). Several countries have adopted targets, roadmaps or mandatory building energy codes requiring net zero energy buildings (NZEBs) for some classes of new buildings (Feng et al. 2019).

<u>Building Labels and Energy Performance Certificates (EPCs)</u>

Buildings labels are an important instrument , with some limitations. Li et al. (2019b) reviewed the EU mandatory Energy Performance Certificates for buildings and proposed several measures to make the EPC more effective in driving the markets towards low consumption buildings. Some authors have indicated that the EPC based on the physical properties of the buildings (asset rating) may be misleading due to occupancy behaviour (Cohen and Bordass 2015) and calculation errors (Crawley et al. 2019). Control authorities can have a large impact on the quality of the label (Mallaburn 2018). Labels can also include information on the GHG embedded in building material or be based on LCA.

US EPA Energy Star and NABERS (Gui and Gou, 2020) are building performance labels based on performance, not on modelled energy use. Singapore has mandatory building energy labels, as do many cities in the U.S., while India and Brazil have mandatory labels for public buildings.

Mandatory energy performance disclosure and benchmarking of building energy consumption is a powerful policy instrument in particular for non-residential buildings (Trencher et al. 2016) and could be more accurate than energy audits. Gabe (2016) showed that mandatory disclosure is more effective than voluntary disclosure. Some US cities (e.g., New York) have adopted Emissions Performance Standards for buildings, capping CO2 emissions. Accurate statistics related to energy use are very important for reducing GHG in building sector. In 2015, the Republic of Korean stablished the National Building Energy Integrated Management System, where building data and energy consumption information are collected for policy development and public information.

<u>Energy audits</u>

Energy audits, help to overcome the information barriers to efficiency investments, in particular buildings owned or occupied by small companies (Kalantzis and Revoltella, 2019). In the EU energy audits are mandatory for large companies under the Energy Efficiency Directive (Nabitz and Hirzel 2019), with some EU Member States having a long experience with energy audits, as part of national voluntary agreements with the private sector (Cornelis 2019; Rezessy and Bertoldi 2011). Singapore has adopted mandatory audit for buildings (Shen et al, 2016). In the United States, several cities have adopted energy informational policies in recent years, including mandatory buildings audits (Trencher et al. 2016; Kontokosta et al., 2020). The State of New York has in place a subsidized energy audit for residential building since 2010 (Boucher et al. 2018). It is important to assure the training of auditors and the quality of the audit.

Minimum Energy Performance Standards (MEPSs)

Mandatory minimum efficiency standards for building technical equipment and appliances (e.g., HVAC, appliances, ICT, lighting, etc.) is a very common, tested and successful policy in most of the OECD countries (e.g. EU, US, Canada, Australia, etc.) for improving energy efficiency (Wu et al. 2019; Scott et al. 2015; Sonnenschein et al. 2019). Brucal and Roberts (2019) showed that efficiency standards reduce product price. McNeil et al. (2019) highlighted how efficiency standards will help developing countries in reducing the power peak demand by a factor of two, thus reducing large investment costs in new generation, transmission, and distribution networks. Mandatory standards have been implemented also other large economies, e.g., Russia, Brazil, India, South Africa, China, Ghana, Kenya, Malaysia (Salleh et al., 2019), with an increase in the uptake also in developing countries, e.g. Ghana, Kenya, Tunisia, etc. In Japan, there is a successful voluntary programme the Top Runner, with similar results of mandatory efficiency standards (Inoue and Matsumoto 2019).

Appliance energy labelling

Mandatory energy labelling schemes for building technical equipment and appliances are very often implemented together with minimum efficiency standards, with the mandatory standard pushing the market towards higher efficiency and the label pulling the market (Bertoldi, 2019). OECD countries, China and many developing countries (for example Ghana, Kenya, India, South Africa, etc.) (Chunekar 2014) (Diawuo et al., 2018; Issock Issock et al., 2018) have adopted mandatory energy labelling. Other labelling schemes are of voluntary nature, e.g. the Energy Star programme in the US (Ohler et al., 2020), which covers many different appliances.

Information campaign

Provision of information (e.g. public campaigns, targeted technical information, etc.) is a common policy instrument to change end-user behaviour. Many authors agree that the effect of both targeted and general advertisement and campaigns have a short lifetime and the effects tend to decrease over time (Simcock et al. 2014; Diffney et al. 2013; Reiss and White 2008). The meta-analysis carried out by (Delmas et al. 2013) showed that energy audits and personal information were the most effective followed by providing individuals with comparisons with their peers' energy use including "non-monetary, information-based" (Delmas et al. 2013). An effective approach integrates the social norm as the basis for information and awareness measures on energy behaviour (Gifford 2011; Schultz et al. 2007). Information is more successful when it inspires and engages people: how people feel about a given situation often has a potent influence on their decisions (Slovic and Peters 2006). The message needs to be carefully selected and kept as simple as possible focusing on the following: entertain, engage, embed and educate (Dewick and Owen 2015).

Energy consumption feedback with smart meters, smart billing and dedicated devices and apps is another instrument recently exploited to reduce energy consumption (Zangheri et al. 2019; Karlin et al. 2015; Buchanan et al. 2018) very often coupled with contest-based interventions or norm-based interventions (Bergquist et al. 2019). (Hargreaves et al. 2018) proposes five core types of action to reduce energy use: turn it off, use it less, use it more carefully, improve its performance, and replace it/use an alternative. According to (Aydin et al. 2018), technology alone will not be enough to achieve the desired energy savings due to the rebound effect. The lack of interest from household occupants, confusing feedback message and difficulty to relate it to practical intervention, overemphasis on financial savings and the risks of "fallback effects" where energy use returns to previous levels after a short time or rebound effects has been pointed out (Buchanan et al. 2015) as the main reasons for the failing of traditional feedback. (Labanca and Bertoldi 2018) highlight the current limitations of policies for energy conservation and suggests complementary policy approach based on social practices theories.

2. *Market-based instruments*

Carbon allowances

A number of authors (Wadud and Chintakayala 2019; Fan et al. 2016; Raux et al. 2015; Marek et al. 2018; Li et al. 2015, 2018; Fawcett and Parag 2017) have investigated personal carbon allowances introduced previously (Fleming 1997; Bristow et al. 2010; Fawcett 2010; Starkey 2012; Raux and Marlot 2005; Ayres 1995). Although there is not yet any practical implementation of this policy, it offers an alternative to carbon taxes, although there are some practical issues to be solved before it could be rolled out. Recently the city of Lahti in Finland has introduced a personal carbon allowance in the transport sector (Kuokkanen et al. 2020). Under this policy instrument governments sets allocates (free allocation, but allowances could also be auctioned) allowances to cover the carbon emission for one year, associated with energy consumption. Trade of allowances between people can be organised. Personal carbon allowances can also foster renewable energies (energy consumption without carbon emissions) both in the grid and in buildings (e.g., solar thermal). Personal carbon allowances can make the carbon price more explicit to consumers, allowing them to know from the market value of each allowance (e.g., 1 kg of CO_2). This policy instrument will shift the responsibility to the individual. Some categories may have limited ability to change their carbon budget or to be engaged by this policy instruments. In addition, in common with many other environmental policies the distributional effects have to be assessed carefully as this policy instrument may favour well off people able to purchase additional carbon allowances or install technologies that reduce their carbon emissions (Burgess 2016; Wang et al. 2017).

The concept of carbon allowances or carbon budget can also be applied to buildings, by assigning a yearly CO_2 emissions budget to each building. This policy would be a less complex than personal allowances as buildings have metered or billed energy sources (e.g., gas, electricity, delivered heat, heating oil, etc.). The scheme stimulates investments in energy efficiency and on-site renewable energies and energy savings resulting from behaviour by buildings occupant. For commercial buildings, similar schemes were implemented in the UK CRC Energy Efficiency Scheme (closed in 2019) or the Tokyo Metropolitan Carbon and Trade Scheme (Nishida and Hua 2011)(Bertoldi et al. 2013a). The Republic of Korea implemented since 2015 an Emission Trading Scheme, covering buildings (Park and Hong 2014; Narassimhan et al. 2018; Lee and Yu 2017). More recently under the New York Climate Mobilization Act enacted in 2019 New York City Local Law 97 established "Carbon Allowances" for large buildings (Spiegel-Feld, 2019; Lee, 2020).

Public money can be used to reward and give incentives to energy saved, as a result of technology implementation, and/or as a result of energy conservation and sufficiency (Eyre 2013; Bertoldi et al. 2013b; Prasanna et al. 2018). This can be seen as a core feature of the Energy Savings Feed-in Tariff (ES-FiT). The ES-FiT is a performance-based subsidy, whereby actions undertaken by end-users – e.g., investments in energy efficiency technology measures – are awarded based on the real energy savings achieved.

Utilities Programmes, Energy Efficiency Resource Standard and Energy Efficiency Obligations

Ratepayers funded efficiency programmes, energy efficiency obligations, energy efficiency resource standards and white certificates have been introduced in some EU Member States, in several US States, Australia, South Korea and Brazil (Bertoldi et al. 2013a; Aldrich and Koerner 2018; Wirl 2015; Choi et al. 2018a; Palmer et al. 2013; Brennan and Palmer 2013; Rosenow and Bayer 2017; Fawcett and Darby 2018; Fawcett et al. 2019; Giraudet and Finon, 2015; Goldman et al, 2020; Nadel, 2019; Sliger and Colburn, 2019). This policy instrument helps in improving energy efficiency in buildings, but there is no evidence that it can foster deep renovations of existing buildings. Recently this policy instrument has been investigated is some non-OECD countries such as Turkey, where white certificates could deliver energy savings with some limitations (Duzgun and Komurgoz 2014) and UAE, as a useful instrument to foster energy efficiency in buildings (Friedrich and Afshari 2015). Another similar market based instrument is the energy saving auction mechanism implemented in some US States, Switzerland, and in Germany (Thomas and Rosenow 2020; Langreder et al. 2019; Rosenow et al. 2019). Energy efficiency projects participate in auctions for energy savings based on the cost of the energy saved and receive a financial incentive, if successful.

Energy or carbon taxes

Energy and/or carbon taxes are a climate policy, which can help in reducing energy consumption (Sen and Vollebergh 2018) and manage the rebound effect (Peng et al. 2019; Font Vivanco et al. 2016; Freire-González 2020; Bertoldi 2020). The carbon tax has been adopted mainly in OECD countries and in particular in EU Member States (Hájek et al. 2019; Bertoldi 2020; Sen and Vollebergh 2018) . There is high agreement that carbon taxes can effective in reducing CO_2 emissions (Andersson 2017; IPCC 2018; Hájek et al. 2019). It is hard to define the optimum level of taxation in order to achieve the desired level of energy consumption or CO_2 emission reduction (Weisbach et al. 2009). As for other energy efficiency policy distributional effect and equity considerations have to be carefully considered and mitigated (Borozan 2019). High energy prices tend to reduce the energy consumption particularly in less affluent households, and thus attention is needed in order to avoid unintended effects such as energy poverty. Bourgeois et al. (2021) showed that using carbon tax revenue to finance energy efficiency investment reduces fuel poverty and increases cost-effectiveness. (Giraudet et al. 2021)assessed the cost-effectiveness of various energy efficiency policies in France, concluding that a carbon tax is the most effective. In particular, revenues could be invested in frontline services that can provide a range of support - including advising householders on how to improve their homes. Hence, the introduction of a carbon tax can be neutral or even positive to the economy, as investments in clean technologies generate additional revenues. In addition, in the long term, a carbon/energy tax could gradually replace the tax on labour reducing labour cost (e.g., the example of the German Eco-tax), thus helping to create additional jobs in the economy. In literature, this is known as double dividend (Murtagh et al. 2013) (Freire-González and Ho 2019). Urban economic researches (Rafaj et al. 2018; Creutzig 2014; Borck and Brueckner 2018) have highlighted that higher carbon price would translate in incentives for citizens to live closer to the city centre, which often means less floor space, less commuting distance and thus reduced emissions. Xiang and Lawley (2019) indicated that the carbon tax in British Columbia substantially reduced residential natural gas consumption. Saelim (2019) showed that simulated carbon tax on residential consumption in Thailand will have a low impact on welfare and it will be slightly progressive. Lin and Li (2011) indicate that a carbon tax could reduce the energy consumption and boost the uptake of energy efficiency and renewable energies, while at the same time may impact social welfare and the competitiveness of industry. Solaymani (2017) showed that in Malaysia a tax with revenue recycling increases in the welfare of rural and urban households. Van Heerden et al. (2016) explored economic and environmental effects of the CO_2 tax in South Africa highlighting the negative impact on GDP. This negative impact of the carbon tax on GDP is however greatly reduced by the manner in which the tax revenue is recycled. National circumstances shall be taken into consideration in introducing energy taxes, considering the local taxation and energy prices context with regard to sustainable development, justice and equity.

A policy, which can have similar impact to a carbon tax and is the energy price/subsidy reform, which also involves raising energy prices. Energy price/subsidy reform reduces energy consumption and greenhouse gas emissions and encourages investment in energy efficiency (Aldubyan and Gasim, 2021; Coady et al., 2018). In a similar manner, government revenues from subsidies reforms can be used to mitigate the distributional impact on vulnerable population groups, including direct cash transfer programmes (Schaffitzel, et al. 2020; Rentschler and Brazilian, 2017).

Taxes could also be used to penalise inefficient behaviour and favour the adoption of efficient behaviour and technologies. Taxes are used in some jurisdictions to promote energy efficient appliances with lower VAT. Similarly, the annual building/property tax (and also the purchase tax) could be based on the CO_2 emissions of the buildings, rather than on the value of the building. Tax credits are also an important subsidy for the renovation of buildings in France (Giraudet, 2020), Italy (Alberini and Bigano, 2015) and other countries.

9.9.4 Financing mechanisms and business models for reducing energy demand

Grants and subsidies are traditional financing instruments used by governments when optimal levels of investments cannot be fully supported by the market alone. They can partly help overcoming the upfront cost barrier as they directly fill an immediate financial gap and thus enable a temporary shift in the market (Newell et al. 2019). These forms of support are usually part of policy mixes including further fiscal and financial instruments such as feed-in tariffs and tax breaks (Polzin et al. 2019). Potential issues with subsidies are the limited availability of public financing, the stop and go due to annual budget and the competition with commercial financing.

Loans provide liquidity and direct access to capital important in deep renovation projects (Rosenow et al. 2014). There is empirical evidence (Giraudet et al. 2021), that banks make large profits on personal loans for renovation purposes. International financing institutions (IFIs) and national governments provided subsidies in public-private partnerships so that financial institutions can offer customers loans with attractive terms (Olmos et al. 2012). Loan guarantees are effective in reducing intervention borrowing costs (Soumaré and Lai 2016). Combination of grants and subsidised loans financed by IFIs could be an effective instrument together with guarantees. An important role in financing energy efficiency can be played by green banks, which are publicly capitalized entities set up to facilitate private investment in low-carbon, including energy efficiency (Linh and Anh, 2017; Tu and Yen, 2015; Khan, 2018; Bahl, 2012) . Green banks have been established at the national level (e.g., UK, Poland) and in the US at state and city level.

Wholesaling of EE of loans and utilities programmes, are other important financing instruments. Another financing mechanism for building efficiency upgrades, mainly implemented so far in the US, is efficiency-as-a-service under an energy services agreement (ESA), where the building owners or tenant pay to the efficiency service provider a charge based on realized energy savings without any upfront cost (Kim et al., 2012; Bertoldi, 2020). ESA providers give performance guarantees assuming the risk that expected savings would occur (Bertoldi, 2020).

Energy Performance Contracting (EPC) is an agreement between a building owner and Energy Services Company (ESCO) for energy efficiency improvements. EPC is a common financing vehicle for large buildings and it is well developed in several markets (Nurcahyanto et al, 2020; Stuart et. al, 2018; Carvallo et al, 2015; Ruan et al., 2018; Zheng et al., 2021; Bertoldi and Boza Kiss, 2017). Quality standards are a part of the EPC (Augustins et al. 2018) . Guarantees can facilitate the provision of affordable and sufficient financing for ESCOs (Bullier and Milin 2013). The ESCO guarantees a certain level of energy savings and it shields the client from performance risk. The loan goes on the client's balance sheet and the ESCO assumes full project performance risk (Deng et al. 2015). One of the limitations is on the depth of the energy renovation in existing buildings. According to (Giraudet et al. 2018), EPC is effective at reducing information problems between contractors and investors.

Energy efficient mortgages are mortgages that credits a home energy efficiency by offering preferential mortgage terms to extend existing mortgages to finance efficiency improvements. There are two types of energy mortgages: (i) the Energy Efficient Mortgages (EEMs), and (ii) the Energy Improvement

Mortgages (EIMs), both can help in overcoming the main barriers to retrofit policies (Miu et al. 2018). The success depends on the improved energy efficiency with a positive impact on property value and on the reduction of energy bills and the income increase in the household. In the EU, the EeMAP Initiative aims to create a standardised energy efficient mortgage template (Bertoldi et al. 2021).

On-bill financing is a mechanism that reduces first-cost barriers by linking repayment of energy efficiency investments to the utility bill and thereby allowing customers to pay back part or all costs of energy efficiency investments over time (Brown 2009). On-bill finance programmes can be categorised into: (i) on-bill loans (assignment of the obligation to the property) and (ii) on-bill tariffs (payment off in case of ownership transfer) (Eadson et al. 2013). On-bill finance programmes can be more effective when set up as a service rather than a loan. (Mundaca and Klocke, 2018).

Property Assessed Clean Energy (PACE) is a means of financing energy renovations and renewable energy through the use of specific bonds offered by municipal governments to investors (Mills 2016). Municipalities use the funds raised to loan money towards energy renovations in buildings. The loans are repaid over the assigned long term (15-20 years) via an annual assessment on their property tax bill (Kirkpatrick and Bennear 2014). This model has been subject to consumer protection concerns. Residential PACE programmes in California have been shown to increase PV deployment in jurisdictions that adopt these programs (Ameli et al., 2017; Kirkpatrick and Bennear 2014). In US commercial buildings, PACE volumes and programs, however, continue to grow (Lee, 2020).

Revolving funds allow reducing investment requirements and enhancing energy efficiency investment impacts by recovering and reinvesting the savings generated (Setyawan 2014). Revolving fund could make retrofit cost-neutral in the long term and could also dramatically increase low carbon investments, including in developing countries (Gouldson et al. 2015).

Carbon finance, started under the Kyoto Protocol with the flexible mechanisms and further enhanced under the Paris Agreement (Michaelowa et al. 2019), is an activity based on "carbon emission rights" and its derivatives (Liu et al. 2015a). Carbon finance can promote low-cost emission reductions (Zhou and Li 2019). Under Emission Trading Schemes or other carbon pricing mechanisms, auctioning carbon allowances creates a new revenue stream. Revenues from auctioning could be used to finance energy efficiency projects in buildings with grants, zero interest loans or guarantees (Wiese et al., 2020).

Crowdfunding is a new and rapidly growing form of financial intermediation that channels funds from investors to borrowers (individuals or companies) or users of equity capital (companies) without involving traditional financial organizations such as banks (Miller and Carriveau 2018). Typically, it involves internet-based platforms that link savers directly with borrowers (European Union 2015). It can play a significant role at the start of a renewable and sustainable energy projects (Dilger et al. 2017).

The One-Stop Shop (OSS) service providers for buildings energy renovations are organizations, consortia, projects, independent experts or advisors that usually cover the whole or large part of the customer renovation journey from information, technical assistance, structuring and provision of financial support, to the monitoring of savings (Mahapatra et al. 2019; Bertoldi 2021b). OSSs are transparent and accessible advisory tools from the client perspective and new, innovative business models from the supplier perspective (Boza-Kiss and Bertoldi 2018).

9.9.5 Policies mechanisms for financing for on-site renewable energy generation

On-site renewable energy generation is a key component for the building sector decarbonisation, complementing sufficiency and efficiency. Renewable energies (RES) technologies still face barriers due to the upfront investment costs, despite the declining price of some technologies, long pay-back period, unpredictable energy production, policy incertitude, architectural (in particular for built-in PV) and landscape considerations, technical regulations for access to the grid, and future electricity costs (Mah et al. 2018; Agathokleous and Kalogirou 2020).

Several policy instruments for RES have been identified by scholars (Azhgaliyeva et al. 2018; Pitelis et al. 2020; Fouquet 2013): direct investments; feed-in tariffs; grants and subsidies; loans, taxes; (tradable) green certificates or renewable/clean energy portfolio standards; information and education; strategic planning; codes and standards; building codes; priority grid access; research, development and deployment; and voluntary approaches. There are specific policies for renewable heating and cooling. (Connor et al. 2013). In 2011, the UK introduced the Renewable Heat Incentive (RHI) support scheme (Balta-Ozkan et al. 2015; Connor et al. 2015). The RHI guarantee a fixed payment per unit of heat generated by a renewable heat technology for a specific contract duration (Yılmaz Balaman et al. 2019).

The most common implemented policy instruments are the feed-in tariffs (FiTs) and the Renewable/ Energy Portfolio Standards (RPSs) (Alizada 2018; Xin-gang et al. 2017a; Bergquist et al., 2020), with FiTs more suited for small scale generation. More than 60 countries and regions worldwide have implemented one of the two policies (Sun and Nie 2015). FiT is a price policy guaranteeing the purchase of energy generation at a specific fixed price for a fixed period (Xin-gang et al. 2020; Barbosa et al. 2018). RPS is a quantitative policy, which impose mandatory quota of RES generation to power generators (Xin-gang et al. 2020) .

A flat rate feed-in tariff (FiT) is a well-tested incentive adopted in many jurisdictions to encourage end-users to generate electricity from RES using rooftop and on-site PV systems (Pacudan 2018). More recently, there has been an increasing interest for dynamic FiTs taking into account electricity costs, hosting capacity, ambient temperature, and time of day (Hayat et al. 2019). Since 2014, EU Member States have been obligated to move from FiT to feed-in premium (FiTP) (Hortay and Rozner 2019); where a FiTP consist in a premium of top of the electricity market price. Lecuyer and Quirion (2019) argued that under uncertainty over electricity prices and renewable production costs a flat FiT results in higher welfare than a FiTP. One of the main concerns with FiT systems is the increasing cost of policies maintenance (Pereira da Silva et al. 2019; Roberts et al. 2019a; Zhang et al. 2018). In Germany, the financial costs, passed on to consumers in the form a levy on the electricity price have increased substantially in recent years (Winter and Schlesewsky 2019) resulting in opposition to the FiT in particular by non-solar customers. A particular set up of the FiT encourage self-consumption through net metering and net billing, which has a lower financial impact on electricity ratepayers compared with traditional FiTs (Roberts et al. 2019b; Vence and Pereira 2019; Pacudan 2018).

In some countries, e.g. Australia (Duong et al. 2019), South Korea (Choi et al. 2018a), China (Yi et al. 2019), there was a transition from subsidies under the FiT to market-based mechanisms, such as RPSs and tendering. Compared with FiT, RPS (or Renewable Obligations) reduce the subsidy costs (Zhang et al. 2018). A number of scholars (Xin-gang et al. 2017; Li et al. 2019a; Liu et al. 2018a) have highlighted the RPSs effectiveness in promoting the development of renewable energy. Other authors (Requate 2015; An et al. 2015) have presented possible negative impacts of RPSs.

Both FiT and RPS can support the development of RES. Scholars compared the effectiveness of RPSs and FiTs with mix results and different opinions, with some scholars indicating the advantages of RPS (Ciarreta et al. 2017, 2014; Xin-gang et al. 2017), while Nicolini and Tavoni (2017) showed that in Italy FiTs are outperforming RPSs and Tradable Green Certificates (TGCs). García-Álvarez et al. (2018) carried out an empirical assessment of FiTs and RPSs for PV systems energy in EU over the period 2000–2014 concluding that that FiTs have a significant positive impact on installed PV capacity. This is due to the small size of many rooftop installations and the difficulties in participating in trading schemes for residential end users. Similar conclusions were reached by (Dijkgraaf et al. 2018) assessing 30 OECD countries and concluding that there is a "positive effect of the presence of a FiT on the development of a country's added yearly capacity of PV". Other scholars (Couture and Gagnon 2010; Lewis and Wiser 2007; Lipp 2007; Cory et al. 2009) concluded that FiT can create a stable investment framework and long-term policy certainty and it is better than RPS for industrial development and job creation. Ouyang and Lin (2014) highlighted that RPS has a better implementation effect than FiT in

China, where FiT required very large subsidy. Ford et al. (2007) showed that TGC is a market-based mechanism without the need for government subsidies. Marchenko (2008) and Wędzik et al. (2017) indicate that the TGCs provide a source of income for investors. Choi et al. (2018a) analysed the economic efficiency of FiT and RPS in the South Korean, where FiT was implemented from 2002 to 2011 followed by an RPS since 2012 (Park and Kim 2018; Choi et al. 2018b). Choi concluded that RPS was more efficient for PV from the government's perspective while from an energy producers' perspective the FiT was more efficient. Some scholars proposed a policy combining FiT and RPS (Cory et al. 2009). Kwon (2015) and del Río et al. (2017) concluded that both FiT and RPS are effective, but policy costs are higher in RPSs than FiTs. RPS, REC trading and FiT subsidy could also be implemented as complementary policies (Zhang et al. 2018).

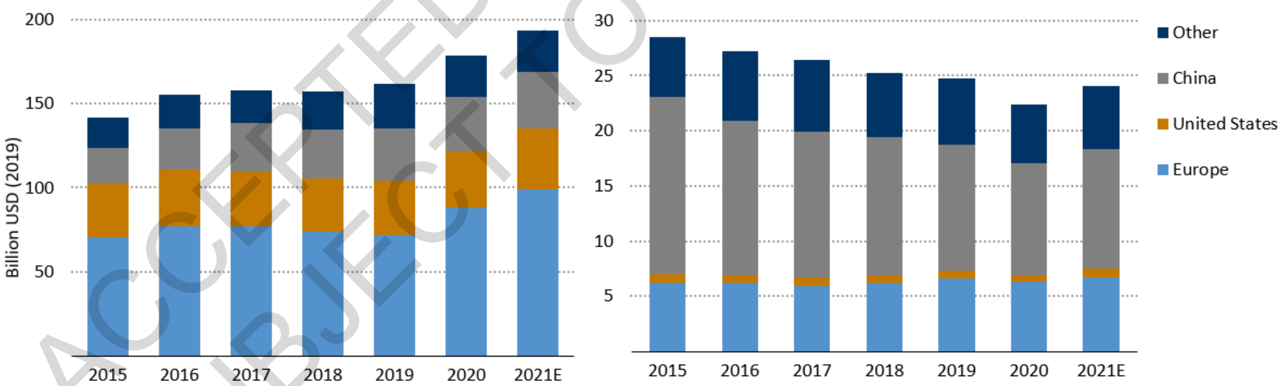
Tenders are a fast spreading and effective instrument to attract and procure new generation capacity from renewable energy sources (Bayer et al. 2018; Bento et al. 2020; Ghazali et al. 2020; Haelg 2020; Batz T. and Musgens 2019). A support scheme based on tenders allows a more precise steering of expansion and lower risk of excessive support (Gephart et al. 2017). Bento et al. (2020) indicated that tendering is more effective in promoting additional renewable capacity comparing to other mechanisms such as FiTs. It is also important to take into account the rebound effect in energy consumption by on-site PV users, which might reduce up to one fifth of the carbon benefit of renewable energy (Deng and Newton 2017).

Financing mechanisms for RES are particularly needed in developing countries. Most of the common supporting mechanisms (FiT, RPSs, PPA, auctions, net metering, etc.) have been implemented in some developing countries (Donastorg et al. 2017). Stable policies and an investment-friendly environment are essential to overcome financing barriers and attract investors (Donastorg et al. 2017). Kimura et al. (2016) identified the following elements as essential for fostering RES in developing countries: innovative business models and financial mechanisms/structures; market creation through the implementation of market-based mechanisms; stability of policies and renewable energy legislation; technical assistance to reduce the uncertainty of renewable energy production; electricity market design, which reflects the impact on the grid capacity and grid balancing; improved availability of financial resources, in particular public, and innovative financial instruments, such as carbon financing (Park et al. 2018; Kim and Park 2018; Lim et al. 2013); green bonds; public foreign exchange hedging facility for renewable energy financing, credit lines; grants and guarantees..

- The end-user will be at the centre as a key participant in the future electricity system (Zepter et al. 2019; Lavrijssen and Carrillo Parra, 2017) providing flexibility, storage, energy productions, peer to peer trading, electric vehicle charging. Zepter indicates that "the current market designs and business models lack incentives and opportunities for electricity consumers to become prosumers and actively participate in the market". Klein et al. (2019) explore the policy options for aligning prosumers with the electricity wholesale market, through price and scarcity signals. Policies should allow for active markets participation of small prosumers (Brown et al. 2019; Zepter et al. 2019), local energy communities and new energy market actors such as aggregators (Iria and Soares 2019; Brown et al. 2019). Energy Communities are new important players in the energy transition (Sokołowski, 2020; Gjorgievski, et al., 2021). Citizens and local communities can establish local energy communities, providing local RES production to serve the community, alleviate energy poverty and export energy into the grid (DellaValle and Sareen, 2020; Hahnel et al. 2020). Energy Communities have as primary purpose to provide environmental, economic, or social community benefits by engaging in generation, aggregation, energy storage, energy efficiency services and charging services for electric vehicles. Energy communities help in increasing public acceptance and mobilise private funding. Demand response aggregators (Mahmoudi et al., 2017; Henriquez at al., 2018) can aggregate load reductions by a group of consumers, and sell the resulting flexibility to the electricity market (Zancanella P. et al. 2017). Regulatory frameworks for electricity markets should allow demand response to compete on equal footing in energy markets and encourage new business models for the provision of flexibility to the electricity grid (Shen et al., 2014). Renewable energy and sufficiency requirements could be included in building energy codes and implemented in coordination with each other and with climate policies, e.g. carbon pricing (Oikonomou et al. 2014).

9.9.6 Investment in building decarbonisation

As Section 9.6.3 points out, the incremental investment cost to decarbonise buildings at national level is up to 3.5% GDP per annum during the next thirty years (the global GDP in 2019 was USD 88 trillion). As the following figures illustrate, only a very small share of it is currently being invested, leaving a very large investment gap still to address. The incremental capital expenditure on energy efficiency in buildings has grown since AR5 to reach the estimated USD 193 billion in 2021; Europe was the largest investing region, followed by the USA and China (Figure 9.21). The incremental capital expenditure on renewable energy heat vice versa declined to reach USD 24 billion in this year; the leading investor was China, followed by Europe (ibid). The total capital expenditure on distributed small-scale (less than 1MW) solar systems in 2019 was USD 52.1 billion, down from the peak of USD 71 billion in 2011; most of this capacity is installed in buildings (Frankfurt School - UNEP Centre/BNEF 2020). The US was the largest country market with USD 9.6 billion investment; notably USD 5 billion was deployed in the Middle East and Africa (ibid). (IEA 2021b) provided an estimate of annual average incremental investment needs in building sector decarbonation between 2026 and 2030 of USD 711 billion, including USD 509 billion in building energy efficiency and USD 202 billion in renewable heat for end-use and electrification in buildings. Such investment would allow being on track towards meeting the goals of the WEO Net Zero Emissions Scenario, as presented in Box 9.2. To reach these levels, the respective investment must grow from their average volumes in 2016-2020 factor 3.6 and 4.5 respectively. As the investment needs estimated by (IEA 2021b) are significantly lower the investment intervals reported by bottom-up literature (Section 9.6.3), the actual investment gap is likely to be higher.



Notes: (i) An energy efficiency investment is defined as the incremental spending on new energy-efficient equipment or the full cost of refurbishments that reduce energy use. (ii) Renewable heat for end-use include solar thermal applications (for district, space, and water heating), bioenergy and geothermal energy, as well as heat pumps. (iii) The investment in 2021 is an estimate.

Figure 9.21 Incremental capital expenditure on energy efficiency investment (left) and renewable heat in buildings, 2015-2021

Source: IEA 2021b

9.9.7 Governance and Institutional Capacity

9.9.7.1 Governance

Multilevel and polycentric governance is essential for implementing sufficiency, energy efficiency and renewable energies policies (IPCC, 2018). Policies can be implemented at different levels of government and decision making, international, national, regional, and local. Policies for building have be adopted at national level (Enker and Morrison 2017), at state or regional level (Fournier et al. 2019), or at city level (Trencher and van der Heijden 2019). Zhao et al. (2019) find that national policies are instrumental in driving low carbon developments in buildings.

International agreements (Kyoto, Montreal/Kigali, Paris, etc.) play an important role in establishing national energy-efficiency and renewable energy policies in several countries (Dhar et al. 2018; Bertoldi 2018). Under the Paris Agreement, some NDCs contain emission reduction targets for subsectors, e.g., buildings, policies for subsectors and energy efficiency and/or renewable targets (see also Cross-Chapter Box 5 in Chapter 4). In the EU since 2007 climate and energy policies are part of a co-ordinated policy package. EU Member States have prepared energy efficiency plans every three years and long term renovation strategies for buildings (Economidou et al. 2020). Under the new Energy and Climate Governance Regulation EU Member States have submitted at the end of 2020 integrated National Energy and Climate Plans, including energy efficiency and renewable plans. (Oberthur, 2019; Schlacke and Knodt, 2019). The integration of energy and climate change policies and their governance has been analysed (von Lüpke and Well, 2020), highlighting the need of reinforcing the institutions, anticipatory governance, the inconsistency of energy policies and the emerging multi-level governance.

Some policies are best implemented at international level. Efficiency requirements for traded goods and the associated test methods could be set at global level in order to enlarge the market, avoid technical barriers to trade; reduce the manufacturers design and compliance costs. International standards could be applied to developing countries when specific enabling conditions exist, particularly in regard to technology transfer, assistance for capacity buildings and financial support. This would also reduce the dumping of inefficient equipment in countries with no or lower efficiency requirements. An example is the dumping of new or used inefficient cooling equipment in developing countries, undermining national and local efforts to manage energy, environment, health, and climate goals. Specific regulations can be put in place to avoid such environmental dumping, beginning with the "prior informed consent" as in the Rotterdam Convention and a later stage with the adoption of minimum efficiency requirements for appliances (Andersen et al. 2018; United Nations Environment Programme (UNEP) 2017). Dreyfus et al. (2020a) indicates that global policies to promote best technologies currently available have the potential to reduce climate emissions from air conditionings and refrigeration equipment by 210–460 $GtCO_2$-eq by 2060, resulting from the phasing down of HFC and from improved energy efficiency. Another example is the commitment by governments in promoting improvements in energy efficiency of cooling equipment in parallel with the phasedown of HFC refrigerants enshrined in the Biarritz Pledge for Fast Action on Efficient Cooling signed in 2019. The policy development and implementation costs will be reduced as the technical analysis leading to the standard could be shared among governments. However, it is important that local small manufacturing companies in developing countries have the capacity to invest in updating production lines for meeting new stringent international efficiency requirements.

Building energy consumption is dependent on local climate and building construction traditions, regional and local government share an important role in promoting energy efficiency in buildings and on-site RES, through local building energy codes, constructions permits and urban planning. In South Korea, there is a green building certification system operated by the government, based on this, Seoul has enacted Seoul's building standard, which includes more stringent requirements. Where it is difficult to retrofit existing buildings, e.g., historical buildings, cities may impose target at district level, where RES could be shared among buildings with energy positive buildings compensating for energy consuming buildings. Local climate and urban plans could also contribute to the integration of the building sector with the local transport, water, and energy sectors, requiring, for example, new constructions in areas served by public transport, close to offices or buildings to be ready for e-mobility.

Buildings GHG emission reduction shall also be considered in greenfield and brownfield developments and urban expansion (Loo et al, 2017; Salviati and Ricciardo Lamonica., 2020), including co-benefis (Zapata-Diomedi et al., 2019).

Energy efficiency, sufficiency, and renewable policies and measures will have a large impact on different stakeholders (citizens, construction companies; equipment manufacturers; utilities, etc.), several studies highlighted the importance of stakeholder consultation and active participation in policy making and policy implementation (Vasileiadou and Tuinstra 2013; Ingold et al. 2020), including voluntary commitments and citizen assemblies. In particular, energy users role will be transformed from passive role to an active role, as outlined in the concept of energy citizenship (Campos and Marín-González, 2020). The energy citizens needs and voice should therefore be included in policy processes among traditional business players, such as incumbent centralised power generation companies and utilities (Van Veelen, 2018). Architects and engineers play an important role in the decarbonisation of buildings. The professional bodies can mandate their members support energy efficiency and sufficiency. For example, the US AIA states in their code of ethics that architects must inform clients of climate risks and opportunities for sustainability. The capacity and quality of workforce and building construction, retrofit, and service firms are essential to execute the fast transition in building systems (see also Cross-Chapter Box 12 in Chapter 16).

9.9.7.2 Institutional capacity

The concept of institutional capacity is increasingly connected with the issue of public governance, emphasising the broad institutional context within which individual policies are adopted. Institutions are durable and are sources of authority (formal or informal) structuring repeated interactions of individuals, companies, civil society groups, governments, and other entities. Thus, institutional capacity also represents a broader "enabling environment" which forms the basis upon which individuals and organisations interact. In general terms, capacity is "the ability to perform functions, solve problems and set and achieve objectives" (Fukuda-Parr et al. 2002). Institutional capacity is an important element for regional sustainable development (Farajirad et al. 2015). The role and importance of institutional capacity is fundamental in implementing the building decarbonisation. Central and local governments, regulatory organisations, financial institutions, standardisation bodies, test laboratories, building construction and design companies, qualified workforce and stakeholders are key players in supporting the implementation of building decarbonisation.

Governments (from national to local) planning to introduce efficiency, RES, and sufficiency policies needs technical capacity to set sectoral targets and design policies and introduce effective and enforcement with adequate structure and resources for their implementation. Policies discussed and agreed with stakeholders and based on impartial data and impact assessments, have a higher possibility of success. Public authorities need technical and economics competences to understand complex technical issues and eliminate the knowledge gap in comparison to private sector experts, human and financial resources to design, implement, revise, and evaluate policies. The role of energy efficiency policy evaluation needs to be expanded, including the assessment of the rebound effect (Vine et al. 2013). For developing countries international support for institutional capacity for policy development, implementation and evaluation is of key importance for testing laboratory, standards institute, enforcement and compliances technicians and evaluation experts. Thus, in development support, addition to technology transfer, also capacity buildings for national and local authorities should be provides. The Paris Agreement Article 11 aims at enhancing the capacity of decision-making institutions in developing countries to support effective implementation.

Enforcement of policies is of key importance. Policies on appliance energy standards needs to establish criteria for random checks and tests of compliance, establish penalties and sanctions for non-compliance. For building code compliance there is the need to verify compliance after construction to verify the consistence with building design (Vine et al. 2017). Often local authorities lack resources and technical capacity to carry out inspections to check code compliance. This issue is even more pressing in countries and cities with large informal settlements, where buildings may not be respecting building energy codes for safety and health.

9.10 Knowledge Gaps

Insights from regions, sectors, and communities

- Due to the dominating amount of literature from developed countries and rapidly developing Asia (China), the evidence and therefore conclusions are limited for the developing world. In particular, there is limited evidence on the potential and costs the countries of South-East Asia and Developing Pacific, Africa, and Latin America and Caribbean.
- The contribution of indigenous knowledge in the evolvement of buildings is not well appreciated. There is a need to understand this contribution and provide methodological approaches for incorporation of indigenous knowledge.
- Analysis of emissions and energy demand trends in non-residential buildings is limited due to the number of building types included in this category and the scarcity of data for each building type. The use of new data gathering techniques such as machine learning, GIS combined with digital technologies to fill in this data gap was not identified in the literature. Consideration of embodied emissions from building stock growth has only recently entered the global scenario literature, and more development is expected in this area.

Measures, potentials, and costs

- There is a lack of scientific reporting of case studies of exemplary buildings, specially from developing countries. Also, there is a lack of identification of researchers on technologies with the mitigation potential of such technologies, bringing a lack in quantification of that potential.
- There is limited evidence on sufficiency measures including those from behavioural energy saving practices: updated categorisations, current adoption rates and willingness to adopt.
- There is limited evidence on circular and shared economy in buildings, including taxonomies, potentials, current adoption rates and willingness to adopt
- Most of the literature on climate change impacts on buildings is focused on thermal comfort. There is need for further research on climate change impacts on buildings structure, materials and construction and the energy and emissions associated with those impacts. Also, more studies that assess the role of passive energy efficiency measures as adaptation options are needed. Finally, regional studies leave out in depth analyses of specific regions.

Feasibility and policies

- Applications of human centred profiles for targeted policy making and considering stages of diffusion of innovation, that is: what works (motivation) for whom (different stakeholders, not only households) and when (stages of market maturity)
- The multiple co-benefits of mitigation actions are rarely integrated into decision-making processes. So, there is a need to further develop methodologies to quantify and monetise these externalities as well as indicators to facilitate their incorporation in energy planning.

- Policies for sufficiency have to be further analysed and tested in real situation, including ex ante simulation and ex-post evaluation. The same is also valid for Personable (tradable) Carbon Allowances.

Methods and models

- There is limited literature on the integration of behavioural measures and lifestyle changes in modelling exercises
- Mitigation potential resulting from the implementation of sufficiency measures is not identified in global energy/climate and building scenarios despite the growing literature on sufficiency. At the best, mitigation potential from behaviour change is quantified in energy scenarios; savings from structural changes and resource efficiency are not identified in the literature on global and building energy models.
- The actual costs of the potential could be higher to rather optimistic assumptions of the modelling literature, e.g., assuming a 2-3% retrofit rate, and even higher, versus the current 1%. The uncertainty ranges of potential costs are not well understood.
- Despite a large number of exemplary buildings achieving very high performance in all parts of the world and a growing amount of modelling literature on the potential, if these will penetrate at scale, there is a lack of modelling literature assessing the costs of respective actions at national, regional, and global level based on comprehensive cost assessments.
- There is a lack of peer-reviewed literature on investment gaps, which compares the investment need in the building sector decarbonisation and recent investment flows into it estimated with the same costing methodologies.

Frequently Asked Questions

FAQ 9.1 To which GHG emissions do buildings contribute?

There are three categories of GHG emissions from buildings:

i. direct emissions which are defined as all on-site fossil fuel or biomass-based combustion activities (i.e., use of biomass for cooking, or gas for heating and hot water) and F-gas emissions (i.e., use of heating and cooling systems, aerosols, fire extinguishers, soundproof)
ii. indirect emissions which occur off-site and are related to heat and electricity production
iii. embodied emissions which are related to extracting, producing, transforming, transporting, and installing the construction material and goods used in buildings

In 2019, global GHG emissions from buildings were at 12 $GtCO_2$-eq out of which 24% were direct emissions, 57% were indirect emissions, and 18% were embodied emissions. More than 95% of emissions from buildings were CO2 emissions, CH_4 and N_2O represented 0.08% each and emissions from halocarbon contributed by 3% to global GHG emissions from buildings.

FAQ 9.2 What are the co-benefits and trade-offs of mitigation actions in buildings?

Mitigation actions in buildings generate multiple co-benefits (e.g., health benefits due to the improved indoor and outdoor conditions, productivity gains in non-residential buildings, creation of new jobs particularly at local level, improvements in social wellbeing etc.) beyond their direct impact on reducing energy consumption and GHG emissions. Most studies agree that the value of these multiple benefits is greater than the value of energy savings and their inclusion in economic evaluation of mitigation actions may improve substantially their cost-effectiveness. It is also worth mentioning that in several cases the buildings sector is characterized by strong rebound effects, which could be considered as a co-benefit in cases where the mechanisms involved provide faster access to affordable energy but also a trade-off in cases where the external costs of increased energy consumption exceed the welfare benefits of the increased energy service consumption, thus lowering the economic performance of mitigation actions. The magnitude of these co-benefits and trade-offs are characterized by several uncertainties, which may be even higher in the future as mitigation actions will be implemented in a changing climate, with changing building operation style and occupant behaviour. Mitigation measures influence the degree of vulnerability of buildings to future climate change. For instance, temperature rise can increase energy consumption, which may lead to higher GHG emissions. Also, sea level rise, increased storms and rainfall under future climate may impact building structure, materials and components, resulting in increased energy consumption and household expenditure from producing and installing new components and making renovations. Well-planned energy efficiency, sufficiency and on-site renewable energy production can help to increase building resilience to climate change impacts and reduce adaptation needs.

FAQ 9.3 Which are the most effective policies and measures to decarbonize the building sector?

Several barriers (information, financing, markets, behavioural, etc.) still prevents the decarbonisation of buildings stock, despite the several co-benefits, including large energy savings. Solutions include investments in technological solutions (e.g., insulation, efficient equipment, and low-carbon energies and renewable energies) and lifestyle changes. In addition, the concept of sufficiency is suggested to be promoted and implemented through policies and information, as technological solutions will be not enough to decarbonise the building sector. Due to the different types of buildings, occupants, and development stage there is not a single policy, which alone will reach the building decarbonisation target. A range of policy instruments ranging from regulatory measures such as building energy code for NZEBs and appliance standards, to market-based instruments (carbon tax, personal carbon allowance, renewable portfolio standards, etc.), and information. Financing (grants, loans, performance base incentives, pays as you save, etc.) is another key enabler for energy efficiency technologies and on-site renewables. Finally, effective governance and strong institutional capacity are key to have an effective and successful implementation of policies and financing.

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Chapter 10: Transport

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Date of Draft: 28/11/2021

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Executive summary

Meeting climate mitigation goals would require transformative changes in the transport sector *(high confidence*). In 2019, direct greenhouse gas (GHG) emissions from the transport sector were 8.7 Gt CO_2-eq (up from 5.0 Gt CO_2-eq in 1990) and accounted for 23% of global energy-related CO_2 emissions. 70% of direct transport emissions came from road vehicles, while 1%, 11%, and 12% came from rail, shipping, and aviation, respectively. Emissions from shipping and aviation continue to grow rapidly. Transport-related emissions in developing regions of the world have increased more rapidly than in Europe or North America, a trend that is likely to continue in coming decades (*high confidence*). {10.1, 10.5, 10.6}.

Since AR5 there has been a growing awareness of the need for demand management solutions combined with new technologies, such as the rapidly growing use of electromobility for land transport and the emerging options in advanced biofuels and hydrogen-based fuels for shipping and aviation. There is a growing need for systemic infrastructure changes that enable behavioural modifications and reductions in demand for transport services that can in turn reduce energy demand. The response to the COVID-19 pandemic has also shown that behavioural interventions can reduce transport-related GHG emissions. For example, COVID-19-based lockdowns have confirmed the transformative value of telecommuting replacing significant numbers of work and personal journeys as well as promoting local active transport. There are growing opportunities to implement strategies that drive behavioural change and support the adoption of new transport technology options. {Chapter 5, 10.2, 10.3, 10.4, 10.8}

Changes in urban form, behaviour programs, the circular economy, the shared economy, and digitalisation trends can support systemic changes that lead to reductions in demand for transport services or expands the use of more efficient transport modes (*high confidence*). Cities can reduce their transport-related fuel consumption by around 25% through combinations of more compact land use and the provision of less car-dependent transport infrastructure. Appropriate infrastructure, including protected pedestrian and bike pathways, can also support much greater localised active travel[1]. Transport demand management incentives are expected to be necessary to support these systemic changes *(high confidence)*. There is mixed evidence of the effect of circular economy initiatives, shared economy initiatives, and digitalisation on demand for transport services. For example, while dematerialisation can reduce the amount of material that need to be transported to manufacturing facilities, an increase in online shopping with priority delivery can increase demand for freight transport. Similarly, while teleworking could reduce travel demand, increased ridesharing could increase vehicle-km travelled. {Chapter 1, Chapter 5, 10.2, 10.8}

Battery-electric vehicles (BEVs) have lower life cycle greenhouse gas emissions than internal combustion engine vehicles (ICEVs) when BEVs are charged with low carbon electricity (*high confidence*). Electromobility is being rapidly implemented in micro-mobility (e-autorickshaws, e-scooters, e-bikes), in transit systems, especially buses, and, to a lesser degree, in the electrification of personal vehicles. BEVs could also have the added benefit of supporting grid operations. The commercial availability of mature Lithium-Ion Batteries (LIBs) has underpinned this growth in electromobility.

As global battery production increases, unit costs are declining. Further efforts to reduce the GHG footprint of battery production, however, are essential for maximising the mitigation potential of BEVs. The continued growth of electromobility for land transport would require investments in electric charging and related grid infrastructure (*high confidence*). Electromobility powered by low-carbon

FOOTNOTE [1] Active travel is travel that requires physical effort, for example journeys made by walking or cycling.

electricity has the potential to rapidly reduce transport GHG and can be applied with multiple co-benefits in the developing world's growing cities (*high confidence*). {10.3, 10.4, 10.8}

Land-based, long-range, heavy-duty trucks can be decarbonised through battery-electric haulage (including the use of Electric Road Systems), complemented by hydrogen- and biofuel-based fuels in some contexts (*medium confidence*). These same technologies and expanded use of available electric rail systems can support rail decarbonisation *(medium confidence*). Initial deployments of battery-electric, hydrogen- and bio-based haulage are underway, and commercial operations of some of these technologies are considered feasible by 2030 (*medium confidence*). These technologies nevertheless face challenges regarding driving range, capital and operating costs, and infrastructure availability. In particular, fuel cell durability, high energy consumption, and costs continue to challenge the commercialisation of hydrogen-based fuel cell vehicles. Increased capacity for low-carbon hydrogen production would also be essential for hydrogen-based fuels to serve as an emissions reduction strategy (*high confidence*). {10.3, 10.4, 10.8}

Decarbonisation options for shipping and aviation still require R&D, though advanced biofuels, ammonia, and synthetic fuels are emerging as viable options *(medium confidence*). Increased efficiency has been insufficient to limit the emissions from shipping and aviation, and natural gas-based fuels are likely inadequate to meet stringent decarbonisation goals for these segments (*high confidence*). High energy density, low carbon fuels are required, but they have not yet reached commercial scale. Advanced biofuels could provide low carbon jet fuel (*medium confidence*). The production of synthetic fuels using low-carbon hydrogen with CO_2 captured through DAC/BECCS could provide jet and marine fuels but these options still require demonstration at scale (*low confidence*). Ammonia produced with low-carbon hydrogen could also serve as a marine fuel (*medium confidence*). Deployment of these fuels requires reductions in production costs. {10.2, 10.3, 10.4, 10.5, 10.6, 10.8}.

Scenarios from bottom-up and top-down models indicate that without intervention, CO_2 emissions from transport could grow in the range of 16% and 50% by 2050 (*medium confidence).* The scenarios literature projects continued growth in demand for freight and passenger services, particularly in developing countries in Africa and Asia (*high confidence*). This growth is projected to take place across all transport modes. Increases in demand not-withstanding, scenarios that limit warming to 1.5°C degree with no or limited overshoot suggest that a 59% reduction (42-68% interquartile range) in transport-related CO_2 emissions by 2050, compared to modelled 2020 levels is required. While many global scenarios place greater reliance on emissions reduction in sectors other than transport, a quarter of the 1.5°C degree scenarios describe transport-related CO_2 emissions reductions in excess of 68% (relative to modelled 2020 levels) (*medium confidence)*. Illustrative mitigation pathways 1.5 REN and 1.5 LD describe emission reductions of 80% and 90% in the transport sector, respectively, by 2050. Transport-related emission reductions, however, may not happen uniformly across regions. For example, transport emissions from the Developed Countries, and Eastern Europe and West-Central Asia (EEA) countries decrease from 2020 levels by 2050 across all scenarios compatible with a 1.5°C degree goal (C1 - C2 group), but could increase in Africa, Asia and developing Pacific (APC), Latin America and Caribbean, and the Middle East in some of these scenarios. {10.7}

The scenarios literature indicates that fuel and technology shifts are crucial to reducing carbon emissions to meet temperature goals. In general terms, electrification tends to play the key role in land-based transport, but biofuels and hydrogen (and derivatives) could play a role in decarbonisation of freight in some contexts (*high confidence*). Biofuels and hydrogen (and derivatives) are likely more prominent in shipping and aviation (high confidence). The shifts towards these alternative fuels must occur alongside shifts towards clean technologies in other sectors (*high confidence*). {10.7}.

There is a growing awareness of the need to plan for the significant expansion of low-carbon energy infrastructure, including low-carbon power generation and hydrogen production, to support emissions reductions in the transport sector (*high confidence*). Integrated energy planning and operations that take into account energy demand and system constraints across all sectors (transport, buildings, and industry) offer the opportunity to leverage sectoral synergies and avoid inefficient allocation of energy resources. Integrated planning of transport and power infrastructure would be particularly useful in developing countries where 'greenfield' development doesn't suffer from constraints imposed by legacy systems. {10.3, 10.4, 10.8}

The deployment of low-carbon aviation and shipping fuels that support decarbonisation of the transport sector could require changes to national and international governance structures (*medium confidence*). Currently, the Paris Agreement does not specifically cover emissions from international shipping and aviation. Instead, accounting for emissions from international transport in the Nationally Determined Contributions is at the discretion of each country. While the ICAO and IMO have established emissions reductions targets, only strategies to improve fuel efficiency and demand reductions have been pursued, and there has been minimal commitment to new technologies. Some literature suggests that explicitly including international shipping and aviation under the governance of the Paris Agreement could spur stronger decarbonisation efforts in these segments. {10.5, 10.6, 10.7}

There are growing concerns about resource availability, labour rights, non-climate environmental impacts, and costs of critical minerals needed for LIBs (*medium confidence*). Emerging national strategies on critical minerals and the requirements from major vehicle manufacturers are leading to new, more geographically diverse mines. The standardisation of battery modules and packaging within and across vehicle platforms, as well as increased focus on design for recyclability are important. Given the high degree of potential recyclability of LIBs, a nearly closed-loop system in the future could mitigate concerns about critical mineral issues (*medium confidence*). {10.3, 10.8}

Legislated climate strategies are emerging at all levels of government, and, together with pledges for personal choices, could spur the deployment of demand and supply-side transport mitigation strategies (***medium confidence*****).** At the local level**,** legislation can support local transport plans that include commitments or pledges from local institutions to encourage behaviour change by adopting an organisational culture that motivates sustainable behaviour with inputs from the creative arts. Such institution-led mechanisms could include bike-to-work campaigns, free transport passes, parking charges, or eliminating car benefits. Community-based solutions like *solar sharing*, *community charging*, and *mobility as a service* can generate new opportunities to facilitate low-carbon transport futures. At the regional and national levels, legislation can include vehicle and fuel efficiency standards, R&D support, and large-scale investments in low-carbon transport infrastructure. {10.8, Chapter 15}

10.1 Introduction and overview

This chapter examines the transport sector's role in climate change mitigation. It appraises the transport system's interactions beyond the technology of vehicles and fuels to include the full life cycle analysis of mitigation options, a review of enabling conditions, and metrics that can facilitate advancing transport decarbonisation goals. The chapter assesses developments in the systems of land-based transport and introduces, as a new feature since AR5, two separate sections focusing on the trends and challenges in aviation and shipping. The chapter assesses the future trajectories emerging from global, energy, and national scenarios and concludes with a discussion on enabling conditions for transformative change in the sector.

This section (10.1) discusses how transport relates to virtually all the Sustainable Development Goals (SDGs), the trends and drivers making transport a big contributor in greenhouse gas (GHG) emissions, the impacts climate change is having on transport that can be addressed as part of mitigation, and the overview of emerging transport disruptions with potential to shape a low carbon transport pathway.

10.1.1 Transport and the sustainable development goals

The adoption of the 2030 Agenda for Sustainable Development by the United Nations (UN) has renewed international efforts to pursue and accurately measure global actions towards sustainable development (United Nations 2015). The 17 SDGs set out the overall goals that are further specified by 169 targets and 232 SDG indicators, many of which relate to transport (United Nations 2017; Lisowski et al. 2020). A sustainable transport system provides safe, inclusive, affordable, and clean passenger and freight mobility for current and future generations (Williams 2017; Litman 2021) so transport is particularly linked to SDGs 3, 7, 8, 9, 11, 12, and 13 (Move Humanity 2018; WBA 2019; SLoCaT 2019; Yin 2019; IRP 2019). Table 10.1 summarises transport-related topics for these SDGs and corresponding research. Section 17.3.3.7 (in Chapter 17) also provides a cross sectoral overview of synergies and trade-offs between climate change mitigation and the SDGs.

Table 10.1 Main transport-related SDGs

	Sustainable Development Goals: Synergies and trade-offs				
	Basic human needs	**Earth preconditions**	**Sustainable resource use**	**Social and economic development**	**Universal values**
					
Transport-related topics (Low carbon Transport; Active transport; Electric vehicles.	- Lower air pollution contributes to positive health outcomes. - Energy access can contribute to poverty alleviation.	- Reduction of GHG emissions along the entire value chain, e.g. Well-to-Wheel (WTW). - Further development addressing minor GHG emissions and pollutants.	- Share of renewable energy use. - Energy efficiency of vehicles. - Clean and affordable energy off-grid.	- Role of transport for economic and human development. - Decarbonised public transport rather than private vehicle use.	- Gender equality in transport. - Reduced Inequalities. - Enables access to quality education.

	- Transport planning a major player in reducing poverty in cities. - Access to healthcare Diseases from air pollution. - Injuries and deaths from traffic accidents. - Reduced stress level from driving. - Links between active transport and good health with positive effects of walking and cycling. - Improving road accessibility to disabled users. - Reduce time spent on transport/mobility.	- Transport Oriented to Sustainable Development (TOD). - Circular economy principle applied to transport.	- Reduce material consumption during production, life cycle analysis of vehicles and their operations including entire value chains. - Close loop carbon and nutrient cycle linked to circular economy.	- Transport Oriented to Sustainable Development (TOD). - Sustainable transport infrastructure and systems for cities and rural areas. - Affordability of mobility services, this can also be covered under "universal access" to public transport. - Accessibility vs. mobility: Mobility to opportunities; Transport equity; Development as freedom. - Positive economic growth (employment) outcomes due to resource efficiency and lower productive energy cost. - Role of transport provision in accessing work, reconfiguration of social norms, as working from home. - Transport manufacturers as key employers changing role of transport-related labour due to platform economy, and innovations in autonomous vehicles.	- Partnership for the goals.

References	(Grant et al. 2016; Haines et al. 2017; Cheng et al. 2018; Nieuwenhuijsen 2018; Smith et al. 2018; Sofiev et al. 2018; Peden and Puvanachandra 2019; King and Krizek 2020; Macmillan et al. 2020)	(Farzaneh et al. 2019); see particularly following chapters.	(SLoCaT 2019); see particularly following chapters.	(Bruun and Givoni 2015; Pojani and Stead 2015; Hensher 2017; ATAG 2018; Grzelakowski 2018; Weiss et al. 2018; Brussel et al. 2019; Gota et al. 2019; Mohammadi et al. 2019; Peden and Puvanachandra 2019; SLoCaT 2019; Xu et al. 2019)	(Hernandez 2018; Prati 2018; Levin and Faith-Ell 2019; Vecchio et al. 2020)

10.1.2 Trends, drivers and the critical role of transport in GHG growth

The transport sector directly emitted around 8.9 Gt Carbon dioxide equivalent (CO_2eq) in 2019, up from 5.1 Gt CO_2eq in 1990 (Figure 10.1). Global transport was the fourth largest source of GHG emissions in 2019 following the power, industry, and the Agriculture, Forestry and Land Use (AFOLU) sectors. In absolute terms, the transport sector accounts for roughly 15% of total greenhouse gas (GHG) emissions and about 23% of global energy-related CO_2 emissions (IEA 2020a). Transport GHG emissions have increased fast over the last two decades, and since 2010, the sector's emissions have increased faster than for any other end-use sector, averaging +1.8% annual growth (see Section 10.7). Addressing emissions from transport is crucial for GHG mitigation strategies across many countries, as the sector represents the largest energy consuming sector in 40% of countries worldwide. In most remaining countries, transport is the second largest energy-consuming sector, reflecting different levels of urbanisation and land use patterns, speed of demographic changes and socio-economic development (IEA 2012; Hasan et al. 2019; Xie et al. 2019; Gota et al. 2019).

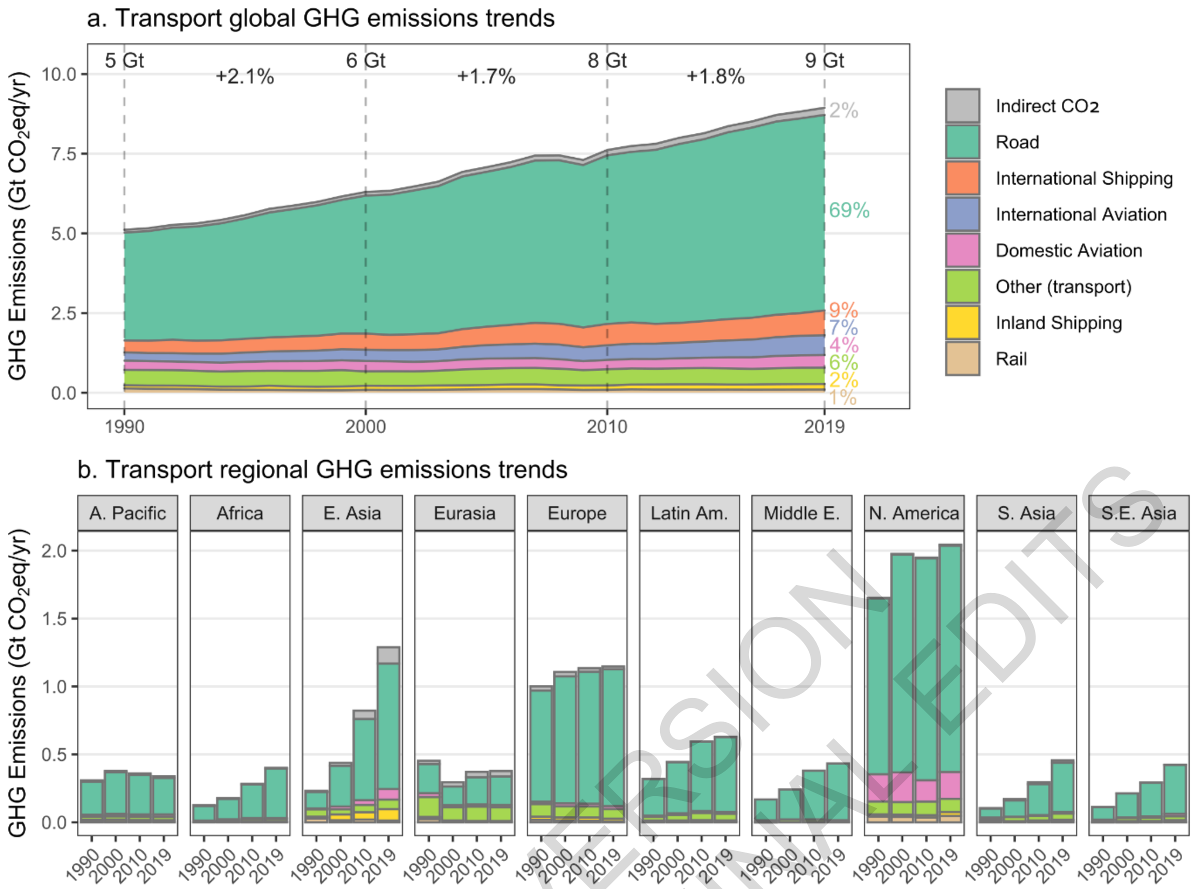

Figure 10.1 Global and regional transport GHG emissions trends. Indirect emissions from electricity and heat consumed in transport are shown in panel (a) and are primarily linked to the electrification of rail systems. These indirect emissions do not include the full life cycle emissions of transportation systems (e.g., vehicle manufacturing and infrastructure), which are assessed in section 10.4. International aviation and shipping are included in panel (a), but excluded from panel (b). Indirect emissions from fuel production, vehicle manufacturing and infrastructure construction are not included in the sector total. Source: Adapted from (Lamb et al. 2021) using data from (Minx et al. 2021)**.**

As of 2019, the largest source of transport emissions is the movement of passengers and freight in road transport (6.1 Gt CO_2eq, 69% of the sector's total). International shipping is the second largest emission source, contributing 0.8 Gt CO_2eq (9% of the sector's total), and international aviation is third with 0.6 Gt CO_2eq (7% of the sector's total). All other transport emissions sources, including rail, have been relatively trivial in comparison, totalling 1.4 Gt CO_2eq in 2019. Between 2010-2019, international aviation had one of the fastest growing GHG emissions among all segments (+3.4% per year), while road transport remained one of the fastest growing (+1.7% per year) among all global energy using sectors. Note that the COVID-19-induced economic lockdowns implemented since 2020 have had a very substantial impact on transport emissions – higher than any other sector (see chapter 2). Preliminary estimates from Crippa et al. (2021) suggest that global transport CO_2 emissions declined to 7.6 $GtCO_2$ in 2020, a reduction of 11.6% compared to 2019 (Crippa et al. 2021; Minx et al. 2021). These lockdowns affected all transport segments, and particularly international aviation (estimated -45% reduction in 2020 global CO_2 emissions), road transport (-10%), and domestic aviation (-9.3%). By comparison, aggregate CO_2 emissions across all sectors are estimated to have declined by 5.1% as a result of the COVID-19 pandemic (Chapter 2, section 2.2.2).

Growth in transport-related GHG emissions has taken place across most world regions (see Figure 10.1, panel b). Between 1990 and 2019, growth in emissions was relatively slow in Europe, Asia Pacific, Eurasia, and North America while it was unprecedently fast in other regions. Driven by economic and population growth, the annual growth rates in East Asia, South Asia, South East Asia, and Africa were 6.1%, 5.2%, 4.7%, and 4.1%, respectively. Latin America and the Middle East have seen somewhat slower growth in transport-related GHG emission (annual growth rates of 2.4% and 3.3%, respectively) (ITF 2019; Minx et al. 2021). Section 10.7 provides a more detailed comparison of global transport emissions trends with those from regional and sub-sectoral studies.

The rapid growth in global transport emissions is primarily a result of the fast growth in global transport activity levels, which grew by 73% between 2000 and 2018. Passenger and freight activity growth have outpaced energy efficiency and fuel economy improvements in this period (ITF 2019) . The global increase in passenger travel activities has taken place almost entirely in non-OECD countries, often starting from low motorization rates (SLoCaT 2018a). Passenger cars, two-and-three wheelers, and mini buses contribute about 75% of passenger transport-related CO_2 emissions, while collective transport services (bus and railways) generates about 7% of the passenger transport-related CO_2 emissions despite covering a fifth of passenger transport globally (Rodrigue 2017; Halim et al. 2018; Sheng et al. 2018; SLoCaT 2018a; Gota et al. 2019). While alternative lighter powertrains have great potential for mitigating GHG emissions from cars, the trend has been towards increasing vehicle size and engine power within all vehicle size classes, driven by consumer preferences towards larger sport utility vehicles (SUVs) (IEA 2020a). On a global scale, SUV sales have been constantly growing in the last decade, with 40% of the vehicles sold in 2019 being SUVs (IEA 2020a) – see Section 10.4, Box 10.3.

Indirect emissions from electricity and heat shown in Figure 10.1 account for only a small fraction of current emissions from the transport sector (2%) and are associated with electrification of certain modes like rail or bus transport (Lamb et al. 2021). Increasing transport electrification will affect indirect emissions, especially where carbon-intense electricity grids operate.

Global freight transport, measured in tonne-kilometres (tkm), grew by 68% between 2000 and 2015 and is projected to grow 3.3 times by 2050 (ITF 2019). If unchecked, this growth will make decarbonisation of freight transport very difficult (McKinnon 2018; ITF 2019). International trade and global supply chains from industries frequently involving large geographical distances are responsible for the fast increase of CO_2 emissions from freight transport (Yeh et al. 2017; McKinnon 2018), which are growing faster than emissions from passenger transport (Lamb et al. 2021). Heavy-duty vehicles (HDVs) make a disproportionate contribution to air pollution, relative to their global numbers, because of their substantial emissions of particulate matter and of black carbon with high short-term warming potentials (Anenberg et al. 2019).

On-road passenger and freight vehicles dominate global transport-related CO_2 emissions and offer the largest mitigation potential (Taptich et al. 2016; Halim et al. 2018). This chapter examines a wide range of possible transport emission reduction strategies. These strategies can be categorised under the 'Avoid- Shift-Improve' (ASI) framework described in Chapter 5 (Taptich et al. 2016). Avoid strategies reduce total vehicle-travel. They include compact communities and other policies that minimise travel distances and promote efficient transport through pricing and demand management programs. Shift strategies shift travel from higher-emitting to lower-emitting modes. These strategies include more multimodal planning that improves active and collective transport modes, complete streets roadway design, High Occupant Vehicle (HOV) priority strategies that favour shared mode, Mobility as a Service (MaaS), and multimodal navigation and payment apps. Improve strategies reduce per-kilometre emission rates. These strategies include hybrid and electric vehicle incentives, lower carbon and cleaner fuels, high emitting vehicle scrappage programs, and efficient driving and anti-idling campaigns (Lutsey and Sperling 2012; Gota et al. 2015). These topics are assessed within the rest of this chapter including how combinations of ASI with new technologies can potentially lead from incremental interventions into low carbon transformative transport improvements that include social and equity benefits (see section 10.8).

10.1.3 Climate adaptation on the transport sector

Climate change impacts such as extremely high temperatures, intense rainfall leading to flooding, more intense winds and/or storms, and sea level rise can seriously impact transport infrastructure, operations, and mobility for road, rail, shipping, and aviation. Studies since AR5 confirm that serious challenges to all transport infrastructures are increasing, with consequent delays or derailing (Miao et al. 2018; Moretti and Loprencipe 2018; Pérez-Morales et al. 2019; Palin et al. 2021). These impacts have been increasingly documented but, according to (Forzieri et al. 2018), little is known about the risks of multiple climate extremes on critical infrastructures at local to continental scales. All roads, bridges, rail systems, and ports are likely to be affected to some extent. Flexible pavements are particularly vulnerable to extreme high temperatures that can cause permanent deformation and crumbling of asphalt (Underwood et al. 2017; Qiao et al. 2019). Rail systems are also vulnerable, with a variety of hazards, both meteorological and non-meteorological, affecting railway asset lifetimes. Severe impacts on railway infrastructure and operations can arise from the occurrence of temperatures below freezing, excess precipitation, storms and wildfires (Thaduri et al. 2020; Palin et al. 2021) as are underground transport systems (Forero-Ortiz et al. 2020).

Most countries are examining opportunities for combined mitigation-adaptation efforts, using the need to mitigate climate change through transport-related GHG emissions reductions and pollutants as the basis for adaptation action (Thornbush et al. 2013; Wang et al. 2020). For example, urban sprawl indirectly affects climate processes, increasing emissions and vulnerability, which worsens the potential to adapt (Congedo and Munafò 2014; Macchi and Tiepolo 2014). Hence, using a range of forms of rapid transit as structuring elements for urban growth can mitigate climate change-related risks as well as emissions, reducing impacts on new infrastructure, often in more vulnerable areas (Newman et al. 2017). Such changes are increasingly seen as having economic benefit (Ha et al. 2017), especially in developing nations (Chang 2016; Monioudi et al. 2018).

Since AR5 there has been a growing awareness of the potential and actual impacts from global sea level rise due to climate change on transport systems (Dawson et al. 2016; Rasmussen et al. 2018; IPCC 2019; Noland et al. 2019), particularly on port facilities (Stephenson et al. 2018; Yang et al. 2018b; Pérez-Morales et al. 2019). Similarly, recent studies suggest changes in global jet streams could affect the aviation sector (Staples et al. 2018; Becken and Shuker 2019), and extreme weather conditions can affect runways (heat buckling) and aircraft lift. Combined, climate impacts on aviation could result in payload restrictions and disruptions (Coffel et al. 2017; Monioudi et al. 2018). According to (Williams 2017), studies have indicated that the amount of moderate-or-greater clear-air turbulence on transatlantic flight routes in winter will increase significantly in the future as the climate changes. More research is needed to fully understand climate induced risks to transportation systems.

10.1.4 Transport disruption and transformation

Available evidence suggests that transport-related CO_2 emissions would need to be restricted to about 2 to 3 Gt in 2050 (1.5°C scenario-1.5DS, B2DS), or about 70 to 80% below 2015 levels, to meet the goals set in the Paris Agreement. It also indicates that a balanced and inter-modal application of Avoid, Shift, and Improve measures is capable of yielding an estimated reduction in transport emissions of 2.39 Gt of CO_2-equivalent by 2030 and 5.74 Gt of CO_2-equivalent by 2050 (IPCC 2018; Gota et al. 2019). Such a transformative decarbonisation of the global transport system requires, in addition to technological changes, a paradigm shift that ensures prioritisation of high-accessibility transport solutions that minimise the amount of mobility required to meet people's needs, and favours transit and active transport modes (Lee and Handy 2018; SLoCaT 2021). These changes are sometimes called disruptive as they are frequently surprising in how they accelerate through a technological system.

The assessment of transport innovations and their mitigation potentials is at the core of how this chapter examines the possibilities for changing transport-related GHG trajectories. The transport technology innovation literature analysed in this chapter emphasises how a mixture of mitigation technology options and social changes are now converging and how, in combination, they may have potential to accelerate trends toward a low carbon transport transition. Such changes are considered disruptive or transformative (Sprei 2018). Of the current transport trends covered in the literature, this chapter focuses on three key technology and policy areas: electro-mobility in land-based transport vehicles, new fuels for ships and planes, and overall demand reductions and efficiency. These strategies are seen as being necessary to integrate at all levels of governance and, in combination with the creation of fast, extensive, and affordable multi-modal public transport networks, can help achieve multiple advantages in accordance with SDGs

Electrification of passenger transport in light-duty vehicles (LDVs) is well underway as a commercial process with socio-technical transformative potential and will be examined in detail in Sections 10.3 and 10.4. But the rapid mainstreaming of EV's will still need enabling conditions for land transport to achieve the shift away from petroleum fuels, as outlined in Chapter 3 and detailed in Section 10.8. The other mitigation options reviewed in this chapter are so far only incremental and are less commercial, especially shipping and aviation fuels, so stronger enabling conditions are likely, as detailed further in Sections 10.5 to 10.8. The enabling conditions that would be needed for the development of an emerging technological solution for such fuels are likely to be very different to electromobility, but nevertheless they both will need demand and efficiency changes to ensure they are equitable and inclusive.

Section 10.2 sets out the transformation of transport through examining systemic changes that affect demand for transport services and the efficiency of the system. Section 10.3 looks at the most promising technological innovations in vehicles and fuels. The next three sections (10.4, 10.5, and 10.6) examine mitigation options for land transport, aviation, and shipping. Section 10.7 describes the space of solutions assessed in a range of integrated modelling and sectoral transport scenarios; Finally, Section 10.8 sets out what would be needed for the most transformative scenario that can manage to achieve the broad goals set out in Chapter 3 and the transport goals set out in Section 10.7.

10.2 Systemic changes in the transport sector

Systemic change is the emergence of new organisational patterns that affect the structure of a system. While much attention has been given to engine and fuel technologies to mitigate GHG emissions from the transport sector, population dynamics, finance and economic systems, urban form, culture, and policy also drive emissions from the sector. Thus, systemic change requires innovations in these components. These systemic changes offer the opportunity to decouple transport emissions from economic growth. In turn, such decoupling allows environmental improvements like reduced GHG emissions without loss of economic activity (UNEP 2011, 2013; Newman et al. 2017; IPCC 2018).

There is evidence that suggests decoupling of transport emissions and economic growth is already happening in developed and developing countries. Europe and China have shown the most dramatic changes (Huizenga et al. 2015; Gao and Newman 2018; SLoCaT 2018b) and many cities are demonstrating decoupling of transport-related emissions through new net zero urban economic activity (Loo and Banister 2016; SLoCaT 2018a). A continued and accelerated decoupling of the growth of transport-related GHG emissions from economic growth is crucial for meeting the SDGs outlined in

Section 1. This section focuses on several overlapping components of systemic change in the transport sector that affect the drivers of GHG emissions: Urban form, physical geography, and infrastructure; behaviour and mode choice; and new demand concepts. Table 10.3, at the end of the section provides a high-level summary of the effect of these systemic changes on emissions from the transport sector.

10.2.1 Urban form, physical geography, and transport infrastructure

The physical characteristics that make up built areas define the urban form. These physical characteristics include the shape, size, density, and configuration of the human settlements. Urban form is intrinsically coupled with the infrastructure that allows human settlements to operate. In the context of the transport sector, urban form and urban infrastructure influence the time and cost of travel, which, in turn, drive travel demand and modal choice (Marchetti and Ausubel 2004; Newman and Kenworthy 2015).

Throughout history, three main urban fabrics have developed, each with different effects on transport patterns based on a fixed travel time budget of around one hour (Newman et al. 2016). The high-density urban fabric developed over the past several millennia favoured walking and active transport for only a few kilometres (kms). In the mid-19th century, urban settlements developed a medium density fabric that favoured trains and trams traveling over 10 to 30-km corridors. Finally, since the mid-20th century, urban form has favoured automobile travel, enabling mass movement between 50-60 kms. Table 10.2 describes the effect of these urban fabrics on GHG emissions and other well-being indicators.

Table 10.2 The systemic effect of city form and transport emissions

Annual Transport Emissions and Co-Benefits	Walking Urban Fabric	Transit Urban Fabric	Automobile Urban Fabric
Transport GHG	4 t/person	6 t/person	8 t/person
Health benefits from walkability	High	Medium	Low
Equity of locational accessibility	High	Medium	Low
Construction and household waste	0.87 t/person	1.13 t/person	1.59 t/person
Water consumption	35 kl/person	42 kl/person	70 kl/person
Land	133 m^2/person	214 m^2/person	547 m^2/person
Economics of infrastructure and transport operations	High	Medium	Low

Source: (Newman et al. 2016; Thomson and Newman 2018; Seto et al. 2021)

Since AR5, urban design has increasingly been seen as a major way to influence the GHG emissions from urban transport systems. Indeed, research suggests that implementing urban form changes could reduce GHG emissions from urban transport by 25% in 2050, compared with a business-as-usual scenario (Creutzig et al. 2015b; Creutzig 2016). Researchers have identified a variety of variables to study the relationship between urban form and transport-related GHG emissions. Three notable aspects summarise these relationships: urban space utilisation, urban spatial form, and urban transportation infrastructure (Tian et al. 2020). Urban density (population or employment density) and land use mix define the urban space utilisation. Increases in urban density and mixed function can effectively reduce per capita car use by reducing the number of trips and shortening travel distances. Similarly, the continuity of urban space and the dispersion of centres reduces travel distances (Tian et al. 2020), though such changes are rarely achieved without shifting transport infrastructure investments away from road capacity increases (Newman and Kenworthy 2015; McIntosh et al. 2017) For example, increased investment in public transport coverage, optimal transfer plans, shorter transit travel time, and improved transit travel efficiency make public transit more attractive (Heinen et al. 2017; Nugroho et al. 2018a,b) and hence increase density and land values (Sharma and Newman 2020). Similarly, forgoing the development of major roads for the development of pedestrian and bike pathways enhances the attractiveness of active transport modes (Zahabi et al. 2016; Keall et al. 2018; Tian et al. 2020).

Ultimately, infrastructure investments influence the structural dependence on cars, which in turn influence the lock-in or path dependency of transport options with their greenhouse emissions (Newman et al. 2015b; Grieco and Urry 2016). The 21st century saw a new trend to reach peak car use in some countries as a result of a revival in walking and transit use (Grieco and Urry 2016; Newman et al. 2017; Gota et al. 2019). While some cities continue on a trend towards reaching peak car use on a per-capita basis, for example Shanghai and Beijing (Gao and Newman 2020), there is a need for increased investments in urban form strategies that can continue to reduce car-dependency around the world.

START CROSS-CHAPTER BOX HERE

Cross-Chapter Box 7 Urban Form: Simultaneously reducing urban transport emissions, avoiding infrastructure lock-in, and providing accessible services

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Urban transport is responsible for about 8% of global CO_2 emissions or 3 Gt CO_2 per year (see Chapters 5 and 8). In contrast to energy supply technologies, urban transport directly interacts with mobility lifestyles (see Section 5.4). Similarly, non-GHG emission externalities, such as congestion, air pollution, noise, and safety, directly affect urban quality of life, and result in considerable welfare losses. Low-carbon, highly accessible urban design is not only a major mitigation option, it also provides for more inclusive city services related to wellbeing (Chapter 5, Sections 5.1 and 5.2). Urban planning and design of cities for people are central to realise emission reductions without relying simply on technologies, though the modes of transport favoured will influence the ability to overcome the lock-in around automobile use (Gehl 2010; Creutzig et al. 2015b).

Where lock-in has occurred, other strategies may alleviate the GHG emissions burden. Urban planning still plays a key role in recreating local hubs. Available land can be used to build rail-based transit, made financially viable by profiting from land value captured around stations (Ratner and Goetz 2013). Shared or pooled mobility can offer flexible on-demand mobility solutions that are efficient also in suburbs and for integrating with longer commuting trips (ITF 2017).

Global emission trajectories of urban transport will be decided in rapidly urbanising Asia and Africa. Urban transport-related GHG emissions are driven by incomes and car ownership but there is considerable variation amongst cities with similar income and car ownership levels (Newman and Kenworthy 2015). While electrification is a key strategy to decarbonise urban transport, urban infrastructures can make a difference of up to a factor of 10 in energy use and induced GHG emissions (Erdogan 2020). Ongoing urbanisation patterns risk future lock-in of induced demand on GHG emissions, constraining lifestyles to energy intensive and high CO_2-related technologies (See Section 5.4; 8.2.3; 10.2.1; (Erickson and Tempest 2015; Seto et al. 2016). Instead, climate solutions can be locked into urban policies and infrastructures (Ürge-Vorsatz et al. 2018) especially through the enhancement of the walking and transit urban fabric. Avoiding urban sprawl, associated with several externalities (Dieleman and Wegener 2004), is a necessary decarbonisation condition, and can be guided macro-economically by increasing fuel prices and marginal costs of motorised transport (Creutzig 2014). Resulting urban forms not only reduce GHG emission from transport but also from buildings, as greater compactness results in reduced thermal loss (Borck and Brueckner 2018). Health benefits from reduced car dependence are an increasing element driving this policy agenda (Section 10.8; (Speck 2018)).

Low-carbon highly accessible urban design is not only a major mitigation option, it also provides for more inclusive city services related to wellbeing (Chapter 5, Sections 5.1 and 5.2). Solutions involve planning cities around walkable sub-centres, where multiple destinations, such as shopping, jobs, leisure activities, and others, can be accessed within a 10 minute walk or bicycle ride (Newman and Kenworthy 2006). Overall, the mitigation potential of urban planning is about 25% in 2050 compared with a business as usual scenario (Creutzig et al. 2015a,b). Much higher levels of decarbonisation can be achieved if cities take on a regenerative development approach and act as geo-engineering systems on the atmosphere (Thomson and Newman 2016).

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10.2.2 Behaviour and mode choice

Behaviour continues to be a major source of interest in the decarbonisation of transport as it directly addresses demand. Behaviour is about people's actions based on their preferences. Chapter 5 described an 'Avoid, Shift, Improve' process for demand-side changes that affect sectoral emissions. This section discusses some of the drivers of behaviour related to the transport sector and how they link to this 'Avoid, Shift, Improve' process.

Avoid - the effect of prices and income on demand: Research has shown that household income and price have a strong influence on people's preferences for transport services (Bakhat et al. 2017; Palmer et al. 2018). The relationship between income and demand is defined by the income elasticity of demand. For example, research suggests that in China, older and wealthier populations continued to show a preference for car travel (Yang et al. 2019) while younger and low-income travellers sought variety in transport modes (Song et al. 2018). Similarly, (Bergantino et al. 2018b) evaluated the income elasticity of transport by mode in the UK. They found that the income elasticity for private cars is 0.714, while the income elasticities of rail and bus use are 3.253 (The greater elasticity the greater the demand will grow or decline, depending on income). Research has also shown a positive relationship between income and demand for air travel, with income elasticities of air travel demand being positive and as large as 2 (Gallet and Doucouliagos 2014; Valdes 2015; Hakim and Merkert 2016, 2019; Hanson et al. 2022). A survey in 98 Indian cities also showed income as the main factor influencing travel demand (Ahmad and de Oliveira 2016). Thus, as incomes and wealth across the globe rise, demand for travel is likely to increase as well.

The price elasticity of demand measures changes in demand as a result of changes in the prices of the services. In a meta-analysis of the price elasticity of energy demand, (Labandeira et al. 2017) report the average long-term price elasticity of demand for gasoline and diesel to be -0.773 and -0.443, respectively. That is, demand will decline with increasing prices. A similar analysis of long-term data in the United States (US), the United Kingdom (UK), Sweden, Australia, and Germany reports the gasoline price elasticity of demand for car travel (as measured through vehicle-kilometre -vkm- per capita) ranges between -0.1 and -0.4 (Bastian et al. 2016). For rail travel, the price elasticity of demand has been found to range between -1.05 and -1.1 (Zeng et al. 2021). Similarly, price elasticities for air travel range from -0.53 to -1.91 depending on various factors such as purpose of travel (business or leisure), season, and month and day of departure (Morlotti et al. 2017). The price elasticities of demand suggest that car use is inelastic to prices, while train use is relatively inelastic to the cost of using rail. Conversely, consumers seem to be more responsive to the cost of flying, so that strategies that increase the cost of flying are likely to contribute to some avoidance of aviation-related GHG emissions.

While the literature continues to show that time, cost, and income dominate people's travel choices (Ahmad and de Oliveira 2016; Capurso et al. 2019; He et al. 2020), there is also evidence of a role for personal values, and environmental values in particular, shaping choices within these structural limitations (Bouman and Steg 2019). For example, individuals are more likely to drive less when they care about the environment (De Groot et al. 2008; Abrahamse et al. 2009; Jakovcevic and Steg 2013; Hiratsuka et al. 2018; Ünal et al. 2019). Moreover, emotional and symbolic factors affect the level of car use (Steg 2005). Differences in behaviour may also result due to differences in gender, age, norms, values, and social status. For example, women have been shown to be more sensitive to parking pricing than men (Simićević et al. 2020).

Finally, structural shocks, such as a financial crisis, a pandemic, or the impacts of climate change could affect the price and income elasticities of demand for transport services (van Ruijven et al. 2019). COVID-19 lock-downs reduced travel demand by 19% (aviation by 32%) and some of the patterns that have emerged from the lockdowns could permanently change the elasticity of demand for transport (Tirachini and Cats 2020; Hendrickson and Rilett 2020; Newman 2020a; SLoCaT 2021; Hanson et al. 2022). In particular, the COVID-19 lock-downs have spurred two major trends: electronic communications replacing many work and personal travel requirements; and, revitalised local active transport and e-micro-mobility (Newman 2020a; SLoCaT 2021). The permanence of these changes post- COVID-19 is uncertain but possible ((Early and Newman 2021); see Box on COVID-19, chapter 1). However, these changes will require growth of infrastructure for better ICT bandwidths in developing countries, and better provision for micro-mobility in all cities.

Shift - Mode choice for urban and intercity transport: Shifting demand patterns (as opposed to avoiding demand) can be particularly important in decarbonising the transport sector. As a result, the cross-elasticity of demand across transport modes is of particular interest for understanding the opportunities for modal shift. The cross-elasticity represents the demand effect on mode i (e.g. bus) when an attribute of mode j (e.g. rail) changes marginally. Studies on the cross-elasticities of mode choice for urban travel suggest that the cross-elasticity for car demand is low, but the cross-elasticities of walking, bus, and rail with respect to cars are relatively large (Fearnley et al. 2017; Wardman et al. 2018). In practice, these cross-elasticities suggest that car drivers are not very responsive to increased prices for public transit, but transit users are responsive to reductions in the cost of driving. When looking at the cross-elasticities of public transit options (bus vs. metro vs. rail), research suggests that consumers are particularly sensitive to in-vehicle and waiting time when choosing public transit modes (Fearnley et al. 2018). These general results provide additional evidence that increasing the use of active and public transport requires interventions that make car use more expensive while making public transit more convenient (e.g. with smart apps that explain the exact time for transit arrival, see Box 10.1).

The literature on mode competition for intercity travel reveals that while cost of travel is a significant factor (Zhang et al. 2017), sensitivity decreases with increasing income as well as when the cost of the trip was paid by someone else (Capurso et al. 2019). Some research suggests little competition between bus and air travel but the cross-elasticity between air and rail suggest strong interactions (Wardman et al. 2018). Price reduction strategies such as discounted rail fares could enhance the switch from air travel to high-speed rail. Both air fares and flight frequency impact high speed rail (HSR) usage (Zhang et al. 2019b). Airline companies reduce fares on routes that are directly competing with HSR (Bergantino et al. 2018a) and charge high fares on non-HSR routes (Xia and Zhang 2016). On the Rome-Milan route, better frequency and connections, and low costs of HSR resulting from competition between HSR companies has significantly reduced air travel and shares of buses and cars (Desmaris and Croccolo 2018).

Finally, and as noted in Chapter 5, recent research shows that individual, social, and infrastructure factors also affect people's mode choices. For example, perceptions about common travel behaviour (what people perceive to be "normal" behaviour) influences their travel mode choice. The research suggests that well-informed individuals whose personal norms match low-carbon objectives, and who believe they have control over their decisions are most motivated to shift mode. Nonetheless, such individual and social norms can only marginally influence mode choice unless infrastructure factors can enable reasonable time and cost savings (Convery and Williams 2019; Javaid et al. 2020; Feng et al. 2020; Wang et al. 2021).

Improve – consumer preferences for improved and alternative vehicles: While reductions in demand for travel and changes in the mode choice can contribute to reducing GHG emissions from the transport sector, cars are likely to continue to play a prominent role. As a result, improving the performance of cars will be crucial for the decarbonisation of the transport sector. Sections 10.3 and 10.4 describe the technological options available for reduced CO_2 emissions from vehicles. The effectiveness in deploying such technologies will partly depend on consumer preferences and their effect on adoption rates. Given the expanded availability of electric vehicles, there is also a growing body of work on the drivers of vehicle choice. A survey in Nanjing found women had more diverse travel purposes than men, resulting in a greater acceptance of electric bikes (Lin et al. 2017). Individuals are more likely to adopt an electric vehicle (EV) when they think this adoption benefits the environment or implies a positive personal attribute (Noppers et al. 2014, 2015; Haustein and Jensen 2018). Other work suggests that people's preference for EVs depends upon vehicle attributes, infrastructure availability, and policies that promote EV adoption, specifically, purchasing and operating costs, driving range, charging duration, vehicle performance, and brand diversity (Liao et al. 2016). Behaviour change to enable transport transformations will need to make the most of these factors whilst also working on the more structural issues of time, space, and cost.

10.2.3 New demand concepts

Structural and behavioural choices that drive transport-related GHG emissions, such as time and cost based on geography of freight and urban fabric, are likely to continue to be major factors. But there is also a variation within each structural choice that is based around personal demand factors related to values that indirectly change choices in transport. Chapter 5 identified three megatrends that affect demand for services, including circular economy, the shared economy, and digitalisation. These three megatrends can have specific effect on transport emissions, as described below.

Circular Economy: The problem of resources and their environmental impacts is driving the move to a circular economy (Bleischwitz et al. 2017). Circular economy principles include increased material efficiency, re-using or extending product lifetimes, recycling, and green logistics. Dematerialisation, the reduction in the quantity of the materials used in the production of one unit of output, is a circular economy principle that can affect the operations and emissions of the transport sector, as reductions in the quantities of materials used reduces transport needs, while reductions in the weight of products improves the efficiency of transporting them. Dematerialisation can occur through more efficient production processes but also when a new product is developed to provide the same functionality as multiple products. The best example of this trend is a smart phone, which provides the service of at least 22 other former devices (Rivkin 2019). A move to declutter lifestyles can also drive dematerialisation (Whitmarsh et al. 2017). Some potential for dematerialisation has been suggested due to 3-D printing, which would also reduce transport emissions through localised production of product components (d'Aveni 2015; UNCTAD 2018). There is evidence to suggest, however, that reductions in material use resulting from more efficient product design or manufacturing are offset by increased consumer demand (Kasulaitis et al. 2019). Whether or not dematerialisation can lead to reduction of emissions from the transport sector is still an open questions that requires evaluating the entire product ecosystem (Van Loon et al. 2014; Coroama et al. 2015; Kasulaitis et al. 2019).

Shared Economy. Shared mobility is arguably the most rapidly growing and evolving sector of the sharing economy and includes bike sharing, e-scooter sharing, car-sharing, and on-demand mobility (Greenblatt and Shaheen 2015). The values of creating a more shared economy are related to both reduced demand and greater efficiency, as well as the notion of community well-being associated with the act of sharing instead of simply owning for oneself (Maginn et al. 2018; Sharp 2018). The literature on shared mobility is expanding, but there is much uncertainty about the effect shared mobility will have on transport demand and associated emissions (Nijland and Jordy 2017; ITF 2018a; Tikoudis et al. 2021).

Asia represents the largest car-sharing region with 58% of worldwide membership and 43% of global fleets deployed (Dhar et al. 2020). Europe accounts for 29% of worldwide members and 37% of shared vehicle fleets (Shaheen et al. 2018). Ride-sourcing and carpooling systems are amongst the many new entrants in the short-term shared mobility options. On-demand transport options complemented with technology have enhanced the possibility of upscaling (Alonso-González et al. 2018). Car-sharing could provide the same level of service as taxis, but taxis could be three times more expensive (Cuevas et al. 2016). The sharing economy, as an emerging economic-technological phenomenon (Kaplan and Haenlein 2010), is likely to be a key driver of demand for transport of goods although data shows increasing container movement due to online shopping (Suel and Polak 2018).

There is growing evidence that this more structured form of behavioural change through shared economy practices, supported by a larger group than a single family, has a much greater potential to save transport emissions, especially when complemented with decarbonised grid electricity (Greenblatt and Shaheen 2015; Sharp 2018). Carpooling, for example, could result in an 11% reduction in vkm and a 12% reduction in emissions, as carpooling requires less empty or non-productive passenger-kilometres (pkm) (ITF 2020a,b). However, the use of local shared mobility systems such as on-demand transport may create more transport emissions if there is an overall modal shift out of transit (ITF 2018a; Schaller 2018). Similarly, some work suggests that commercial shared vehicle services such as Uber and Lyft are leading to increased vehicle kms travelled (and associated GHG emissions) in part due to deadheading (Schaller 2018; Tirachini and Gomez-Lobo 2020; Ward et al. 2021). Successful providers compete by optimising personal comfort and convenience rather than enabling a sharing culture (Eckhardt and Bardhi 2015), and concerns have been raised regarding the wider societal impacts of these systems and for specific user groups such as older people (Fitt 2018; Marsden 2018). Concerns have also been expressed over the financial viability of demand-responsive transport systems (Ryley et al. 2014; Marsden 2018), how the mainstreaming of shared mobility systems can be institutionalised equitably, and the operation and governance of existing systems that are only mode and operator-focused (Akyelken et al. 2018; Jittrapirom et al. 2018; Pangbourne et al. 2020; Marsden 2018).

Digitalisation: In the context of the transport sector, digitalisation has enabled teleworking, which in turn reduces travel demand. On the other hand, the prevalence of online shopping, enabled by the digital economy, could have mixed effects on transport emissions (Le et al. 2021). For example, online shopping could reduce vkm travelled but the move to expedited or rush delivery could mitigate some benefits as they prevent consolidation of freight (Jaller and Pahwa 2020).

Digitalisation could also lead to systemic changes by enabling smart mobility. The smart mobility paradigm refers to the process and practices of assimilation of ICTs and other sophisticated hi-technology innovations into transport (Noy and Givoni 2018). Smart mobility can be used to influence transport demand and efficiency (Benevolo et al. 2016). The synergies of emerging technologies (ICT, IOT, Big Data) and shared economy could overcome some of the challenges facing the adoption of emerging technologies (Marletto 2014; Chen et al. 2016; Weiss et al. 2018; Taiebat and Xu 2019) and enable the expected large growth in emerging cities to be more sustainable (Docherty et al. 2018). However, ICT, in particular IoT, could also cause more global energy demand (Hittinger and Jaramillo 2019). Box 10.1 summarises the main smart technologies being adopted rapidly by cities across the world and their use in transport. There is a growing body of literature about the effect of smart technology (including sensors guiding vehicles) on the demand for transport services. Smart technologies can improve competitiveness of transit and active transport over personal vehicle use by combining the introduction of new electro-mobility that improves time and cost along with behaviour change factors (Henrik et al. 2017; SLoCaT 2018a,b, 2021). However, it is unclear what will be the net effect of smart technology on the GHG emissions from the transport sector (Debnath et al. 2014; Lenz and Heinrichs 2017).

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Box 10.1 Smart city technologies and transport

Information and Communication Technology (ICT): ICT is at the core of Smart Mobility and will provide the avenue for data to be collected and shared across the mobility system. The use of ICT can help cities by providing real-time information on mobility options that can inform private vehicles along with transit users or those using bikes, or who are walking. ICT can help with ticketing and payment for transit or for road user charges (Tafidis et al. 2017; Gössling 2018) when combined with other technologies such as Blockchain (Hargroves et al. 2020).

Internet of Things (IoT) Sensors: Sensors can be used to collect data to improve road safety, improve fuel efficiency of vehicles, and reduce CO_2 emissions (Kubba and Jiang 2014; Kavitha et al. 2018). Sensors can also provide data to digitally simulate transport planning options, inform the greater utilisation of existing infrastructure and modal interconnections, and significantly improve disaster and emergency responses (Hargroves et al. 2017). In particular, IoT sensors can be used to inform the operation of fast-moving Trackless Tram and its associated last mile connectivity shuttles as part of a transit activated corridor (Newman et al. 2019, 2021).

Mobility as a Service (MaaS): New, app-based mobility platforms will allow for the integration of different transport modes (such as last mile travel, shared transit, and even micro-transit such as scooters or bikes) into easy-to-use platforms. By integrating these modes, users will be able to navigate from A to B to C based on which modes are most efficient with the necessary bookings and payments being made through the one service. With smart city planning, these platforms can steer users towards shared and rapid-transit (which should be the centre-piece of these systems), rather than encourage more people to opt for the perceived convenience of booking a single-passenger ride (Becker et al. 2020). In low density car-dependent cities, however, MaaS services such as the use of electric scooters/bikes are less effective as the distances are too long and they do not enable the easy sharing that can happen in dense station precincts (Jittrapirom et al. 2017).

Artificial Intelligence (AI) and Big Data Analytics: The rapidly growing level of technology enablement of vehicles and urban infrastructure, combined with the growing ability to analyse larger and larger data sets, presents a significant opportunity for transport planning, design, and operation in the future. These technologies are used together to enable decisions about what kind of transport planning is used down particular corridors. Options such as predictive congestion management of roads and freeways, simulating planning options, and advanced shared transit scheduling can provide value to new and existing transit systems (Toole et al. 2015; Anda et al. 2017; Hargroves et al. 2017).

Blockchain or Distributed Ledger Technology: Blockchain Technology provides a non-hackable database that can be programmed to enable shared services like a local, solar microgrid where both solar and shared electric vehicles can be managed (Green and Newman 2017). Blockchain can be used for many transport-related applications including being the basis of MaaS or any local shared mobility service as it facilitates shared activity without intermediary controls. Other applications include verified vehicle ownership documentation, establishing identification, real-time road user pricing, congestion zone charging, vehicle generated collision information, collection of tolls and charges, enhanced freight tracking and authenticity, and automated car parking and payments (Hargroves et al. 2020). This type of functionality will be particularly valuable for urban regeneration along a transit-activated corridor where it can be used for managing shared solar in and around station precincts as well as managing shared vehicles linked to the whole transport system (Newman et al. 2021). This technology can also be used for road user charging along any corridor and by businesses accessing any services and in managing freight (Carter and Koh 2018; Nguyen et al. 2019; Sedlmeir et al. 2020; Hargroves et al. 2020).

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Autonomous vehicles are the other emerging transport technology that have the potential to significantly improve ride quality and safety. Planes and high-speed trains are already largely autonomous as they are guided in all their movements, especially coming into stations and airports, although that does not necessarily mean they are driverless. Automation is also being used in new on-road transit systems like Trackless Trams (Ndlovu and Newman 2020)). Private vehicles are being fitted with more and more levels of autonomy and many are being trialled as 'driverless' in cities (Aria et al. 2016; Skeete 2018). If autonomous systems can be used to help on-road transit become more time and cost competitive with cars, then the kind of transformative and disruptive changes needed to assist decarbonisation of transport become more feasible (Bösch et al. 2018; Kassens-Noor et al. 2020; Abe 2021). Similarly, vehicle automation could improve vehicle efficiency and reduce congestion, which would in turn reduce emissions (Vahidi and Sciarretta 2018; Massar et al. 2021). On the other hand, if autonomous cars make driving more convenient, they could reduce demand for transit (Auld et al. 2017; Sonnleitner et al. 2021). Paradoxically, autonomous cars could provide access to marginal groups such as the elderly, people with disabilities, and those who cannot drive, which could in turn increase travel demand (as measured by pkm) (Harper et al. 2016).

Heavy haulage trucks in the mining industry are already autonomous (Gaber et al. 2021) and automation of long-haul trucks may happen sooner than automation of LDVs (Hancock et al. 2019). Autonomous trucks may facilitate route, speed optimisation, and reduced fuel use, which can in turn reduce emissions (Nasri et al. 2018; Paddeu and Denby 2021). There is growing interest in using drones for package delivery. Drones could have lower impacts than ground-based delivery and, if deployed carefully, drones could reduce energy use and GHG emissions from freight transport (Stolaroff et al. 2018). Overall, some commentators are optimistic that smart and autonomous technologies can transform the GHG from the transport sector (Seba 2014; Rivkin 2019; Sedlmeir et al. 2020). Others are more sanguine unless policy interventions can enable the technologies to be used for purposes that include zero carbon and the SDGs (Faisal et al. 2019; Hancock et al. 2019).

10.2.4 Overall perspectives on systemic change

The interactions between systemic factors set out here and technology factors discussed in much more detail in the next sections, show that there is always going to be a need to integrate both approaches. Good technology that has the potential to transform transport will not be used unless it fulfils broad mobility and accessibility objectives related to time, cost, and well-being. Chapter 5 has set out three transport transformations based on demand-side factors with highly transformative potential. Table 10.3 provides a summary of these systemic changes and their likely impact on GHG emissions. Note that the quantitative estimates provided in the table may not be additive and the combined effect of these strategies on GHG emissions from the transport sector require additional analysis.

Table 10.3 Components of systemic change and their impacts on the transport sector

Systemic Change	**Mechanisms through which it affects emissions in transport sector and likely impact on emissions**
Changes in urban form	Denser, more compact polycentric cities with mixed land use patterns can reduce the distance between where people live, work, and pursue leisure activities, which can reduce travel demand. Case studies suggest that these changes in urban form could reduce transport-related GHG emissions between 4-25%, depending on the setting (Creutzig et al. 2015a,b; Pan et al. 2020).
Investments in transit and active transport infrastructure	Improving public transit systems and building infrastructure to support active transport modes (walking and biking) could reduce car travel. Case studies suggest that active mobility could reduce emissions from urban transport by 2%-10% depending on the setting (Creutzig et al. 2016; Zahabi et al. 2016; Keall et al. 2018; Gilby et al. 2019; Neves and Brand 2019; Bagheri et al. 2020; Ivanova et al. 2020; Brand et al. 2021). A shift to public transit modes can likely offer significant emissions reductions, but estimates are uncertain.
Changes in economic structures	Higher demand as a result of higher incomes could increase emissions, particularly in aviation and shipping. Higher prices could have the opposite effect and reduce emission. Structural changes associated with financial crises, pandemics, or the impacts of climate change could affect the elasticity of demand in uncertain ways. Thus, the effect of changes in economic structures on the GHG emissions from the transport sectors is uncertain.
Teleworking	A move towards a digital economy that allows workers to work remotely and access information remotely could reduce travel demand. Case studies suggest that teleworking could reduce transport emissions by 20% in some instances, but are likely 1%, at most, across the entire transport system (Roth et al. 2008; O'Keefe et al. 2016; Shabanpour et al. 2018; O'Brien and Aliabadi 2020).
Dematerialisation of the economy	A reduction in goods needed due to combining multiple functions into one device would reduce the need for transport. Reduced weights associated with dematerialisation would improve the efficiency of freight transport. However, emissions reductions from these efforts are likely dwarfed by increased consumption of goods.
Supply chain management	Supply chains could be optimised to reduce the movement or travel distance of product components. Logistics planning could optimise the use of transport infrastructure to increase utilization rates and decrease travel. The effect of these strategies on the GHG emissions from the transport sector is uncertain.
e-commerce	The effect of e-commerce on transport emissions is uncertain. Increased e-commerce would reduce demand for trips to stores but could increase demand for freight transport (particularly last-mile delivery) (Jaller and Pahwa 2020; Le et al. 2021).
Smart mobility	ICT and smart city technologies can be used to improve the efficiency of operating the transport system. Furthermore, smart technologies can improve competitiveness of transit and active transport over personal vehicle use by streamlining mobility options to compete with private cars. The effect of smart mobility on the GHG emissions from the transport sector is uncertain (Creutzig 2021).

Shared mobility	Shared mobility could increase utilisation rates of LDVs, thus improving the efficiency of the system. However, shared mobility could also divert users from transit systems or active transport modes. Studies on ride-sourcing have reported both potential for reductions and increases in transport-related emissions (Schaller 2018; Ward et al. 2021). Other case studies suggests that carpooling to replace 20% of private car trips could result in a 12% reduction in GHG (ITF 2020a,b).Thus, the effect of shared mobility on transport-related GHG emissions is highly uncertain.
Vehicle automation	Vehicle automation could have positive or negative effects on emissions. Improved transit operations, more efficient traffic management, and better routing for light- and heavy-duty transport could reduce emissions (Vahidi and Sciarretta 2018; Nasri et al. 2018; Massar et al. 2021; Paddeu and Denby 2021). However, autonomous cars could make car travel more convenient, removing users from transit systems and increasing access to marginalised groups, which would in turn increase vkms travelled (Harper et al. 2016; Auld et al. 2017; Sonnleitner et al. 2021). Drones could reduce energy use and GHG emissions from freight transport (Stolaroff et al. 2018)

10.3 Transport technology innovations for decarbonisation

This section focuses on vehicle technology and low-carbon fuel innovations to support decarbonisation of the transport sector. Figure 10.2 summarises the major pathways reviewed in this section. The advancements in energy carriers described in Figure 10.2 are discussed in greater detail in Chapter 6 (Energy) and Chapter 11 (Industry) but the review presented in this chapter highlights their application in the transport sector. This section pays attention to the advancements in alternative fuels, electric, and fuel cell technologies since AR5.

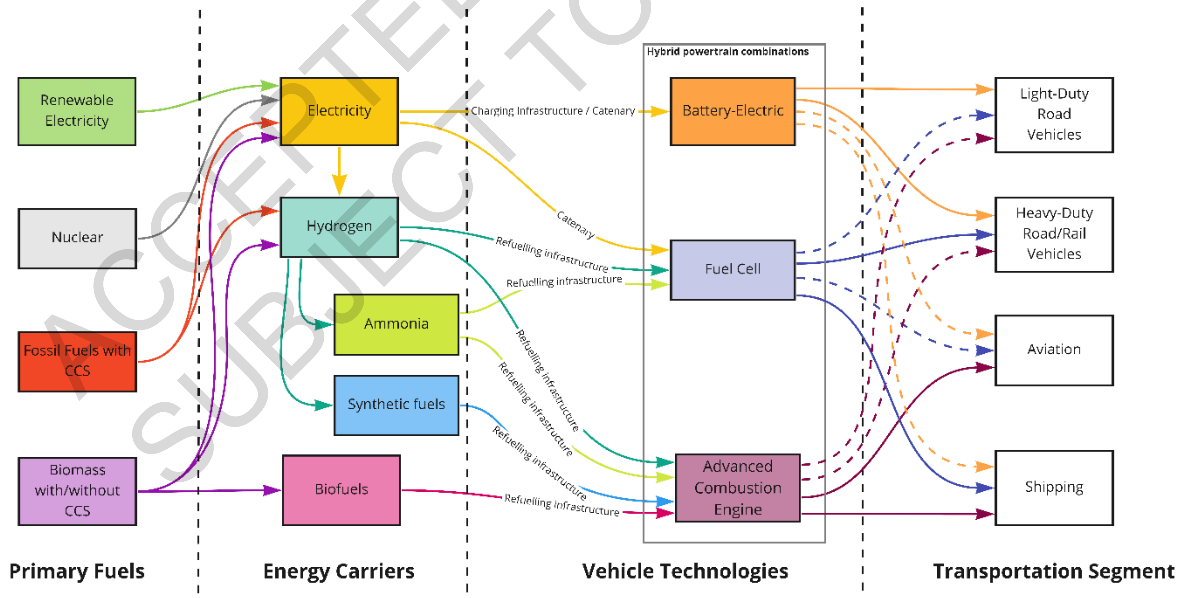

Figure 10.2 Energy pathways for low-carbon transport technologies. Primary energy sources are shown in the far left, while the segments of the transport system are in the far right. Energy carriers and vehicle technologies are represented in the middle. Primary pathways are shown with solid lines, while dashed lined represent secondary pathways.

10.3.1 Alternative fuels – an option for decarbonising internal combustion engines

The average fuel consumption of new Internal Combustion Engine (ICE) vehicles has improved significantly in recent years due to more stringent emission regulations. However, improvements are now slowing down. The average fuel consumption of LDVs decreased by only 0.7 % between 2016 and 2017, reaching 7.2 litres of gasoline-equivalent (Lge) per 100 km in 2017, much slower than the 1.8 % improvement per year between 2005 and 2016 (GFEI 2020). Table 10.4 summarises recent and forthcoming improvements to ICE technologies and their effect on emissions from these vehicles. However, these improvements are not sufficient to meet deep decarbonisation levels in the transport sector. While there is significant and growing interest in electric and fuel-cell vehicles, future scenarios indicate that a large number of LDV may continue to be operated by ICE in conventional, hybrid, and plug-in hybrid configurations over the next 30 years (IEA 2019a) unless they are regulated away through ICE vehicle sales bans (as some nations have announced) (IEA 2021a). Moreover, ICE technologies are likely to remain the prevalent options for shipping and aviation. Thus, reducing CO_2 and other emissions from ICEs through the use of low-carbon or zero-carbon fuels is essential to a balanced strategy for limiting atmospheric pollutant levels. Such alternative fuels for ICE vehicles include natural gas-based fuels, biofuels, Ammonia, and other synthetic fuels.

Table 10.4 Engine technologies to reduce emissions from light-duty ICE vehicles and their implementation stage. Table nomenclature: GDI = Gasoline direct injection, VVT = Variable valve technology, CDA = Cylinder deactivation, CR = compression ratio, GDCI = Gasoline direct injection compression ignition, EGR = exhaust gas recirculation, RCCI = Reactivity controlled compression ignition, GCI = Gasoline compression ignition. Source: (Joshi 2020)

Implementation Stage	Engine Technology	CO_2 Reduction (%)
Implemented	Baseline: GDI, turbo, stoichiometry.	0
Development	Atkinson cycle (+ VVT)	3 - 5
	Dynamic CDA + Mild Hybrid or Miller	10 -15
	Lean-burn GDI	10 - 20
	Variable CR	10
	Spark assisted GCI	10
	GDCI	15 - 25
	Water Injection	5 - 10
	Pre-chamber concepts	15 - 20
	Homogeneous Lean	15 - 20
	Dedicated EGR	15 - 20
	2-stroke opp. piston Diesel	25 - 35
	RCCI	20 - 30

Natural Gas: Natural gas could be used as an alternative fuel to replace gasoline and diesel. Natural gas in vehicles can be used as compressed natural gas (CNG) and liquefied natural gas (LNG). CNG is gaseous at relatively high pressure (10 to 25 MPa) and temperature (-40 to 30ºC). In contrast, LNG is used in liquid form at relatively low pressure (0.1 MPa) and temperature (-160ºC). Therefore, CNG is particularly suitable for commercial vehicles and light- to medium-duty vehicles, whereas LNG is better suited to replace diesel in HDVs (Dubov et al. 2020; Dziewiatkowski et al. 2020; Yaïci and Ribberink 2021). CNG vehicles have been widely deployed in some regions, particularly in Asian-Pacific countries. For example, there are about 6 million CNG vehicles domiciled in China, the most of any country (Qin et al. 2020). However, only 20% of vehicles that operate using CNG were originally designed as CNG vehicles, with the rest being gasoline-fuelled vehicles that have been converted to operate with CNG (Chala et al. 2018).

Natural gas-based vehicles have certain advantages over conventional fuel-powered ICE vehicles, including lower emissions of criteria air pollutants, no soot or particulate, low carbon to Hydrogen ratio, moderate noise, a wide range of flammability limits, and high-octane numbers (Kim 2019; Bayat and Ghazikhani 2020). Furthermore, the technology readiness of natural gas vehicles is very high (TRL 8-9), with direct modification of existing gasoline and diesel vehicles possible (Transport and Environment 2018; Peters et al. 2021; Sahoo and Srivastava 2021). On the other hand, methane emissions from the natural gas supply chain and tailpipe CO_2 emissions remain a significant concern (Trivedi et al. 2020). As a result, natural gas as a transition transportation fuel may be limited due to better alternative options being available and due to regulatory pressure to decarbonise the transport sector rapidly. For example, the International Maritime Office (IMO) has set a target of 40% less carbon intensity in shipping by 2030, which cannot be obtained by simply switching to natural gas.

Biofuels: Since AR5, the faster than anticipated adoption of electromobility, primarily for LDVs, has partially shifted the debate around the primary use of biofuels from land transport to the shipping and aviation sectors (Davis et al. 2018; IEA 2017a).At the same time, other studies highlight that biofuels may have to complement electromobility in road transport, particularly in developing countries, offering relevant mitigation opportunities in the short- and mid-term (up to 2050) (IEA 2021b). An important advantage of biofuels is that they can be converted into energy carriers compatible with existing technologies, including current powertrains and fuel infrastructure. Also, biofuels can diversify the supply of transport fuel, raise energy self-sufficiency in many countries, and be used as a strategy to diversify and strengthen the agro-industrial sector (Puricelli et al. 2021). The use of biofuels as a mitigation strategy is driven by a combination of factors, including not only the costs and technology readiness levels of the different biofuel conversion technologies, but also the availability and costs of both biomass feedstocks and alternative mitigation options, and the relative speed and scale of the energy transition in energy and transport sectors (Box 10.2).

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Box 10.2 – Bridging land use and feedstock conversion footprints for biofuels

Under specific conditions, biofuels may represent an important climate mitigation strategy for the transport sector (Muratori et al. 2020; Daioglou et al. 2020). Both SR1.5 and SRCCL highlighted that biofuels could be associated with climate mitigation co-benefits and adverse side effects to many SDGs. These side-effects depend on context-specific conditions, including deployment scale, associated land-use changes and agricultural management practices (see Section 7.4.4 and Box 7.10 in Chapter 7). There is broad agreement in the literature that the most important factors in determining the climate footprint of biofuels are the land use and land use change characteristics associated with biofuel deployment scenarios e.g. (Elshout et al. 2015; Daioglou et al. 2020). This issue is covered in more detail in Chapter 7, Box 7.1. While the mitigation literature primarily focuses on the GHG-related climate forcings, note that land is an integral part of the climate system through multiple geophysical and geochemical mechanisms (albedo, evaporation, etc.). For example, Sections 2.2.7, 7.3.4 in the WGI report indicate that geophysical aspects of historical land use change outweigh the geochemical effects, leading to a net cooling effect. The land-related carbon footprints of biofuels presented in sections 10.4-10.6 are adopted from Chapter 7 (See section 7.4.4 and Box 7, Figure 7.1). The results show how the land-related footprint increases due to an increased outtake of biomass, as estimated with different models that rely on global supply scenarios of biomass for energy and fuel of 100 EJ. The integrated assessment models and scenarios used include the EMF 33 scenarios (IAM-EMF33), from partial models with constant land cover (PM-CLC), and from partial models with natural regrowth (PM-NGR). These results are combined with both biomass cultivation emission ranges for advanced biofuels aligned with (Edwards et al. 2017; El Akkari et al. 2018; Jeswani et al. 2020; Puricelli et al. 2021) and conversion efficiencies and conversion phase emissions as described in Table 10.5. The modelled footprints resulting from land use changes related to delivering 100 EJ of biomass at global level are in the range of 3 – 77 gCO_2eq./MJ of advanced biofuel (median 38 gCO_2eq./MJ) at an aggregate level for IAMs and partial models, with constant land cover (Rose et al. 2020; Daioglou et al. 2020). The results for partial models with natural regrowth are much higher (91-246 CO_2eq./MJ advanced biofuel. The latter ranges may appear in contrast with the results from the scenario literature in 10.7, where biofuels play a role in many scenarios compatible low warming levels. This contrast is a result of different underlying modelling practices. The general modelling approach used for the scenarios in the AR6 database accounts for the land-use change and all other GHG emissions along a given transformation trajectory, enabling assessments of the warming level incurred. The results labelled "EMF33" and "partial models with constant land cover" are obtained with this modelling approach. The results in the category "partial models with natural regrowth" attribute additional CO_2 emissions to the bioenergy system, corresponding to estimated uptake of CO_2 in a counterfactual scenario where land is not used for bioenergy, but instead subject to natural vegetation regrowth. While the partial analysis provides insights into the implications of alternative land-use strategies, such analysis does not identify the actual emissions of bioenergy production. As a result, the partial analysis is not compatible with the identification of warming levels incurred by an individual transformation trajectory, and therefore not aligned with the general approach applied for the scenarios in the AR6 database.

More details on land-use change impacts and the potential to deliver the projected demands of biofuels at the global level are further addressed in Chapter 7. While, in general, the above results cover most of the variety of GHG range intensities of biofuel options presented in the literature, the more specific LCA literature should be consulted when considering specific combinations of biomass feedstock and conversion technologies in specific regions.

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Many studies have addressed the life cycle emissions of biofuel conversion pathways for land transport, aviation, and marine applications, e.g. (Edwards et al. 2017; Staples et al. 2018; Tanzer et al. 2019). Bioenergy technologies generally struggle to compete with existing fossil fuel-based ones because of the higher costs involved. However, the extent of the cost gap depends critically on the availability and costs of biomass feedstock (IEA 2021b). Ethanol from corn and sugarcane is commercially available in countries such as Brazil and the US. Biodiesel from oil crops and hydro-processed esters and fatty acids are available in various countries, notably in Europe and parts of Southeast Asia. On the infrastructure side, biomethane blending is being implemented in some regions of the US and Europe, particularly in Germany, with the help of policy measures (IEA 2021b). While many of these biofuel conversion technologies could also be implemented using seaweed feedstock options, these value chains are not yet mature (Jiang et al. 2016).

Technologies to produce advanced biofuels from lignocellulosic feedstocks have suffered from slow technology development and are still struggling to achieve full commercial scale. Their uptake is likely to require carbon pricing and/or other regulatory measures, such as clean fuel standards in the transport sector or blending mandates. Several commercial-scale advanced biofuels projects are in the pipeline in many parts of the world, encompassing a wide selection of technologies and feedstock choices, including carbon capture and sequestration (CCS) that supports carbon dioxide removal (CDR). The success of these projects is vital to moving forward the development of advanced biofuels and bringing many of the advanced biofuels' value chains closer to the market (IEA 2021b). Finally, biofuel production and distribution supply chains involve notable transport and logistical challenges that need to be overcome. (Mawhood et al. 2016; Skeer et al. 2016; IEA 2017a; Puricelli et al. 2021).

Table **10.5** summarises performance data for different biofuel technologies, while Figure 10.3 shows the technology readiness levels, which are based on (Mawhood et al. 2016; Skeer et al. 2016; IEA 2017a; Puricelli et al. 2021).

Table 10.5 Ranges of efficiency, GHG emissions, and relative costs of selected biofuel conversion technologies for road, marine, and aviation biofuels.

Main application	Conversion technology	Energy efficiency of conversion[a]	GHG emissions of conversion process ($gCO_{2eq.}/MJ_{fuel}$)[b]	Relative cost of conversion process
Road	Lignocellulosic ethanol	35%[c]	5[d]	Medium
Road/Aviation	Gasification and Fischer-Tropsch synthesis	57%[e]	<1[d]	High
Road	Ethanol from sugar and starch	60-70%[f]	1 – 31[d]	Low
Road	Biodiesel from oil crops	95%[g]	12 - 30 [d]	Low
Marine	Upgraded pyrolysis oil	30 - 61%[h]	1-4[h]	Medium
Aviation/Marine	Hydro-processed esters and fatty acids	80%[i]	3[i]	Medium
Aviation	Alcohol to jet	90%[j]	<1[k]	High
Road/Marine	Biomethane from residues	60%[l]	n.a.	Low
Marine/Aviation	Hydrothermal liquefaction	35-69%[h]	<1[h]	High
Aviation	Sugars to hydrocarbons	65%[m]	15[m]	High

Road	Gasification and syngas fermentation	40%n	30-40n	High

Notes: [a]Calculated as liquid fuels output divided by energy in feedstock entering the conversion plant; [b]GHG emission here refers only the conversion process. Impacts form the different biomass options are not included here as they are addressed in Chapter 7; [c](Olofsson et al. 2017); [d](Edwards et al. 2017); [e](Simell et al. 2014); [f](de Souza Dias et al. 2015); [g](Castanheira et al. 2015); [h](Tanzer et al. 2019); [i](Klein et al. 2018); [j](Narula et al. 2017); [k](de Jong et al. 2017); [l](Salman et al. 2017); [m](Moreira et al. 2014; Roy et al. 2015; Handler et al. 2016)

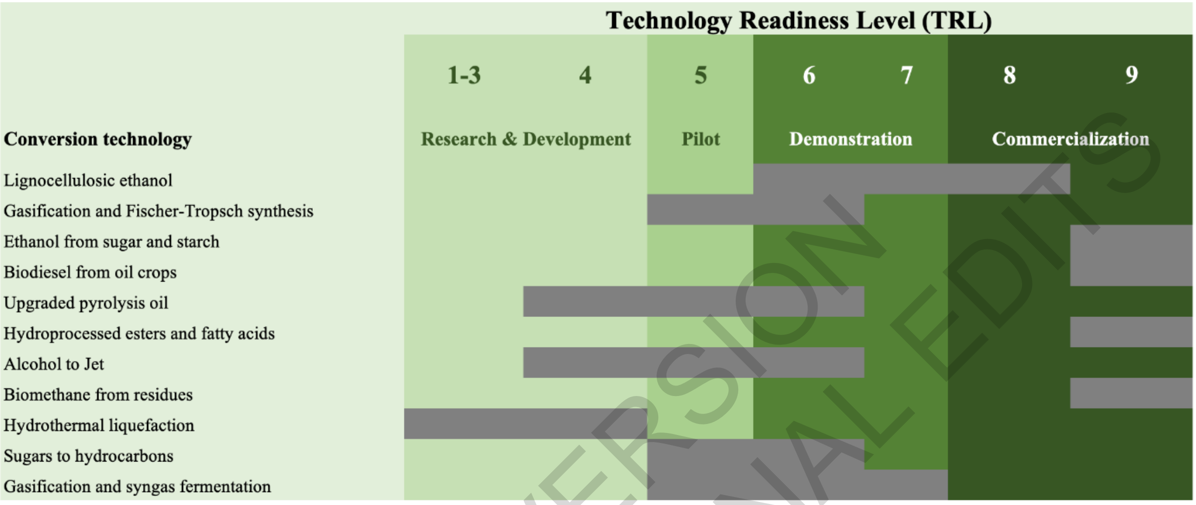


Figure 10.3 Commercialisation status of selected biofuels conversion technologies. The grey boxes represent the current TRL of each conversion technology.

Within the aviation sector, jet fuels produced from biomass resources (so-called sustainable aviation fuels, SAF) could offer significant climate mitigation opportunities under the right policy circumstances. Despite the growing interest in aviation biofuels, demand and production volumes remain negligible compared to conventional fossil aviation fuels. Nearly all flights powered by biofuels have used fuels derived from vegetable oils and fats, and the blending level of biofuels into conventional aviation fuels for testing is up to 50% today (Mawhood et al. 2016). To date, only one facility in the US is regularly producing sustainable aviation fuels based on waste oil feedstocks. The potential to scale up bio-based SAF volumes is severely restricted by the lack of low cost and sustainable feedstock options (see Chapter 7). Lignocellulosic feedstocks are considered to have a great potential for the production of financially competitive bio-based SAF in many regions. However, production facilities involve significant capital investment and estimated levelised costs are typically more than twice the selling price of conventional jet fuel. In some cases (notably for vegetable oils), the feedstock price is already higher than that of the fossil jet fuel (Mawhood et al. 2016). Some promising technological routes for producing SAF from lignocellulosic feedstocks are below technology readiness level (TRL) 6 (pilot scale) with just a few players involved in the development of these technologies. Although it would be physically possible to address the mid-century projections for substantial use of biofuels in the aviation sector (from IEA and other sectoral organisations (ICAO 2017)), this fuel deployment scale could only be achieved with very large capital investments in bi-based SAF production infrastructure, and substantial policy support.

In comparison to the aviation sector, the prospects for technology deployment are better in the shipping sector. The advantage of shipping fuels is that marine engines have a much higher operational flexibility on a mix of fuels, and shipping fuels do not need to undergo as extensive refining processes as road and aviation fuels to be considered drop-in. However, biofuels in marine engines have only been tested at an experimental or demonstration stage, leaving open the question about the scalability of the operations, including logistics issues. Similar to the aviation sector, securing a reliable, sustainable biomass feedstock supply and mature processing technologies to produce price-competitive biofuels at a large scale remains a challenge for the shipping sector (Hsieh and Felby 2017). Other drawbacks include industry concerns about oxidation, storage, and microbial stability for less purified or more crude biofuels. Assuming that biofuels are technically developed and available for the shipping sector in large quantities, a wider initial introduction of biofuels in the sector is likely to depend upon increased environmental regulation of particulate and GHG emissions. Biofuels may also may offer a significant advantage in meeting ambitious sulphur emission reduction targets set by the sectoral organisations. More extensive use of marine biofuels will most likely be first implemented in inner-city waterways, inland river freight routes, and coastal green zones. Given the high efficiency of the diesel engine, a large-scale switch to a different standard marine propulsion method in the near to medium-term future seems unlikely. Thus, much of the effort has been placed on developing biofuels compatible with diesel engines. So far, biodiesel blends look promising, as used in land transport. Hydrotreated vegetable oil (HVO) is also a technically good alternative and is compatible with current engines and supply chains, while the introduction of multifuel engines may open the market for ethanol fuels (Hsieh and Felby 2017).

Ammonia: At room temperature and atmospheric pressure, Ammonia is a colourless gas with a distinct odour. Due to relatively mild conditions for liquefaction, Ammonia is transferred and stored as a liquefied or compressed gas and has been used as an essential industrial chemical resource for many products. In addition, since the chemical structure of Ammonia is without carbon molecules, Ammonia has attracted attention as a carbon-neutral fuel that can also improve combustion efficiency (Gill et al. 2012). Furthermore, Ammonia could also serve as a Hydrogen carrier and used in fuel cells. These characteristics have driven increased interest in the low-carbon production of Ammonia, which would have to be coupled to low-carbon Hydrogen production (with low-carbon electricity providing the needed energy or with CCS).

For conventional internal combustion engines, the use of Ammonia remains challenging due to the relatively low burning velocity and high ignition temperature. Therefore, Frigo and Gentili (2014) have suggested a dual-fuelled spark-ignition engine operated by liquid Ammonia and Hydrogen, where Hydrogen is generated from Ammonia using the thermal energy of exhaust gas. On the other hand, the high-octane number of Ammonia means good knocking resistance of spark ignition engines and is promising for improving thermal efficiency. For compression ignition engines, the high-ignition temperature of Ammonia requires a high compression ratio causing an increase in mechanical friction. Since Gray et al. (1966), many studies have shown that the compression ratio can be reduced by mixing combustion with secondary fuels such as diesel and Hydrogen with low self-ignition temperatures, as summarised by Dimitriou and Javaid (2020). Using a secondary fuel with a high cetane number and the adoption of a suitable fuel injection timing has enabled highly efficient combustion of compression ignition engines in the dual fuel mode with Ammonia ratios up to 95% (Dimitriou and Javaid 2020). One major challenge for realising an Ammonia-fuelled engine is the reduction of unburned Ammonia, as described in Section 6.4.5. (Reiter and Kong 2011). Processes being examined include the use of exhaust gas recirculation (EGR) (Pochet et al. 2017) and after treatment systems. However, these processes require space, which is a constraint for LDVs and air transport but more practical for ships. Shipbuilders are developing an Ammonia engine based on the existing diesel dual-fuel engine to launch a service in 2025 (Brown 2019; MAN-ES 2019). Ammonia could therefore contribute significantly to decarbonisation in the shipping sector (as expanded in section 10.6) with potential niche applications elsewhere.

Synthetic fuels: Synthetic fuels can contribute to transport decarbonisation through synthesis from electrolytic Hydrogen produced with low carbon electricity or Hydrogen produced with CCS, and captured CO_2 using the Fischer-Tropsch process (Liu et al. 2020a). Due to similar properties of synthetic fuels to those of fossil fuels, synthetic fuels can reduce GHG emissions in both existing and new vehicles without significant changes to the engine design. While the Fischer-Tropsch process is a well-established technology (Liu et al. 2020a), low-carbon synthetic fuel production is still in the demonstration stage. Even though their production costs are expected to decline in the future due to lower renewable electricity prices, increased scale of production, and learning effects, synthetic fuels are still up to 3 times more expensive than conventional fossil fuels (Section 6.6.2.4). Furthermore, since the production of synthetic fuels involves thermodynamic conversion loss, there is a concern that the total energy efficiency is lower than that of electric vehicles (Soler 2019). Given these high costs and limited scales, the adoption of synthetic fuels will likely focus on the aviation, shipping, and long-distance road transport segments, where decarbonisation by electrification is more challenging. In particular, synthetic fuels are considered promising as an aviation fuel (as expanded in section 10.5).

10.3.2 Electric technologies

Widespread electrification of the transport sector is likely crucial for reducing transport emissions and depends on appropriate energy storage systems (EES). However, large-scale diffusion of EES depends on improvements in energy density (energy stored per unit volume), specific energy (energy stored per unit weight), and costs (Cano et al. 2018). Recent trends suggest EES-enabled vehicles are on a path of becoming the leading technology for LDVs, but their contribution to heavy-duty freight is more uncertain.

Electrochemical storage of light and medium-duty vehicles: Electrochemical storage, i.e., batteries, are one of the most promising forms of energy storage for the transport sector and have dramatically improved in their commerciality since AR5. Rechargeable batteries are of primary interest for applications within the transport sector, with a range of mature and emerging chemistries able to support the electrification of vehicles. The most significant change since AR5 and SPR1.5 is the dramatic rise in lithium-ion batteries (LIB), which has enabled electromobility to become a major feature of decarbonisation.

Before the recent growth in market share of LIBs, lead-acid batteries, nickel batteries, high-temperature sodium batteries, and redox flow batteries were of particular interest for the transport sector (Placke et al. 2017). Due to their low costs, lead-acid batteries have been used in smaller automotive vehicles, e.g. e-scooters and e-rickshaws (Dhar et al. 2017). However, their application in electric vehicles will be limited due to their low specific energy (Andwari et al. 2017). Nickel-metal hydride (NiMH) batteries have a better energy density than lead-acid batteries and have been well-optimised for regenerative braking (Cano et al. 2018). As a result, NiMH batteries were the battery of choice for hybrid electric vehicles (HEVs). Ni-Cadmium (NiCd) batteries have energy densities lower than NiMH batteries and cost around ten times more than lead-acid batteries (Table 6.5, Chapter 6). For this reason, NiCd batteries do not have major prospects within automotive applications. There are also no examples of high-temperature sodium or redox flow batteries being used within automotive applications.

Commercial application of LIBs in automotive applications started around 2000 when the price of LIBs was more than 1,000 USD per kWh (Schmidt et al. 2017). By 2020, the battery manufacturing capacity for automotive applications was around 300 GWh per year (IEA 2021a). Furthermore, by 2020, the average battery pack cost had come down to 137 USD per kWh, a reduction of 89% in real terms since 2010 (Henze 2020). Further improvements in specific energy, energy density (Nykvist et al. 2015; Placke et al. 2017) and battery service life (Liu et al. 2017) of LIBs are expected through additional design optimisation (Table 6.5, Chapter 6). These advancements are expected to lead to EVs with even longer driving ranges, further supporting the uptake of LIBs for transport applications (Cano et al. 2018). However, the performance of LIBs under freezing and high temperatures is a concern (Liu et al.

2017) for reliability. Auto manufacturers have some pre-heating systems for batteries to see that they perform well in very cold conditions (Wu et al. 2020).

For EVs sold in 2018, the material demand was about 11 kilotonnes (kt) of optimised lithium, 15 kt of cobalt, 11 kt of manganese, and 34 kt of nickel (IEA 2019a, 2021a). IEA projections for 2030 in the EV 30@30 scenario show that the demand for these materials would increase by 30 times for lithium and around 25 times for cobalt. While there are efforts to move away from expensive materials such as cobalt (IEA 2019a, 2021a), dependence on lithium will remain, which may be a cause of concern (Olivetti et al. 2017; You and Manthiram 2018). A more detailed discussion on resource constraints for lithium is provided in Box 10.6 on critical materials.

Externalities from resource extraction are another concern, though current volumes of lithium are much smaller than other metals (steel, aluminium). As a result, lithium was not even mentioned in the global resource outlook of UNEP (IRP 2019). Nonetheless, it is essential to manage demand and limit externalities since the demand for lithium is going to increase many times in the future. Reuse of LIBs used in EVs for stationary energy applications can help in reducing the demand for LIBs. However, the main challenges are the difficulty in accessing the information on the health of batteries to be recycled and technical problems in remanufacturing the batteries for their second life (Ahmadi et al. 2017). Recycling lithium from used batteries could be another possible supply source (Winslow et al. 2018). While further R&D is required for commercialisation (Ling et al., 2018), recent efforts at recycling LIBs are very encouraging (Ma et al. 2021). The standardisation of battery modules and packaging within and across vehicle platforms, increased focus on design for recyclability, and supportive regulation are important to enable higher recycling rates for LIBs (Harper et al. 2019).

Several next-generation battery chemistries are often referred to as post-LIBs (Placke et al. 2017). These chemistries include metal-sulphur, metal-air, metal-ion (besides Li) and all-solid-state batteries (ASSB). The long development cycles of the automotive industry (Cano et al. 2018) and the advantages of LIBs in terms of energy density and cycle life (Table 6.5, Chapter 6) mean that it is unlikely that post-LIB technologies will replace LIBs in the next decade. However, lithium-sulphur, lithium-air, and zinc-air have emerged as potential alternatives for LIBs. These emerging chemistries may also be used to supplement LIBs in dual-battery configurations, to extend the driving range at lower costs or with higher energy density (Cano et al. 2018). Lithium-sulphur (Li-S) batteries have a lithium metal anode with a higher theoretical capacity than lithium-ion anodes and much lower cost sulphur cathodes relative to typical Li-ion insertion cathodes (Manthiram et al. 2014). As a result, Li-S batteries are much cheaper than LIB to manufacture and have a higher energy density (Table 6.5, Chapter 6). Conversely, these batteries face challenges from sulphur cathodes, such as low conductivity of the sulphur and lithium sulphide phases, and the relatively high solubility of sulphur species in common lithium battery electrolytes, leading to low cycle life (Cano et al. 2018). Lithium-air batteries offer a further improvement in specific energy and energy density above Li–S batteries owing to their use of atmospheric oxygen as a cathode in place of sulphur. However, their demonstrated cycle-life is much lower (Table 6.5, Chapter 6). Lithium-air batteries also have low specific power. Therefore, lithium-air require an extra battery for practical applications (Cano et al. 2018). Finally, zinc–air batteries could more likely be used in future EVs because of their more advanced technology status and higher practically achievable energy density (Fu et al. 2017). Like Li-air batteries, their poor specific power and energy efficiency will probably prevent zinc-air batteries from being used as a primary energy source for EVs. Still, they could be promising when used in a dual-battery configuration (Cano et al. 2018).

The technological readiness of batteries is a crucial parameter in the advancement of EVs (Manzetti and Mariasiu 2015). Energy density, power density, cycle life, calendar life, and the cost per kWh are the pertinent parameters for comparing the technological readiness of various battery technologies (Manzetti and Mariasiu 2015; Andwari et al. 2017; Lajunen et al. 2018). Table 6.5 in Chapter 6 provides a summary of the values of these parameters for alternative battery technologies. LIBs comprehensively dominate the other battery types and are at a readiness level where they can be applied for land transport applications (cars, scooters, electrically assisted cycles) and at battery pack costs below 150 USD per kWh, making EVs cost-competitive with conventional vehicles (Nykvist et al. 2019). In 2020 the stock of battery-electric LDVs had crossed the 10 million mark (IEA 2021a). (Schmidt et al. 2017) project that the cost of a battery pack for LIBs will reach 100 USD per kWh by 2030, but more recent trends show this could happen much earlier. For example, according to IEA, battery pack costs could be as low as 80 USD per kWh by 2030 (IEA 2019a). In addition, there are clear trends that now vehicle manufacturers are offering vehicles with bigger batteries, greater driving ranges, higher top speeds, faster acceleration, and all size categories (Nykvist et al. 2019). In 2020 there were over 600,000 battery-electric buses and over 31,000 battery-electric trucks operating globally (IEA 2021a).

LIBs are not currently envisaged to be suitable for long-haul transport. However, several battery technologies are under development (Table 6.5, Chapter 6), which could further enhance the competitiveness of EVs and expand their applicability to very short-haul aviation and ships, especially smaller vehicles. Li-S, Li-air, and Zn-air hold the highest potential for these segments (Cano et al. 2018). All three of these technologies rely on making use of relatively inexpensive elements, which can help bring down battery costs (Cano et al. 2018). The main challenge these technologies face is in terms of the cycle life. Out of the three, Li-S has already been used for applications in unmanned aerial vehicles (Fotouhi et al., 2017) due to relatively high specific energy (almost double the state of art LIBs). However, even with low cycle life, Li-air and Zn-air hold good prospects for commercialisation as range extender batteries for long-range road transport and with vehicles that are typically used for city driving (Cano et al. 2018).

Alternative electricity storage technologies for heavy-duty transport: While LIBs described in the previous section are driving the electrification of LDVs, their application to railways, aviation, ships, and large vehicles faces challenges due to the higher power requirements of these applications. The use of a capacitor with a higher power density than LIBs could be suitable for the electrification of such vehicles. It is one of the solutions for regenerating large and instantaneous energy from regenerative brakes. Classical capacitors generally show more attractive characteristics in power density (8,000-10,000 W/kg) than batteries. However, the energy density is poor (1-4 Wh/kg) compared to batteries, and there is an issue of self-discharge (González et al. 2016; Poonam et al. 2019). To improve the energy density, electrochemical double layer capacitors (EDLCs; supercapacitor) and hybrid capacitors (10-24 Wh/kg, 900-9000 W/kg in the product-level) such as Li-ion capacitors (LICs) have been developed. The highest energy density of the LIC system (100-140 Wh/kg in the research stage) are approaching that of the Li-ion battery systems (80-240 Wh/kg in the product stage) (Naoi et al. 2012; Panja et al. 2020). Examples of effective use of capacitors include a 12 tonne truck with a capacitor-based kinetic energy recovery system (KERS) that has been reported to save up to 32% of the fuel use of standard truck (Kamdar 2017). Similarly, an EDLC bank applied to electric railway systems has been shown to result in a 10% reduction in power consumption per day (Takahashi et al. 2017). Finally, systems in which capacitors are mounted on an electric bus for charging at a stop have been put into practical use, e.g., Trackless Tram (Newman et al. 2019). At the bus stop, the capacitor is charged at 600 kW for 10 ~ 40 seconds, which provides enough power for 5 ~ 10 km (Newman et al. 2019). In addition, more durable capacitors can achieve a longer life than LIB systems (ADB 2018).

Hybrid energy storage (HES) systems, which combine a capacitor and a battery, achieve both high power and high energy, solving problems such as capacity loss of the battery and self-discharge of the capacitor. In these systems, the capacitor absorbs the steeper power, while the LIB handles the steady power, thereby reducing the power loss of the EV to half. Furthermore, since the in-rush current of the battery is suppressed, there is an improvement in the reliability of the LIB (Noumi et al., 2014). In a hybrid diesel train, 8.2% of the regenerative energy is lost due to batteries' limited charge-discharge performance; however, using an EDLC with batteries can save this energy (Takahashi et al. 2017; Mayrink et al. 2020)

The development of power storage devices and advanced integrated system approaches, including power electronics circuits such as HES and their control technologies, are important for the electrification of mobility. These technologies are solutions that could promote the electrification of systems, reduce costs, and contribute to the social environment through multiple outcomes in the decarbonisation agenda.

10.3.3 Fuel cell technologies

In harder-to-electrify transport segments, such as heavy-duty vehicles, shipping, and aviation, Hydrogen holds significant promise for delivering emissions reductions if it is produced using low-carbon energy sources. In particular, Hydrogen fuel cells are seen as an emerging option to power larger vehicles for land-based transport (Tokimatsu et al. 2016; IPCC 2018; IEA 2019b). Despite this potential, further advancements in technological and economic maturity will be required in order for Hydrogen fuel cells to play a greater role. While this section focuses primarily on Hydrogen fuel cells, Ammonia and Methanol fuel cells may also emerge as options for low power applications.

During the last decade, Hydrogen fuel cell vehicles (HFCVs) have attracted growing attention, with fuel cell technology improving through research and development. Fuel cell systems cost 80 to 95 per cent less than they did in the early 2000s, at approximately $50 per kW for light-duty (80 kW) and $100 per kW for medium-heavy duty (160 kW). These costs are approaching the US Department of Energy's (US DOE) goal of $40 per kW in 2025 at a production target of 500,000 systems per year(IEA 2019c). In addition to cost reductions, the power density of fuel cell stacks has now reached around 3.0 kW/L, and average durability has improved to approximately 2,000-3,000 hours (Jouin et al. 2016; Kurtz et al. 2019). Despite these improvements, fuel cell systems are not yet mature for many commercial applications. For example, the US DOE has outlined that for Hydrogen fuel cell articulated trucks (semi-trailers) to compete with diesel vehicles, fuel cell durability will need to reach 30,000 hours (US DOE 2019). While some fuel cell buses have demonstrated durability close to these targets (Eudy and Post 2018a), another review of light fuel cell vehicles found maximum durability of 4,000 hours (Kurtz et al. 2019). As more fuel cell vehicles are trialled, it is expected that further real-world data will become available to track ongoing fuel cell durability improvements.

Ammonia and Methanol fuel cells are considered to be less mature than Hydrogen fuel cells. However, they offer the benefit of using a more easily transported fuel that can be directly used without converting to Hydrogen (Zhao et al. 2019). Conversely, both Methanol and Ammonia are toxic, and in the case of Methanol fuel cells, carbon dioxide is released as a by-product of generating electricity with the fuel cell (Zhao et al. 2019). Due to the lower power output, Methanol and Ammonia fuel cells are also not well-suited to heavy duty vehicles (Jeerh et al. 2021). They are therefore unlikely to compete with Hydrogen fuel cells. However, Ammonia and Methanol could be converted at refuelling stations to Hydrogen as an alternative to being directly used in fuel cells (Zhao et al. 2019).

Several FCV-related technologies are fully ready for demonstration and early market deployment, however, further research and development will be required to achieve full-scale commercialisation, likely from 2030 onwards (Staffell et al. 2019; Energy Transitions Commission 2020; IEA 2021b). Some reports argue that it may be possible to achieve serial production of fuel cell heavy-duty trucks in the late 2020s, with comparable costs to diesel vehicles achieved after 2030 (Jordbakker et al. 2018). Over the next decade or so, Hydrogen FCVs could become cost-competitive for various transport applications, potentially including long-haul trucks, marine ships, and aviation (FCHEA 2019; FCHJU 2019; BloombergNEF 2020; Hydrogen Council 2017, 2020). The speed of fuel cell system cost reduction is a key factor for achieving widespread uptake. Yet, experts disagree on the relationship between the scale of fuel cell demand, cost, and performance improvements (Cano et al. 2018). Costs of light-, medium-, and heavy-duty fuel cell powertrains have decreased by orders of magnitude with further reductions of a factor of two expected with continued technological progress (Whiston et al. 2019). For example, the costs of platinum for fuel cell stacks have decreased by an order of magnitude (Staffell et al. 2019); current generation FCVs use approximately 0.25 g/kW Pt and a further reduction of 50-80% is expected by 2030 (Hao et al. 2019).

Hydrogen is likely to take diverse roles in the future energy system: as a fuel in industry and buildings, as well as transport, and as energy storage for variable renewable electricity. Further research is required to understand better how a Hydrogen transport fuel supply system fits within the larger Hydrogen energy system, especially in terms of integration within existing infrastructure, such as the electricity grid and the natural gas pipeline system (IEA 2015).

Strong and durable policies would be needed to enable widespread use of Hydrogen as a transport fuel and to sustain momentum during a multi-decade transition period for Hydrogen FCVs to become cost-competitive with electric vehicles (IEA 2019c; FCHEA 2019; FCHJU 2019; BNEF 2020; Hydrogen Council 2017, 2020). The analysis suggests that Hydrogen is likely to have strategic and niche roles in transport, particularly in long-haul shipping and aviation. With continuing improvements, Hydrogen and electrification will likely play a role in decarbonising heavy-duty road and rail vehicles.

10.3.4 Refuelling and charging infrastructure

The transport sector relies on liquid gasoline, and diesel for land-based transport, jet fuel for aviation, and heavy fuel oil for shipping. Extensive infrastructure for refuelling liquid fossil fuels already exists. Ammonia, synthetic fuels, and biofuels have emerged as alternative fuels for powering combustion engines and turbines used in land, shipping, and aviation (Figure 10.2). Synthetic fuels such as e-Methanol and Fischer-Tropsch liquids have similar physical properties and could be used with existing fossil fuel infrastructure (Soler, 2019). Similarly, biofuels have been used in several countries together with fossil fuels (Panoutsou et al. 2021). Ammonia is a liquid, but only under pressure, and therefore will not be compatible with liquid fossil fuel refuelling infrastructure. Ammonia is, however, widely used as a fertiliser and chemical raw material and 10% of annual Ammonia production is transported via sea (Gallucci 2021). As such, a number of port facilities include Ammonia storage and transport infrastructure and the shipping industry has experience in handling Ammonia (Gallucci 2021). This infrastructure would likely need to be extended in order to support the use of Ammonia as a fuel for shipping and therefore ports are likely to be the primary sites for these new refuelling facilities.

EVs and HFCV require separate infrastructure than liquid fuels. The successful diffusion of new vehicle technologies is dependent on the preceding deployment of infrastructure (Leibowicz 2018), so that the deployment of new charging and refuelling infrastructure will be critical for supporting the uptake of emerging transport technologies like EVs and HFCVs, where it makes sense for each to be deployed. As a result, there is likely a need for the simultaneous investment in both infrastructure and vehicle technologies to accelerate decarbonisation of the transport sector.

Charging infrastructure: Charging infrastructure is important for a number of key reasons. From a consumer perspective, robust and reliable charging infrastructure networks are required to build confidence in the technology and overcome the often-cited barrier of 'range anxiety' (She et al. 2017). Range anxiety is where consumers do not have confidence that an EV will meet their driving range requirements. For LDVs, the majority of charging (75-90%) has been reported to take place at or near homes (Figenbaum 2017; Webb et al. 2019; Wenig et al. 2019). Charging at home is a particularly significant factor in the adoption of EVs as consumers are less willing to purchase an EV without home charging (Berkeley et al. 2017; Funke and Plötz 2017; Nicholas et al. 2017). However, home charging may not be an option for all consumers. For example, apartment dwellers may face specific challenges in installing charging infrastructure (Hall and Lutsey 2020). Thus, the provision of public charging infrastructure is another avenue for alleviating range anxiety, facilitating longer distance travel in EVs, and in turn, encouraging adoption (Hall and Lutsey 2017; Melliger et al. 2018; Narassimhan and Johnson 2018; Melton et al. 2020). Currently, approximately 10% of charging occurs at public locations, roughly split equally between AC (slower) and DC (fast) charging (Figenbaum 2017; Webb et al. 2019; Wenig et al. 2019). Deploying charging infrastructure at workplaces and commuter car parks is also important, particularly as these vehicles are parked at these locations for many hours. Indeed, around 15-30% of EV charging currently occurs at these locations (Figenbaum 2017; Webb et al. 2019; Wenig et al. 2019). It has been suggested that automakers and utilities could provide support for the installation of home charging infrastructure (Hardman et al. 2018), while policy-makers can provide support for public charging. Such support could come via supportive planning policy, building regulations, and financial support. Policy support could also incentivise the deployment of charging stations at workplaces and commuter car parks. Charging at these locations would have the added benefit of using excess solar energy generated during the day (Hardman et al. 2018; Webb et al. 2019).

While charging infrastructure is of high importance for the electrification of light-duty vehicles, arguably, it is even more important for heavy-duty vehicles given the costs of high-power charging infrastructure. It is estimated that the installed cost of fast-charging hardware can vary between approximately USD 45,000 to 200,000 per charger, depending on the charging rate, the number of chargers per site, and other site conditions (Nicholas 2019; Hall and Lutsey 2019; Nelder and Rogers 2019). Deployment of shared charging infrastructure at key transport hubs, such as bus and truck depots, freight distribution centres, marine shipping ports and airports, can encourage a transition to electric vehicles across the heavy transport segments. Furthermore, if charging infrastructure sites are designed to cater for both light and heavy-duty vehicles, infrastructure costs could decrease by increasing utilisation across multiple applications and/or fleets (Nelder and Rogers 2019).

There are two types of charging infrastructure for electric vehicles: conductive charging involving a physical connection and wireless/induction charging. The majority of charging infrastructure deployed today for light and heavy-duty vehicles is conductive. However, wireless charging technologies are beginning to emerge – particularly for applications like bus rapid transit – with vehicles able to charge autonomously while parked and/or in motion (IRENA 2019). For road vehicles, electric road systems, or road electrification, is also emerging as an alternative form of conductive charging infrastructure that replaces a physical plug (Ainalis et al. 2020; Hill et al. 2020). This type of charging infrastructure is particularly relevant for road freight where load demand is higher. Road electrification can take the form of a charging rail built into the road pavement, run along the side of the road, through overhead catenary power lines - similar to electrical infrastructure used for rail - or at recharging facilities at stations along the route. This infrastructure can also be used to directly power other electrified powertrains, such as hybrid and HFCV (Hardman et al. 2018; Hill et al. 2020).

Charging infrastructure also varies in terms of the level of charging power. For light vehicles, charging infrastructure is generally up to 350 kW, which provide approximately 350 kilometres for every 10 minutes of charging. For larger vehicles, like buses and trucks, charging infrastructure is generally up to 600 kW, providing around 50-100 km for every 10 minutes of charging (depending on the size of the bus/truck). Finally, even higher power charging infrastructure is currently being developed at rates greater than 1 MW, particularly for long-haul trucks and for short-haul marine shipping and aviation. For example, one of the largest electric ferries in the world, currently operating in Denmark, uses a 4.4 MW charger (Heinemann et al. 2020).

Finally, there are several different charging standards, varying across transport segments and across geographical locations. Like electrical appliances, different EV charging connectors and sockets have emerged in different regions, e.g. CCS2 in Europe (ECA 2021), GB/T in China (Hove and Sandalow 2019). Achieving interoperability between charging stations is seen as another important issue for policy-makers to address to provide transparent data to the market on where EV chargers are located and a consistent approach to paying for charging sessions (van der Kam and Bekkers 2020). Interoperability could also play an important role in enabling smart charging infrastructure (Neaimeh and Andersen 2020).

Smart charging - electric vehicle-grid integration strategies: EVs provide several opportunities for supporting electricity grids if appropriately integrated. Conversely, a lack of integration could negatively affect the grid, particularly if several vehicles are charged in parallel at higher charging rates during peak demand periods (Webb et al. 2019; Jochem et al. 2021). There are three primary approaches to EV charging. In unmanaged charging, EVs are charged ad-hoc, whenever connected, regardless of conditions on the broader electricity grid (Webb et al. 2019; Jochem et al. 2021). Second, in managed charging, EVs are charged during periods beneficial to the grid, e.g. high renewable generation and/or low demand periods. Managed charging also allows utilities to regulate the rate of charge and can thus provide frequency and regulation services to the grid (Weis et al. 2014). Finally, in bidirectional charging or vehicle-to-grid (V2G), EVs are generally subject to managed charging, but an extension provides the ability to export electricity from the vehicle's battery back to the building and/or wider electricity grid (Ercan et al. 2016; Noel et al. 2019; Jochem et al. 2021). The term 'smart charging' has become an umbrella term to encompass both managed charging (often referred to as a V1G) and vehicle-to-grid (V2G). For electric utilities, smart charging strategies can provide backup power, support load balancing, reduce peak loads (Zhuk et al. 2016; Noel et al. 2019; Jochem et al. 2021), reduce the uncertainty in forecasts of daily and hourly electrical loads (Peng et al. 2012), and allow greater utilisation of generation capacity (Hajimiragha et al. 2010; Madzharov et al. 2014).

Smart charging strategies can also enhance the climate benefits of EVs (Yuan et al. 2021). Controlled charging can help avoid high carbon electricity sources, decarbonisation of the ancillary service markets, or peak shaving of high carbon electricity sources (Jochem et al. 2021). V2G-capable EVs can result in even lower total emissions, particularly when compared to other alternatives (Reddy et al. 2016). Noel et al.(2019) analysed V2G pathways in Denmark and noted that at a penetration rate of 75% by 2030, $34 billion in social benefits could be accrued (through things like displaced pollution). These social benefits translate to $1,200 per vehicle. V2G-capable EVs were found to have the potential to reduce carbon emissions compared to a conventional gasoline vehicle by up to 59%, assuming optimised charging schedules (Hoehne and Chester 2016).

Projections of energy storage suggest smart charging strategies will come to play a significant role in future energy systems. Assessment of different energy storage technologies for Europe showed that V2G offered the most storage potential compared to other options and could account for 200 GW of installed capacity by 2060, whereas utility-scale batteries and pumped hydro storage could provide 160 GW of storage capacity (Després et al., 2017). Another study found that EVs with controlled charging (V1G) could provide similar services to stationary storage but at a far lower cost (Coignard et al. 2018). While most deployments of smart charging strategies are still at the pilot stage, the number of projects continues to expand, with the V2G Hub documenting at least 90 V2G projects across 22 countries in 2021 (Vehicle to Grid (VG) 2021). Policymakers have an important role in facilitating collaboration between vehicle manufacturers, electricity utilities, infrastructure providers, and consumers to enable smart charging strategies and ensure EVs can support grid stability and the uptake of renewable energy. This is a critical part of decarbonising transport.

Hydrogen infrastructure: HFCVs are reliant on the development of widespread and convenient Hydrogen refuelling stations (FCHEA 2019; IEA 2019c; BNEF 2020). Globally, there are around 540 Hydrogen refuelling stations, with the majority located in North America, Europe, Japan, and China (IEA 2021a). Approximately 70% of these refuelling stations are open to the public (Coignard et al. 2018). Typical refuelling stations currently have a refuelling capacity of 100 to 350 kg/day (CARB

2019, 2020; H2 Tools 2020; AFDC 2021). At most, current Hydrogen refuelling stations have daily capacities under 500 kg/day (Liu et al. 2020b).

The design of Hydrogen refuelling stations depends on the choice of methods for Hydrogen supply and delivery, compression and storage, and the dispensing strategy. Hydrogen supply could happen via on-site production or via transport and delivery of Hydrogen produced off-site. At the compression stage, Hydrogen is compressed to achieve the pressure needed for economic stationery and vehicle storage. This pressure depends on the storage strategy. Hydrogen can be stored as a liquid or a gas. Hydrogen can also be dispensed to the vehicles as a gas or a liquid, depending on the design of the vehicles (though it tests the extremes of temperature range and storage capacity for an industrial product). The technological and economic development of each of these components continues to be researched.

If Hydrogen is produced off site in a large centralised plant, it must be stored and delivered to refuelling stations. The cost of Hydrogen delivery depends on the amount of Hydrogen delivered, the delivery distance, the storage method (compressed gas or cryogenic liquid), and the delivery mode (truck vs. pipeline). Table 10.6 describes the three primary options for Hydrogen delivery. Most Hydrogen refuelling stations today are supplied by trucks and, very occasionally, Hydrogen pipelines. Gaseous tube trailers could also be used to deliver Hydrogen in the near term, or over shorter distances, due to the low fixed cost (although the variable cost is high). Both liquefied truck trailers and pipelines are recognised as options in the medium to long-term as they have higher capacities and lower costs over longer distances (FCHJU 2019; Li et al. 2020; EU 2021). Alternatively, Hydrogen can be produced on site using a small-scale onsite electrolyser or steam methane reforming unit combined with CCS. Hydrogen is generally dispensed to vehicles as a compressed gas at pressures 350 or 700 bar, or as liquified Hydrogen at – 253ºC (Hydrogen Council 2020).

Table 10.6 Overview of three transport technologies for Hydrogen delivery in the transport sector showing relative differences. Source: (IEA 2019c)

	Capacity	*Delivery distance*	*Energy loss*	*Fixed costs*	*Variable costs*	*Deployment phase*
Gaseous tube trailers	Low	Low	Low	Low	High	Near term
Liquefied truck trailers	Medium	High	High	Medium	Medium	Medium to long term
Hydrogen pipelines	High	High	Low	High	Low	Medium to long term

The costs for Hydrogen refuelling stations vary widely and remain uncertain for the future (IEA 2019c). The IEA reports that the investment cost for one Hydrogen refuelling station ranges between USD 0.6–2 million for Hydrogen at a pressure of 700 bar and a delivery capacity of 1,300 kg per day. The investment cost of Hydrogen refuelling stations with lower refuelling capacities (~50 kg H_2 per day) delivered at lower pressure (350 bar) range between USD 0.15–1.6 million. A separate estimate by the International Council for Clean Transport suggests that at a capacity of 600 kg of Hydrogen per day, the capital cost of a single refuelling station would be approximately USD 1.8 million (ICCT 2017). Given the high investment costs for Hydrogen refuelling stations, low utilisation can translate into a high price for delivered Hydrogen. In Europe, most pumps operate at less than 10% capacity. For small refuelling stations with a capacity of 50 kg H_2 per day, this utilisation rate translates to a high price of around USD 15–25 per kg H_2 – in line with current retail prices (IEA 2019c). The dispensed cost of

Hydrogen is also highly correlated with the cost of electricity, when H_2 is produced using electrolysis, which is required to produce low-carbon Hydrogen.

10.4 Decarbonisation of land-based transport

10.4.1 Light-duty vehicles for passenger transport

LDVs represent the main mode of transport for private citizens (ITF 2019) and currently represent the largest share of transport emissions globally (IEA 2019d). Currently, powertrains depending on gasoline and diesel fuels remain the dominant technology in the LDV segment (IEA 2019d). HEVs, and fully battery electric vehicles (BEVs), however, have become increasingly popular in recent years (IEA 2021a). Correspondingly, the number of life cycle assessment (LCA) studies investigating HEVs, BEVs, and fuel cell vehicles have increased. While historically the focus has been on the tailpipe emissions of LDVs, LCA studies demonstrate the importance of including emissions from the entire vehicle value chain, particularly for alternative powertrain technologies.

Figure 10.4 presents the cumulative life cycle emissions for selected powertrain technologies and fuel chain combinations for compact and mid-sized LDV. This figure summarizes the harmonized findings from the academic literature reviewed and the data submitted through an IPCC data collection effort, as described in Appendix 10.1 (Cusenza et al. 2019; Hawkins et al. 2013; Tong et al. 2015b; Bauer et al. 2015; Gao et al. 2016; Ellingsen et al. 2016; Kim and Wallington 2016; Cai et al. 2017; Ke et al. 2017; Lombardi et al. 2017; Miotti et al. 2017; Evangelisti et al. 2017; Valente et al. 2017; de Souza et al. 2018; Elgowainy et al. 2018; Luk et al. 2018; Bekel and Pauliuk 2019; Messagie et al. 2014; Hoque et al. 2019; IEA 2019a; Rosenfeld et al. 2019; Shen et al. 2019; Wang et al. 2019; Wu et al. 2019; Benajes et al. 2020; Ambrose et al. 2020; Hill et al. 2020; Knobloch et al. 2020; JEC 2020; Qiao et al. 2020; Cox et al. 2018; Sacchi 2021; Zheng et al. 2020; Wolfram et al. 2020; Valente et al. 2021). The values in the figure (and the remaining figures in this section) depend on the 100-year GWP used in each study, which may differ from the recent GWP updates from WGI. However, it is unlikely that the qualitative insights gained from the figures in this section would change using the update 100-year GWP values.

Furthermore, note that the carbon footprint of biofuels used in Figure 10.4 are aggregate numbers not specific to any individual value chain or fuel type. They are derived by combining land use-related carbon emissions from Chapter 7 with conversion efficiencies and emissions as described in Section 10.3. Specifically, land use footprints derived from the three modelling approaches employed here are: 1) Integrated Assessment Models – Energy Modelling Forum 33 (IAM EMF33); 2) Partial models assuming constant land cover (CLC), and, 3) Partial models using natural regrowth (NRG). The emissions factors used here correspond to scenarios where global production of biomass for energy purposes are 100 EJ/year, with lower emissions factors expected at lower levels of consumption and vice-versa. Further details are available in Box 10.2 and Chapter 7.

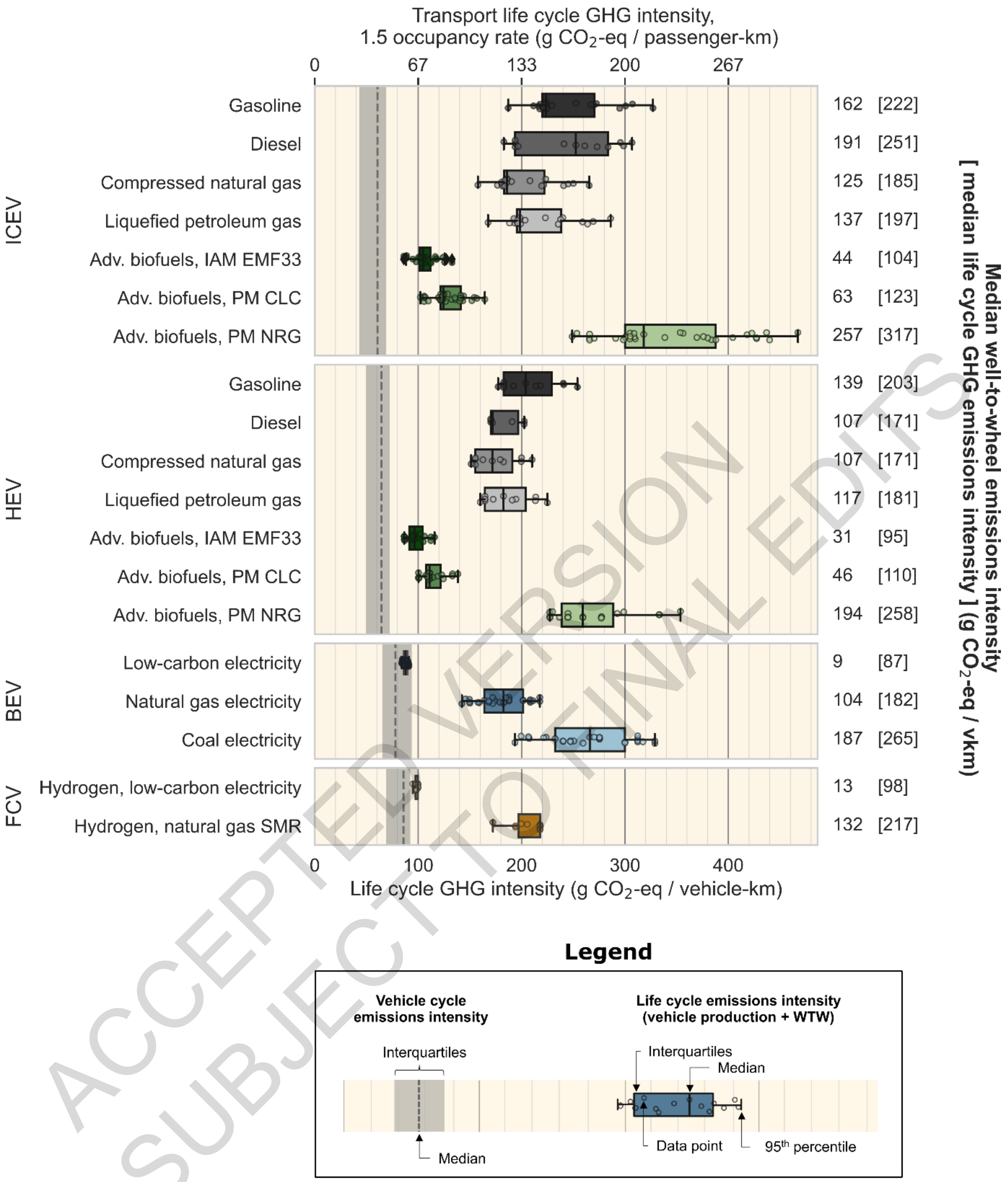


Figure 10.4 Life cycle GHG emissions intensities for mid-sized light-duty vehicle and fuel technologies from the literature. The primary x-axis reports units in g CO_2-eq vkm^{-1}, assuming a vehicle life of 180,000 km. The secondary x-axis uses units of g CO_2-eq pkm^{-1}, assuming a 1.5 occupancy rate. The values in the figure rely on the 100-year GWP value embedded in the source data, which may differ slightly with the updated 100-year GWP values from WGI. The shaded area represents the interquartile range for combined vehicle manufacturing and end-of-life phases. The length of the box and whiskers represent the interquartile range of the operation phase for different fuel chains, while their placement on the x-axis represents the absolute life cycle climate intensity, that is, includes manufacturing and end-of-life phases. Each individual marker indicates a data point. 'Adv. Biofuels' i.e., advanced biofuels, refers to the use of

second-generation biofuels and their respective conversion and cultivation emission factors. 'IAM EMF33' refers to emissions factors for advanced biofuels derived from simulation results from the integrated assessment models EMF33 scenarios. 'PM' refers to partial models, where 'CLC' is with constant land cover and 'NRG' is with natural regrowth. 'Hydrogen, low-carbon electricity' is produced via electrolysis using low-carbon electricity. 'Hydrogen, natural gas SMR' refers to fuels produced via steam methane reforming of natural gas.

The tailpipe emissions and fuel consumption reported in the literature generally do not use empirical emissions data. Rather, they tend to report fuel efficiency using driving cycles such as New European Driving Cycle (NEDC) or the US EPA Federal Test Procedure. As a result, depending on the driving cycle used, operating emissions reported in literature are possibly underestimated by as much as 15-38%, in comparison to actual real driving emissions (Fontaras et al. 2017; Tsiakmakis et al. 2017; Triantafyllopoulos et al. 2019). The extent of these underestimations, however, vary between powertrain types, engine sizes, driving behaviour and environment.

Current average life cycle impacts of mid-size ICEVs span from approximately 65 g CO_2-eq pkm^{-1} to 210 g CO_2-eq pkm^{-1}, with both values stemming from ICEVs running on biofuels. Between this range of values, the current reference technologies are found, with diesel-powered ICEVs having total median life cycle impacts of 130 g CO_2-eq pkm^{-1} and gasoline-fuelled vehicles with 160 g CO_2-eq pkm^{-1}. Fuel consumption dominates the life cycle emissions of ICEVs, with approximately 75% of these emissions arising from the tailpipe and fuel chain.

HEVs and plug-in HEVs (PHEVs) vary in terms of degree of powertrain electrification. HEVs mainly rely on regenerative braking for charging the battery. PHEVs combine regenerative braking with external power sources for charging the battery. Operating emissions intensity is highly dependent on the degree to which electrified driving is performed, which in turn is user- and route-dependent. For PHEVs, emissions intensity is also dependent on the source of the electricity for charging. HEV and PHEV production impacts are comparable to the emissions generated for producing ICEVs as the batteries are generally small compared to those of BEVs. Current HEVs may reduce emissions compared to ICEVs by up to 30%, depending on the fuel, yielding median life cycle intensities varying between 60 g CO_2-eq pkm^{-1} (biofuels, EMF33) and 165-170 g CO_2-eq pkm^{-1} (biofuels, partial models NRG). Within this wide range, all the combinations of electric/fossil driving can be found, as well as the life cycle intensity for driving 100% on fossil fuel. Because HEVs rely on combustion as the main energy conversion process, they offer limited mitigation opportunities. However, HEVs represent a suitable temporary solution, yielding a moderate mitigation potential, in areas where the electricity mix is currently so carbon intensive that the use of PHEVs and BEVs is not an effective mitigation solution (Wolfram and Wiedmann 2017; Wu et al. 2019).

In contrast to HEVs, PHEVs may provide greater opportunities for use-phase emissions reductions for LDVs. These increased potential benefits are due to the ability to charge the battery with low-carbon electricity and the longer full-electric range in comparison to HEVs (Laberteaux et al. 2019). Consumer behaviour (e.g., utility factor (UF) and charging patterns), manufacturer settings, and access to renewable electricity for charging strongly influence the total operational impacts (Wu et al, 2019). The UF is a weighting of the percentage of distance covered using the electric charge (charge depleting (CD) stage) versus the distance covered using the internal combustion engine (charge sustaining (CS) stage) (Paffumi et al. 2018). When the PHEV operates in CS mode, the internal combustion engine is used for propulsion and to maintain the state of charge of the battery within a certain range, together with regenerative braking (Plötz et al. 2018; Raghavan and Tal 2020). When running in CS mode, PHEVs have a reduced mitigation potential and have impacts comparable to those of HEVs. On the other hand, when the PHEV operates in CD mode, the battery alone provides the required propulsion energy (Plötz et al. 2018; Raghavan and Tal 2020). Thus, in CD mode, PHEVs hold potential for higher mitigation potential, due to the possibility of charging the battery with low carbon electricity sources. Consequently, the UF greatly influences the life cycle emissions of PHEVs. The current peer-reviewed literature presents a wide range of UFs mainly due to varying testing protocols applied for estimating the fuel efficiency and user behaviour (Pavlovic et al. 2017; Paffumi et al. 2018; Plötz et al. 2018, 2020; Raghavan and Tal 2020; Hao et al. 2021). These factors make it difficult to harmonize and compare impacts across PHEV studies. Due to the low number of appropriate PHEV studies relative to the other LDV technologies and the complications in harmonizing available PHEV results, this technology is omitted from Figure 10.4. However, due to the dual operating nature of PHEV vehicles, one can expect that the life cycle GHG emissions intensities for these vehicles will lie between those of their ICEV and BEV counterparts of similar size and performance.

Currently, BEVs have higher manufacturing emissions than equivalently sized ICEVs, with median emissions of 14 t CO_2-eq/vehicle against approximately 10 t CO_2-eq/vehicle of their mid-sized fossil-fuelled counterparts. These higher production emissions of BEVs are largely attributed to the battery pack manufacturing and to the additional power electronics required. As manufacturing technology and capacity utilization improve and globalizes to regions with low-carbon electricity, battery manufacturing emissions will likely decrease. Due to the higher energy efficiency of the electric powertrain, BEVs may compensate for these higher production emissions in the driving phase. However, the mitigation ability of this technology relative to ICEVs is highly dependent on the electricity mix used to charge the vehicle. As a consequence of the variety of energy sources available today, current BEVs have a wide range of potential average life cycle impacts, ranging between 60 and 180 g CO_2-eq pkm^{-1} with electricity generated from wind and coal, respectively. The ability to achieve large carbon reductions via vehicle electrification is thus highly dependent on the generation of low-carbon electricity, with the greatest mitigation effects achieved when charging the battery with low-carbon electricity. The literature suggests that current BEVs, if manufactured on low carbon electricity as well as operated on low carbon electricity would have footprints as low 22 g CO_2-eq pkm^{-1} for a compact sized car (Ellingsen et al. 2014, 2016). This value suggests a reduction potential of around 85% compared to similarly sized fossil fuel vehicles (median values). Furthermore, BEVs have a co-benefit of reducing local air pollutants that are responsible for human health complications, particularly in densely populated areas (Hawkins et al. 2013; Ke et al. 2017).

As with BEVs, current HFCVs have higher production emissions than similarly sized ICEVs and BEVs, generating on average approximately 15 t CO_2-eq/vehicle. As with BEVs, the life cycle impacts of FCVs are highly dependent on the fuel chain. To date, the most common method of Hydrogen production is steam methane reforming from natural gas (Khojasteh Salkuyeh et al. 2017), which is relatively carbon intensive, resulting in life cycle emissions of approximately 88 g CO_2-eq pkm^{-1}. Current literature covering life cycle impacts of the FCVs show that vehicles fuelled with Hydrogen produced from steam methane reforming through natural gas offer little or no mitigation potential over ICEVs. Other available Hydrogen fuel chains vary widely in carbon intensity, depending on the synthesis method and the energy source used (electrolysis or steam methane reforming; fossil fuels vs. renewables). The least carbon-intensive Hydrogen pathways rely on electrolysis powered by low-carbon electricity. Compared to ICEVs and BEVs, FCVs for LDVs are at a lower technology readiness level as discussed in section 10.3.

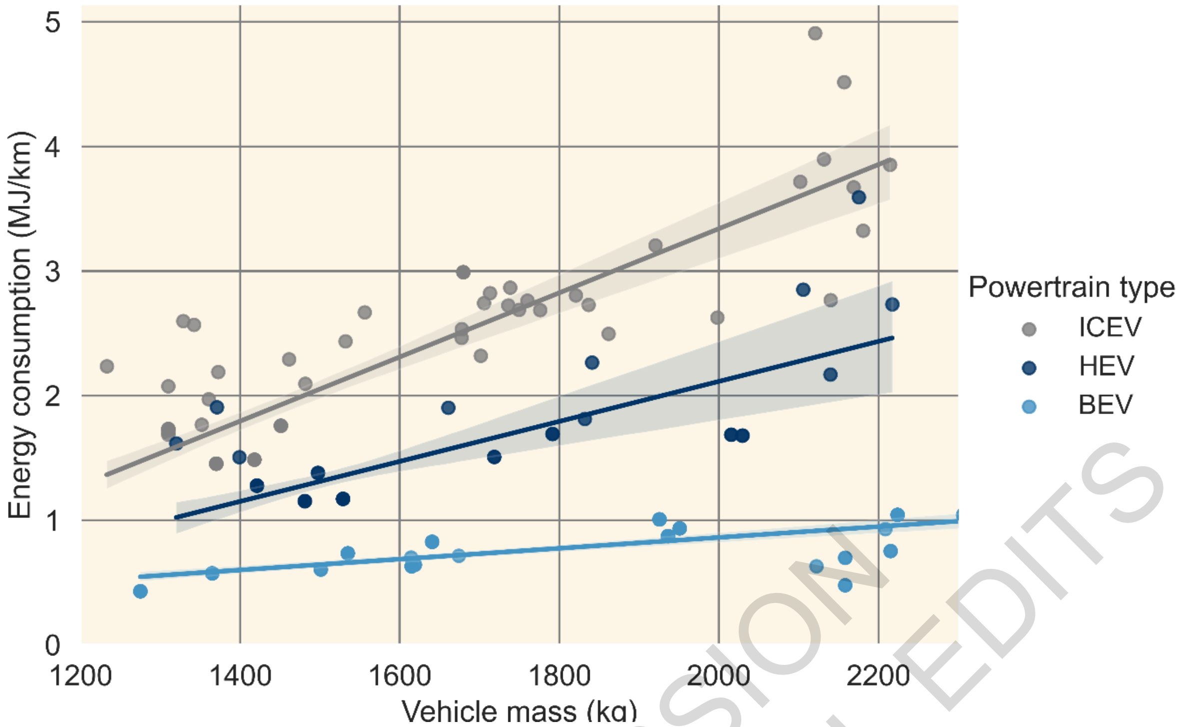
START BOX HERE

Box 10.3 – Vehicle size trends and implications on the fuel efficiency of LDVs

Vehicle size trends: On a global scale, SUV sales have been constantly growing in the last decade, with 39% of the vehicles sold in 2018 being SUVs (IEA 2019d). If the trend towards increasing vehicle size and engine power continues, it may result in higher overall emissions from the LDV fleet (relatively to smaller vehicles with the same powertrain technology). The magnitude of the influence vehicle mass has on fuel efficiency varies with the powertrain, which have different efficiencies. Box 10.3 Figure 1 highlights this relationship using data from the same literature used to create Figure 10.4. Higher powertrain efficiency results in lower energy losses in operation, and thus requires less energy input to move a given mass than a powertrain of lower efficiency. This pattern is illustrated by the more gradual slope of BEVs in Box 10.3 Figure 1. The trend towards bigger and heavier vehicles with consequently higher use phase emissions can be somewhat offset by improvements in powertrain design, fuel efficiency, light weighting, and aerodynamics (Gargoloff et al. 2018; Wolfram et al. 2020). The potential improvements provided by these strategies are case-specific and not thoroughly evaluated in the literature, either individually or as a combination of multiple strategies.

Light weighting: There is an increasing use of advanced materials such as high-strength steel, aluminium, carbon fibre, and polymer composites for vehicle light weighting (Hottle et al. 2017). These materials reduce the mass of the vehicle and thereby also reduce the fuel or energy required to drive. Light-weighted components often have higher production emissions than the components they replace due to the advanced materials used (Kim and Wallington 2016). Despite these higher production emissions, some studies suggest that the reduced fuel consumption over the lifetime of the light-weighted vehicle may provide a net mitigation effect in comparison to the non-light-weighted vehicle (Hottle et al. 2017; Kim and Wallington 2013; Upadhyayula et al. 2019; Milovanoff et al. 2019; Wolfram et al. 2020). However, multiple recent publications have found that in some cases, depending on, for example, vehicle size and carbon intensity of the light weighting materials employed, the GHG emissions avoided due to improved fuel efficiency do not offset the higher manufacturing emissions of the vehicle (Luk et al. 2018; Wu et al. 2019). In addition, these advanced materials may be challenging to recycle in a way that retains their high technical performance (Meng et al. 2017).

Co-effects on particulate matter: Light weighting may also alleviate the particulate matter (PM) emissions arising from road and brake wear. BEVs are generally heavier than their ICEV counterparts, which may potentially cause higher stress on the road surfaces and tires, with consequently higher PM emissions per kilometre driven (Timmers and Achten 2016). Regenerative braking in HEVs, BEVs and FCVs, however, reduces the mechanical braking required, and therefore may compensate for the higher brake wear emissions from these heavier vehicle types. In addition, BEVs have no tailpipe emissions, which further offsets the increased PM emissions from road and tire wear. Therefore, light-weighting strategies may offer a carbon and particulates mitigation effect; however, in some cases, other technological options may reduce CO_2 emissions even further.



Box 10.3, Figure 1 Illustration of energy consumption as a function of vehicle size (using mass as a proxy) and powertrain technology. FCVs omitted due to lacking data.

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Two-wheelers, consisting mainly of lower-powered mopeds and higher-powered motorcycles, are popular for personal transport in densely populated cities, especially in developing countries. LCA studies for this class of vehicle are relatively uncommon compared to four-wheeled LDVs. In the available results, however, two-wheelers exhibit similar trends for the different powertrain technologies as the LDVs, with electric powertrains having higher production emissions, but usually lower operating emissions. The life cycle emissions intensity for two-wheelers is also generally lower than four-wheeled LDVs on a vehicle-kilometre basis. However, two-wheelers generally cannot carry as many passengers as four-wheeled LDVs. Thus, on a passenger-kilometre basis, a fully occupied passenger vehicle may still have lower emissions than a fully occupied two-wheeler. However, today, most passenger vehicles have relatively low occupancy and thus have a correspondingly high emissions intensity on a pkm basis. This points to the importance of utilization of passenger vehicles at higher occupancies to reduce the life cycle intensity of LDVs on a pkm basis. For example, the median emissions intensity of a gasoline passenger vehicle is 222 g CO_2-eq vkm^{-1}, and 160 g CO_2-eq vkm^{-1} for a gasoline two-wheeler (Cox and Mutel 2018). At a maximum occupancy factor of four and two passengers, respectively, the transport emissions intensity for these vehicles are 55 and 80 g CO_2-eq pkm^{-1}. Under the same occupancy rates assumption, BEV two-wheelers recharged on the average European electricity mix, achieve lower life cycle GHG intensities than BEV four-wheeled LDVs. On the other hand, FCV two-wheelers with Hydrogen produced via steam methane reforming present higher GHG intensity than their four-wheeled counterparts, when compared on a pkm basis at high occupancy rates.

ICEV, HEV, and PHEV technologies, which are powered using combustion engines, have limited potential for deep reduction of GHG emissions. Biofuels offer good mitigation potential if low land use change emissions are incurred (e.g., the IAM EMF33 and partial models, CLC biofuels pathways shown in Figure 10.4). The literature shows large variability, depending on the method of calculating associated land use changes. Resolving these apparent methodological differences is important to consolidating the role biofuels may play in mitigation, as well as the issues raised in Chapter 7 about the conflicts over land use. The mitigation potential of battery and fuel cell vehicles is strongly dependent on the carbon intensity of their production and the energy carriers used in operation. However, these technologies likely offer the highest potential for reducing emissions from LDVs. Prior work on the diffusion dynamics of transport technologies suggests that "the diffusion of infrastructure precedes the adoption of vehicles, which precedes the expansion of travel" (Leibowicz 2018). These dynamics reinforce the argument for strong investments in both the energy infrastructure and the vehicle technologies.

To successfully transition towards LDVs utilizing low-carbon fuels or energy sources, the technologies need to be accessible to as many people as possible, which requires competitive costs compared to conventional diesel and gasoline vehicles. The life cycle costs (LCCs) of LDVs depend on the purchasing costs of the vehicles, their efficiency, the fuel costs, and the discount rate. Figure 10.5 shows the results of a parametric analysis of LCC for diesel LDVs, BEVs, and FCVs. The range of vehicle efficiencies captured in Figure 10.5 are the same as the ranges used for Figure 10.4, while the ranges for fuel costs and vehicle purchase prices come from the literature. The assumed discount rate for this parametric analysis is 3%. Appendix 10.2 includes the details about the method and underlying data used to create this figure.

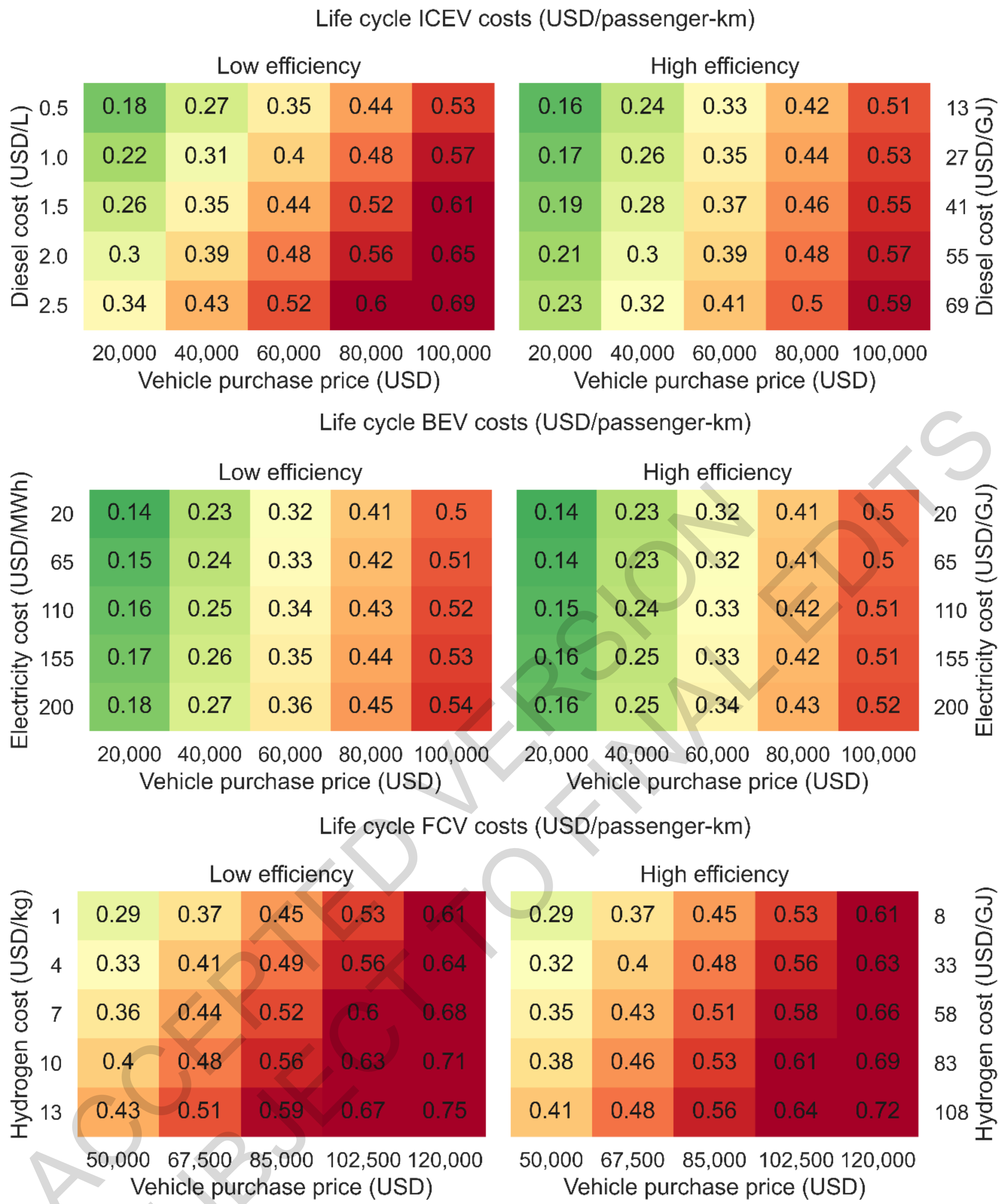


Figure 10.5 LCC for light-duty ICEVs, BEVs, and HFCVs. The results for ICEVs represent the LCC of a vehicle running on gasoline. However, these values are also representative for ICEVs running on diesel as the costs ranges in the literature for these two solutions are similar. The secondary y-axis depicts the cost of the different of the energy carriers normalized in USD/GJ for easier cross-comparability.

Figure 10.5 shows the range of LCC, in USD per pkm, for different powertrain technologies, and the influence of vehicle efficiency (low or high), vehicle purchase price, and fuel/electricity cost on the overall LCC. For consistency with Figure 10.4, an occupancy rate of 1.5 is assumed. Mid-sized ICEVs have a purchase price of USD 20,000-40,000, and average fuel costs are in the range of 1-1.5 USD/L. With these conditions, the LCC of fossil-fuelled LDVs span between 0.22-0.35 USD per pkm or between 0.17-0.28 USD per pkm, for low and high efficiency ICEVs respectively (Figure 10.5).

BEVs have higher purchase prices than ICEVs, though a sharp decline has been observed since AR5. Due to the rapid development of the lithium-ion battery technology over the years (Schmidt et al. 2017) and the introduction of subsidies in several countries, BEVs are quickly reaching cost parity with ICEVs. Mid-sized BEVs average purchase prices are in the range of USD 30,000-50,000 but the levelised cost of electricity shows a larger spread (65-200 USD/MWh) depending on the geographical location and the technology (see Chapter 6). Therefore, assuming purchase price parity between ICEVs and BEVs, BEVs show lower LCC (Figure 10.5) due to higher efficiency and the lower cost of electricity compared to fossil fuels on a per-GJ basis (secondary y-axis on Figure 10.5).

FCVs represent the most expensive solution for LDV, mainly due to the currently higher purchase price of the vehicle itself. However, given the lower technology readiness level of FCVs and the current efforts in the research and development of this technology, FCVs could become a viable technology for LDVs in the coming years. The issues regarding the extra energy involved in creating the Hydrogen and its delivery to refuelling sites remain, however. The levelized cost of Hydrogen on a per GJ basis is lower than conventional fossil fuels but higher than electricity. In addition, within the levelized cost of Hydrogen, there are significant cost differences between the Hydrogen producing technologies. Conventional technologies such as coal gasification and steam methane reforming from natural gas, both with and without carbon capture and storage, represent the cheapest options (Bekel and Pauliuk 2019; Parkinson et al. 2019; Khzouz et al. 2020; Al-Qahtani et al. 2021). Hydrogen produced via electrolysis is currently the most expensive technology, but with significant potential cost reductions due to the current technology readiness level.

10.4.2 Transit technologies for passenger transport

Buses provide urban and peri-urban transport services to millions of people around the world and a growing number of transport agencies are exploring alternative-fuelled buses. Alternative technologies to conventional diesel-powered buses include buses powered with CNG, LNG, synthetic fuels, and biofuels (e.g., biodiesel, renewable diesel, dimethyl ether); diesel hybrid-electric buses; battery electric buses; electric catenary buses, and Hydrogen fuel cell buses. Rail is an alternative mode of transit that could support decarbonisation of land-based passenger mobility. Electric rail systems can provide urban services (light rail and metro systems), as well as longer distance transport. Indeed, many cities of the world already have extensive metro systems, and regions like China, Japan and Europe have a robust high-speed inter-city railway network. Intercity rail transport can be powered with electricity; however, fossil fuels are still prevalent for long-distance rail passenger transport in some regions. Battery electric long-distance trains may be a future option for these areas.

Figure 10.6 shows the life cycle GHG emissions from different powertrain and fuel technologies for buses and passenger rail. The data in each panel came from a number of relevant scientific studies (IEA 2019e; Tong et al. 2015a; Dimoula et al. 2016; de Bortoli et al. 2017; Meynerts et al. 2018; Cai et al. 2015; de Bortoli and Christoforou 2020; Hill et al. 2020; Liu et al. 2020a; Valente et al. 2021, 2017). The width of the bar represents the variability in available estimates, which is primarily driven by variability in reported vehicle efficiency, size, or drive cycle. While some bars overlap, the figure may not fully capture correlations between results. For example, low efficiency associated with aggressive drive cycles may drive the upper end of the emission ranges for multiple technologies; thus, an overlap does not necessarily suggest uncertainty regarding which vehicle type would have lower emissions for a comparable trip. Additionally, reported life cycle emissions do not include embodied GHG emissions associated with infrastructure construction and maintenance. These embodied emissions are potentially a larger fraction of life cycle emissions for rail than for other transport modes (Chester and Horvath 2012; Chester et al. 2013). One study reported values ranging from 10-25 g CO_2 per passenger-kilometre (International Union of Railways 2016), although embodied emissions from rail are known to vary widely across case studies (Olugbenga et al. 2019). These caveats are also applicable to the other figures in this section.

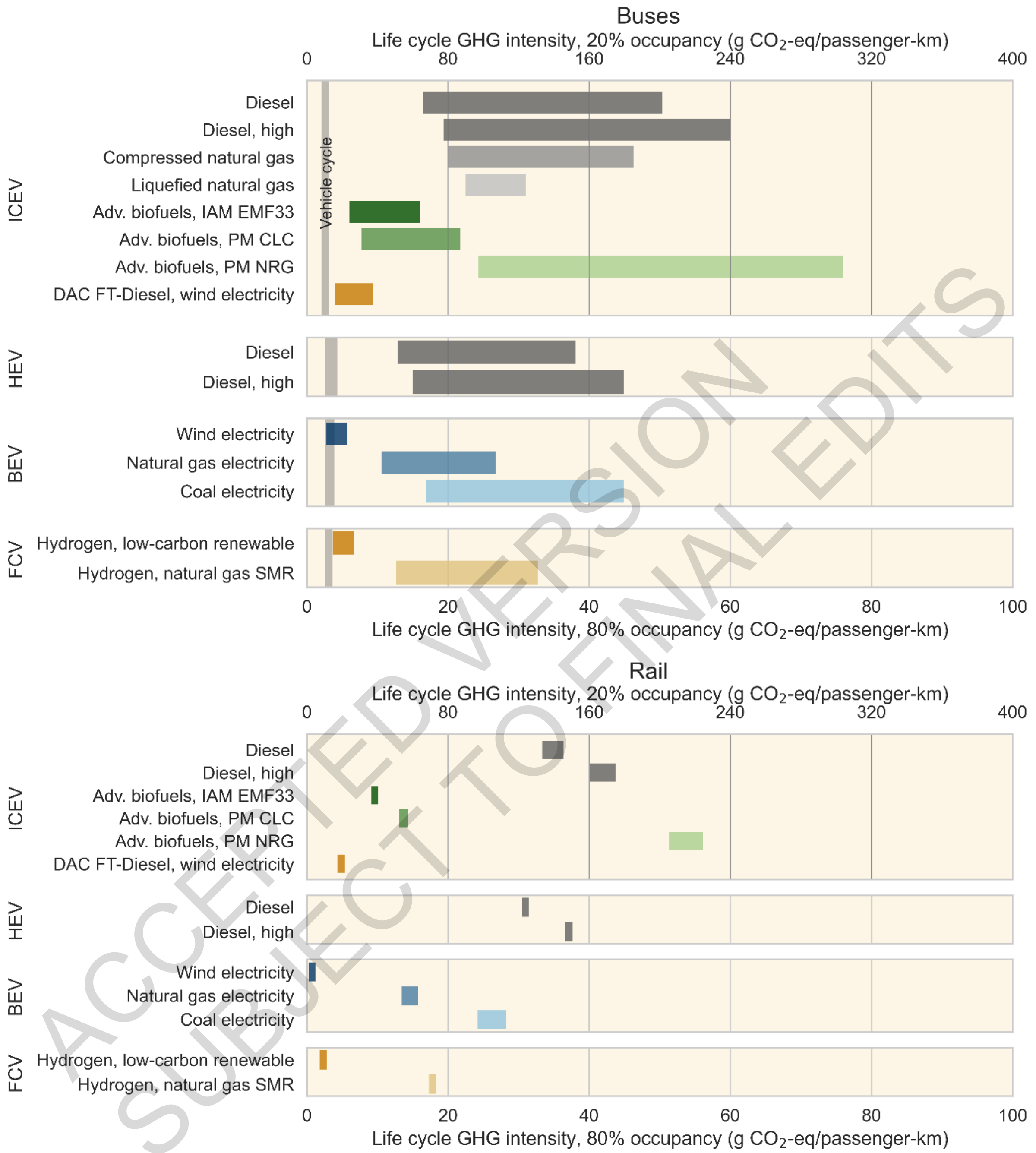


Figure 10.6 Life cycle GHG intensity of land-based bus and rail technologies. Each bar represents the range of the life cycle estimates, bounded by minimum and maximum energy use per pkm, as reported for each fuel/powertrain combination. The ranges are driven by differences in vehicle characteristics and operating efficiency. For energy sources with highly variable upstream emissions low, medium and/or high representative values are shown as separate rows. The primary x-axis shows life cycle GHG emissions, in g CO_2-eq per pkm, assuming 80% occupancy; the secondary x-axis assumes 20% occupancy. The values in the figure rely on the 100-year GWP value embedded in the source data, which may differ slightly with the updated 100-year GWP values from WGI. For buses, the main bars show full

life cycle, with vertical bars disaggregating the vehicle cycle. 'Diesel, high' references emissions factors for diesel from oil sands. 'Adv. Biofuels' i.e., advanced biofuels, refers to the use of second-generation biofuels and their respective conversion and cultivation emission factors. 'IAM EMF33' refers to emissions factors for advanced biofuels derived from simulation results from the integrated assessment models EMF33 scenarios. 'PM' refers to partial models, where 'CLC' is with constant land cover and 'NRG' is with natural regrowth. 'DAC FT-Diesel, wind electricity' refers to Fischer-Tropsch diesel produced via a CO_2 direct air capture process that uses wind electricity. 'Hydrogen, low-carbon renewable' refers to fuels produced via electrolysis using low-carbon electricity. 'Hydrogen, natural gas SMR' refers to fuels produced via steam methane reforming of natural gas. Results for ICEVs with 'high emissions DAC FT-Diesel from natural gas' are not included here since the life cycle emissions are estimated to be substantially higher than petroleum diesel ICEVs.

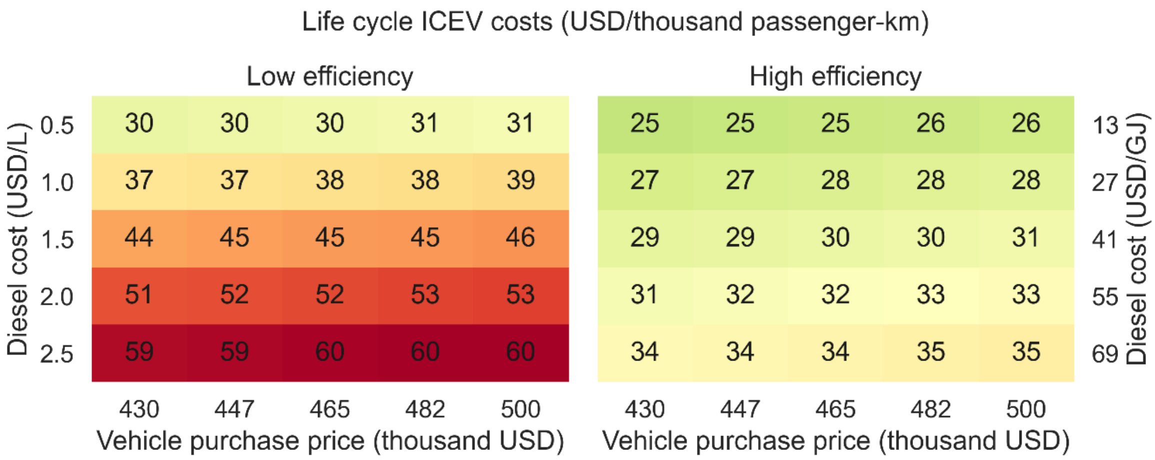
Figure 10.6 highlights that BEV and FCV buses and passenger rail powered with low carbon electricity or low carbon Hydrogen, could offer reductions in GHG emissions compared to diesel-powered buses or diesel-powered passenger rail. However, and not surprisingly, these technologies would offer only little emissions reductions if power generation and Hydrogen production rely on fossil fuels. While buses powered with CNG and LNG could offer some reductions compared to diesel-powered buses, these reductions are unlikely to be sufficient to contribute to deep decarbonisation of the transport sector and they may slow down conversion to low or zero-carbon options already commercially available. Biodiesel and renewable diesel fuels (from sources with low upstream emissions and low risk of induced land use change) could offer important near-term reductions for buses and passenger rail, as these fuels can often be used with existing vehicle infrastructure. They could also be used for long haul trucks and trains, shipping and aviation as discussed below and in later sections.

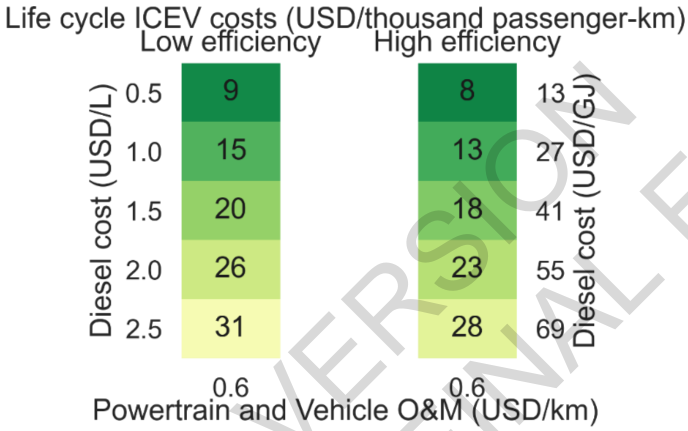
There has been growing interest in the production of synthetic fuels from CO_2 produced by direct air capture (DAC) processes. Figure 10.6 includes the life cycle GHG emissions from buses and passenger rail powered with synthetic diesel produced through a DAC system paired with a Fischer-Tropsch (FT) process based on (Liu et al. 2020a). This process requires the use of Hydrogen (as shown in Figure 10.2 in section 10.3), so the emissions factors of the resulting fuel depend on the emissions intensity of Hydrogen production. An electricity emissions factor less than 140 g CO_2-eq kWh^{-1} would be required for this pathway to achieve lower emissions than petroleum diesel (Liu et al. 2020a); e.g., this would be equivalent to 75% wind and 25% natural gas electricity mix (see Appendix 10.1). If the process relied on steam methane reforming for Hydrogen production or fossil-based power generation, synthetic diesel from the DAC-FT process would not provide GHG emissions reductions compared to conventional diesel. DAC-FT from low-carbon energy sources appears to be promising from an emissions standpoint and could warrant the R&D and demonstration attention outlined in the rest of the chapter, but it cannot be contemplated as a decarbonisation strategy without the availability of low-carbon Hydrogen.

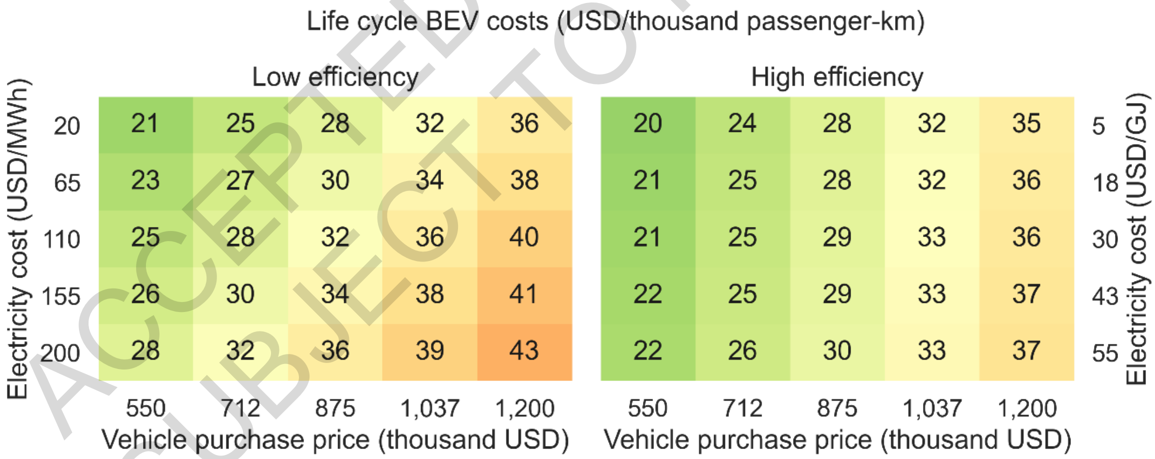
At high occupancy, both bus and rail transport offer substantial GHG reduction potential per pkm, even compared with the lowest-emitting private vehicle options. Even at 20% occupancy, bus and rail may still offer emission reductions compared to passenger cars, especially notable when comparing BEVs with low-carbon electricity (the lowest emission option for all technologies) across the three modes. Only when comparing a fossil fuel-powered bus at low occupancy with a low-carbon powered car at high occupancy is this conclusion reversed. Use of public transit systems, especially those that rely on buses and passenger rail fuelled with the low carbon fuels previously described would thus support efforts to decarbonise the transport sector. Use of these public transit systems will depend on urban design and consumer preferences (as described in Section 10.2 and Chapters 5 and 8), which in turn depend on time, costs, and behavioural choices.

Figure 10.7 shows the results of a parametric analysis of the LCCs of transit technologies with the highest potential for GHG emissions reductions. As with Figure 10.5, the vehicle efficiency ranges are the same as those from the LCA estimates (80% occupancy). Vehicle, fuel, and maintenance costs represent ranges in the literature (Eudy and Post 2018b; IEA 2019e; Argonne National Laboratory 2020; BNEF 2020; Eudy and Post 2020; Hydrogen Council 2020; IEA 2020b,c; IRENA 2020; Johnson et al. 2020; Burnham et al. 2021; IEA 2021c,d; U.S. Energy Information Administration 2021), and the discount rate is 3% where applicable. Appendix 10.2 of the chapter provides the details behind these estimates. The panels for the ICEV can represent buses and passenger trains powered with any form of diesel, whether derived from petroleum, synthetic hydrocarbons, or biofuels. For reference, global average automotive diesel prices from 2015-2020 fluctuated around 1 USD/L, and the 2019 world average industrial electricity price was approximately 100 USD/MWh (IEA 2021d). Retail Hydrogen prices in excess of 13 USD/kg have been observed (Eudy and Post 2018a; Argonne National Laboratory 2020; Burnham et al. 2021) though current production cost estimates for Hydrogen produced from electrolysis are far lower ((IRENA 2020), and as reported in Chapter 6), at around 5-7 USD/kg with future forecasts as low as 1 USD/kg ((IRENA 2020; BNEF 2020; Hydrogen Council 2020), and as reported in Chapter 6).

Under most parameter combinations, rail is the most cost-effective option, followed by buses, both of which are an order of magnitude cheaper than passenger vehicles. Note that costs per pkm are strongly influenced by occupancy assumptions; at low occupancy (e.g., <20% for buses and <10% for rail), the cost of transit approaches the LCC for passenger cars. For diesel rail and buses, cost ranges are driven by fuel costs, whereas vehicle are both important drivers for electric or Hydrogen modes due to high costs (but also large projected improvements) associated with batteries and fuel cell stacks. Whereas the current state of ICEV technologies is best represented by cheap vehicles and low fuel costs for diesel (top left of each panel), these costs are likely to rise in future due to stronger emission/efficiency regulations and rising crude oil prices. On the contrary, the current status of alternative fuels is better represented by high capital costs and mid-to-high fuel costs (right side of each panel; mid-to-bottom rows), but technology costs are anticipated to fall with increasing experience, research, and development. Thus, while electric rail is already competitive with diesel rail, and electric buses are competitive with diesel buses in the low efficiency case, improvements are still required in battery costs to compete against modern diesel buses on high efficiency routes, at current diesel costs. Similarly, improvements to both vehicle cost and fuel costs are required for Hydrogen vehicles to become cost effective compared to their diesel or electric counterparts. At either the upper end of the diesel cost range (bottom row of ICEV panels), or within the 2030-2050 projections for battery costs, fuel cell costs and Hydrogen costs (top left of BEV and FCV panels) – both battery and Hydrogen powered vehicles become financially attractive.


Life cycle ICEV costs (USD/thousand passenger-km)
Low efficiency
High efficiency
Diesel cost (USD/L)
0.5
1.0
1.5
2.0
2.5
30 30 30 31 31
37 37 38 38 39
44 45 45 45 46
51 52 52 53 53
59 59 60 60 60
25 25 25 26 26
27 27 28 28 28
29 29 30 30 31
31 32 32 33 33
34 34 34 35 35
Diesel cost (USD/GJ)
13
27
41
55
69
430 447 465 482 500
Vehicle purchase price (thousand USD)
430 447 465 482 500
Vehicle purchase price (thousand USD)


Life cycle ICEV costs (USD/thousand passenger-km)
Low efficiency
High efficiency
Diesel cost (USD/L)
0.5
1.0
1.5
2.0
2.5
9 8
15 13
20 18
26 23
31 28
Diesel cost (USD/GJ)
13
27
41
55
69
0.6
0.6
Powertrain and Vehicle O&M (USD/km)


Life cycle BEV costs (USD/thousand passenger-km)
Low efficiency
High efficiency
Electricity cost (USD/MWh)
20
65
110
155
200
21 25 28 32 36
23 27 30 34 38
25 28 32 36 40
26 30 34 38 41
28 32 36 39 43
20 24 28 32 35
21 25 28 32 36
21 25 29 33 36
22 25 29 33 37
22 26 30 33 37
Electricity cost (USD/GJ)
5
18
30
43
55
550 712 875 1,037 1,200
Vehicle purchase price (thousand USD)
550 712 875 1,037 1,200
Vehicle purchase price (thousand USD)

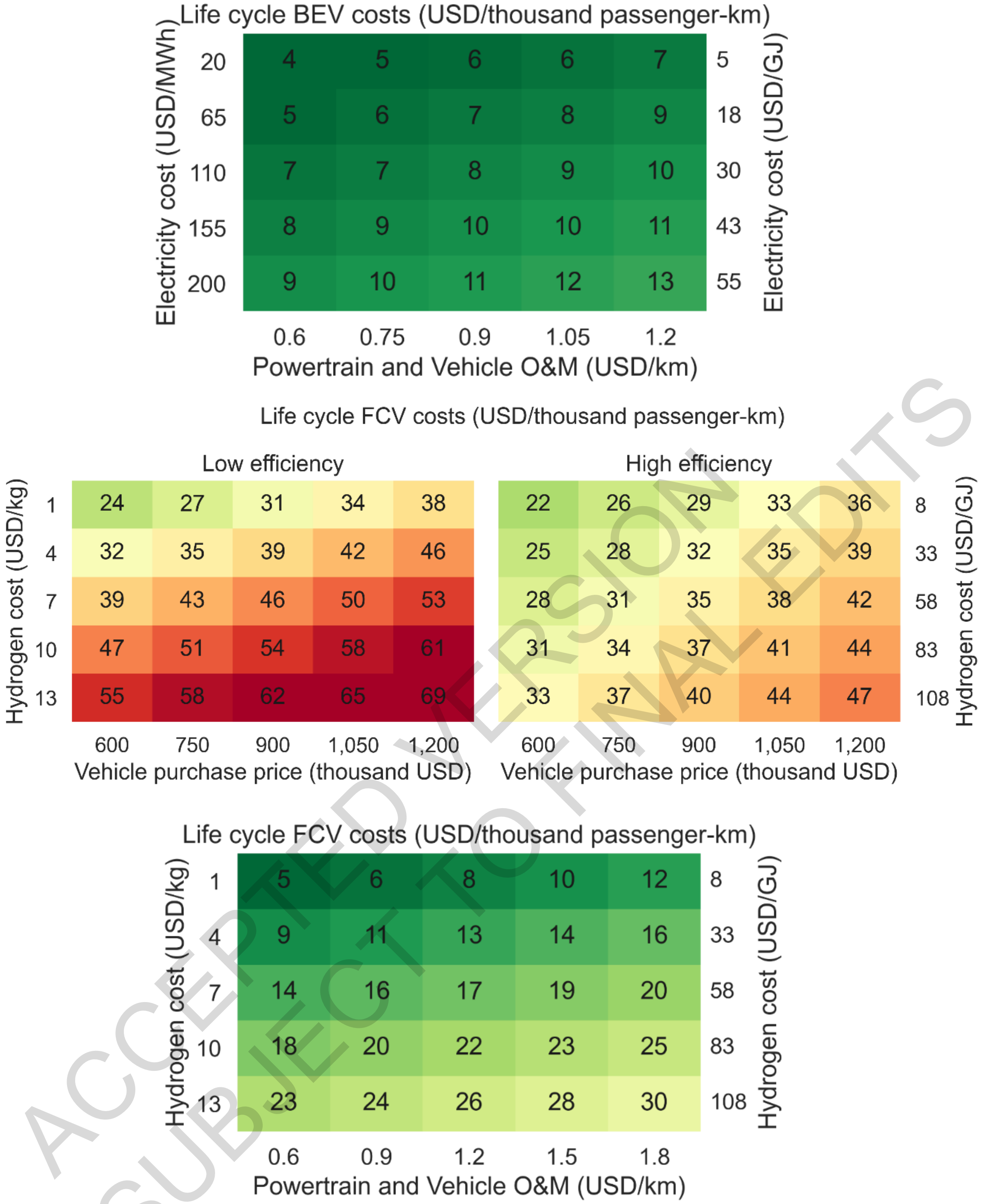


Figure 10.7 Life cycle costs for internal combustion engine vehicles ICEV, BEV, and HFCV for buses and passenger rail. The range of efficiencies for each vehicle type are consistent with the range of efficiencies in Figure 10.6 (80% occupancy). The results for the ICEV can be used to evaluate the life cycle costs of ICE buses and passenger rail operated with any form of diesel, whether from petroleum, synthetic hydrocarbons, or biofuel, as the range of efficiencies of vehicles operating with all these fuels is similar. The secondary y-axis depicts the cost of the different energy carriers normalized in USD/GJ for easier cross-comparability.

10.4.3 Land-based freight transport

As is the case with passenger transport, there is growing interest in alternative fuels that could reduce GHG emissions from freight transport. Natural gas-based fuels (e.g., CNG, LNG) are an example, however these may not lead to drastic reductions in GHG emissions compared to diesel. Natural gas-powered vehicles have been discussed as a means to mitigate air quality impacts (Khan et al. 2015; Pan et al. 2020; Cai et al. 2017) but those impacts are not the focus of this review. Decarbonisation of medium and heavy-duty trucks would likely require the use of low-carbon electricity in battery-electric trucks, low-carbon Hydrogen or Ammonia in fuel-cell trucks, or bio-based fuels (from sources with low upstream emissions and low risk of induced land use change) used in ICE trucks.

Freight rail is also a major mode for the inland movement of goods. Trains are more energy efficient (per tkmm) than trucks, so expanded use of rail systems (particularly in developing countries where demand for goods could grow exponentially) could provide carbon abatement opportunities. While diesel-based locomotives are still a major propulsion used in freight rail, interest in low-carbon propulsion technologies is growing. Electricity already powers freight rail in many European countries using overhead catenaries. Other low-carbon technologies for rail may include advanced storage technologies, biofuels, synthetic fuels, Ammonia, or Hydrogen.

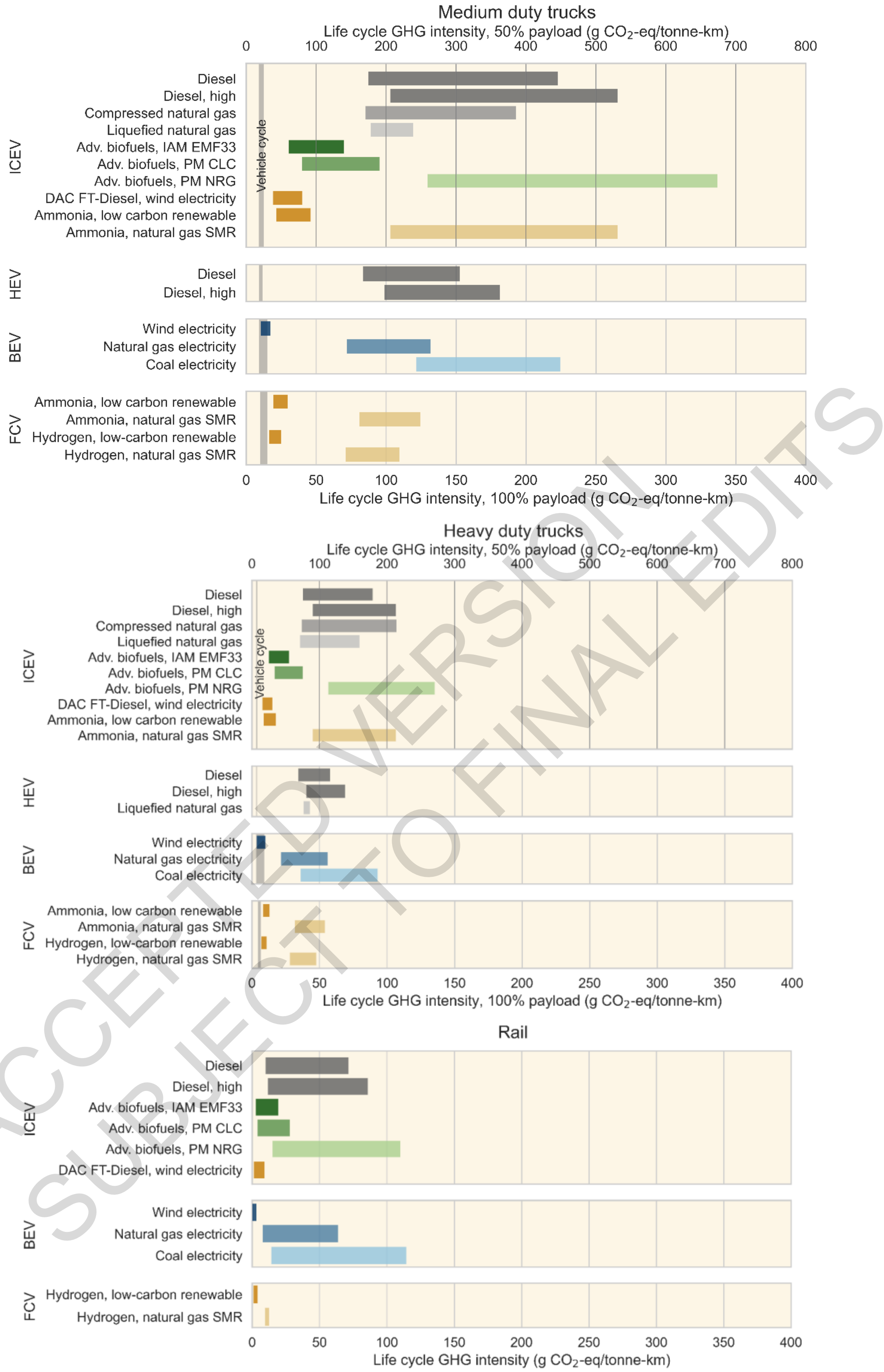


Figure 10.8 Life cycle GHG intensity of land-based freight technologies and fuel types. Each bar represents the range of the life cycle estimates, bounded by minimum and maximum energy use per tkm, as reported for each fuel/powertrain combination. The ranges are driven by differences in vehicle characteristics and operating efficiency. For energy sources with highly variable upstream emissions, low, medium and/or high representative values are shown as separate rows. For trucks, the primary x-axis

shows life cycle GHG emissions, in g CO_2-eq per tkm, assuming 100% payload; the secondary x-axis assumes 50% payload. The values in the figure rely on the 100-year GWP value embedded in the source data, which may differ slightly with the updated 100-year GWP values from WGI. For rail, values represent average payloads. For trucks, main bars show full life cycle, with vertical bars disaggregating the vehicle cycle. 'Diesel, high' references emissions factors for diesel from oil sands. 'Adv. Biofuels' refers to the use of second-generation biofuels and their respective conversion and cultivation emission factors. 'IAM EMF33' refers to emissions factors for advanced biofuels derived from simulation results from the EMF33 scenarios. 'PM' refers to partial models, where 'CLC' is with constant land cover and 'NRG' is with natural regrowth. DAC FT-Diesel, wind electricity refers to Fischer-Tropsch diesel produced via a CO_2 direct air capture process that uses wind electricity. 'Ammonia and Hydrogen, low-carbon renewable' refers to fuels produced via electrolysis using low-carbon electricity. 'Ammonia and Hydrogen, natural gas SMR' refers to fuels produced via steam methane reforming of natural gas.

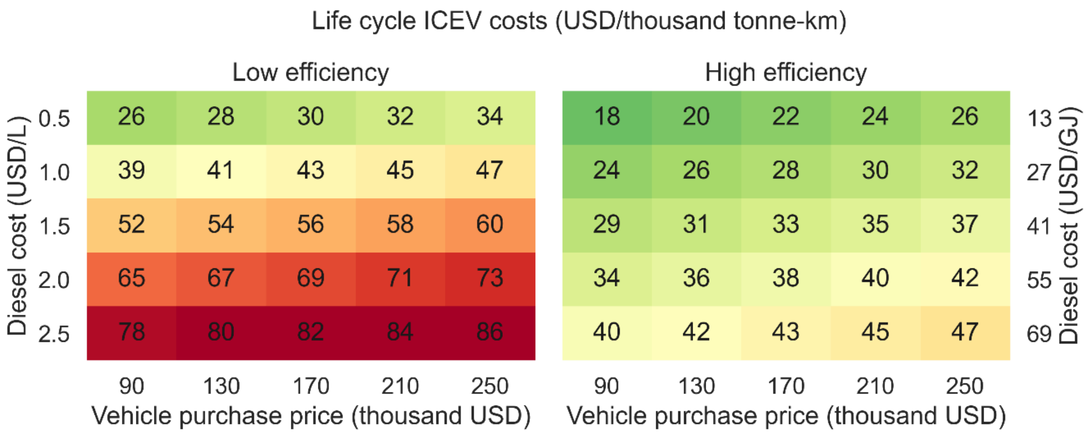
Figure 10.8 presents a review of life cycle GHG emissions from land-based freight technologies (heavy and medium-duty trucks, and rail). Each panel within the figure represents data in GHG emissions per tkm of freight transported by different technology and/or fuel types, as indicated by the labels to the left. The data in each panel came from a number of relevant scientific studies (Merchan et al. 2020; Frattini et al. 2016; Zhao et al. 2016; CE Delft 2017; Isaac and Fulton 2017; Song et al. 2017; Cooper and Balcombe 2019; S. Mojtaba et al. 2019; Nahlik et al. 2016; Prussi et al. 2020; Hill et al. 2020; Liu et al. 2020a; Valente et al. 2021; Gray et al. 2021; Valente et al. 2017; Tong et al. 2015a). Similar to the results for buses, technologies that offer substantial emission reductions for freight include: ICEV trucks powered with the low carbon variants for biofuels, Ammonia or synthetic diesel; BEVs charged with low carbon electricity; and FCVs powered with renewable-based electrolytic Hydrogen, or Ammonia. Since Ammonia and Fischer-Tropsch diesel are produced from Hydrogen, their emissions are higher than the source Hydrogen, but their logistical advantages over Hydrogen are also a consideration (as discussed in Section 10.3).

Trucks exhibit economies of scale in fuel consumption, with heavy duty trucks generally showing lower emissions per tkm than medium duty trucks. Comparing the life cycle GHG emissions from trucks and rail, it is clear that rail using internal combustion engines is more carbon efficient than using internal combustion trucks. Note that the rail emissions are reported for an average representative payload, while the trucks are presented at 50% and 100% payload, based on available data. The comparison between trucks and rail powered with electricity or Hydrogen is less clear – especially considering that these values omit embodied GHG from infrastructure construction. One study reported embodied rail infrastructure emissions of 15 g CO_2 per tonne-kilometre for rail (International Union of Railways 2016), although such embodied emissions from rail are known to vary widely across case studies (Olugbenga et al. 2019). Regardless, trucks and rail with low carbon electricity or low-carbon Hydrogen have substantially lower emissions than incumbent technologies.

For trucks, Figure 10.8 includes two x-axes representing two different assumptions about their payload, which substantially influence emissions per tonne-kilometre. These results highlight the importance of truckload planning as an emissions reduction mechanism, for example, as also shown in (Kaack et al. 2018). Several studies also point to improvements in vehicle efficiency as an important mechanism to reduce emissions from freight transport (Taptich et al. 2016; Kaack et al. 2018). However, projections for diesel vehicles using such efficiencies beyond 2030 are promising, but still far higher emitting than vehicles powered with low carbon sources.

Figure 10.9 shows the results of a parametric analysis of the LCC of trucks and freight rail technologies with the highest potential for deep GHG reductions. As with Figure 10.8, the vehicle efficiency ranges are the same as those from the LCA estimates (80% payload for trucks; effective payload as reported by original studies for rail). Vehicle, fuel and maintenance costs represent ranges in the literature (Moultak et al. 2017; Eudy and Post 2018b; IEA 2019e; Argonne National Laboratory 2020; BNEF

2020; IRENA 2020; Burnham et al. 2021; IEA 2021c), and the discount rate is 3% where applicable (details are in Appendix 10.2). The panels for the ICEV can represent trucks and freight trains powered with any form of diesel, whether derived from petroleum, synthetic hydrocarbons, or biofuels. See discussion preceding Figure 10.7 for additional details about current global fuel costs. Under most parameter combinations, rail is the more cost-effective option, but the high efficiency case for trucks (representing fuel efficient vehicles, favourable drive cycles and high payload) can be more cost-effective than the low efficiency case for rail (representing systems with higher fuel consumption and lower payload). For BEV trucks, cost ranges are driven by vehicle purchase price due to the large batteries required and the associated wide range between their current high costs and anticipated future cost reductions. For all other truck and rail technologies, fuel cost ranges play a larger role. Similar to transit technologies, the current state of freight ICEV technologies is best represented by cheap vehicles and low fuel costs for diesel (top left of each panel), and the current status of alternative fuels is better represented by high capital costs and mid-to-high fuel costs (right side of each panel; mid-to-bottom rows), with expected future increases in ICEV LCC and decreases in alternative fuel vehicle LCC. Electric and Hydrogen freight rail are potentially already competitive with diesel rail (especially electric catenary (IEA 2019e)), but low data availability (especially for Hydrogen efficiency ranges) and wide ranges for reported diesel rail efficiency (likely encompassing low capacity utilization) makes this comparison challenging. Alternative fuel trucks are currently more expensive than diesel trucks, but future increases in diesel costs or a respective decrease in Hydrogen costs or in BEV capital costs (especially the battery) would enable either alternative fuel technology to become financially attractive. These results are largely consistent with raw results reported in existing literature, which suggest ambiguity over whether BEV trucks are already competitive, but more consistency that Hydrogen is not yet competitive, but could be in future (Zhao et al. 2016; White and Sintov 2017; Moultak et al. 2017; Sen et al. 2017; Zhou et al. 2017; Mareev et al. 2018; Yang et al. 2018a; El Hannach et al. 2019; S. Mojtaba et al. 2019; Tanco et al. 2019; Burke and Sinha 2020; Jones et al. 2020). There is limited data available on the LCC for freight rail, but at least one study IEA (2019g) suggests that electric catenary rail is likely to have similar costs as diesel rail, while battery electric trains remain more expensive and Hydrogen rail could become cheaper under forward-looking cost reduction scenarios.


Life cycle ICEV costs (USD/thousand tonne-km)
Low efficiency
High efficiency
Diesel cost (USD/L)
0.5
1.0
1.5
2.0
2.5
26 28 30 32 34
39 41 43 45 47
52 54 56 58 60
65 67 69 71 73
78 80 82 84 86
18 20 22 24 26
24 26 28 30 32
29 31 33 35 37
34 36 38 40 42
40 42 43 45 47
13
27
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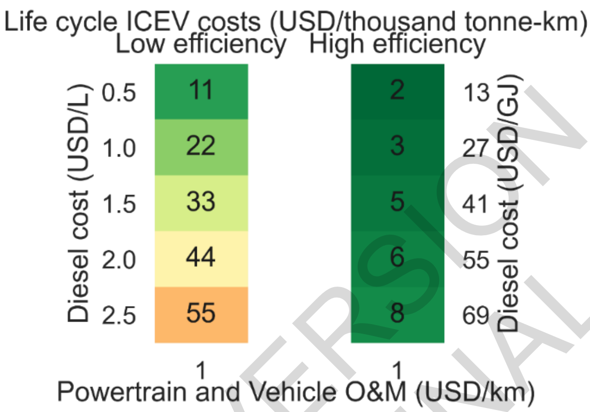
55
69
Diesel cost (USD/GJ)
90 130 170 210 250
Vehicle purchase price (thousand USD)
90 130 170 210 250
Vehicle purchase price (thousand USD)


Life cycle ICEV costs (USD/thousand tonne-km)
Low efficiency
High efficiency
Diesel cost (USD/L)
0.5
1.0
1.5
2.0
2.5
11
22
33
44
55
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3
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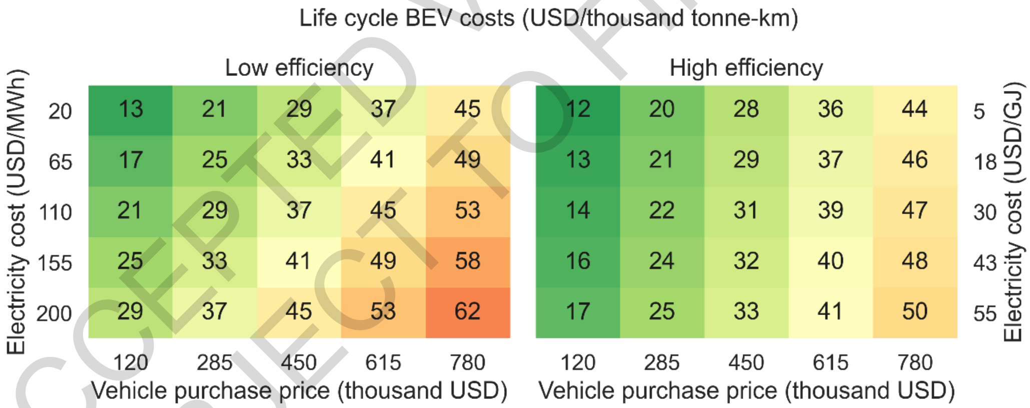
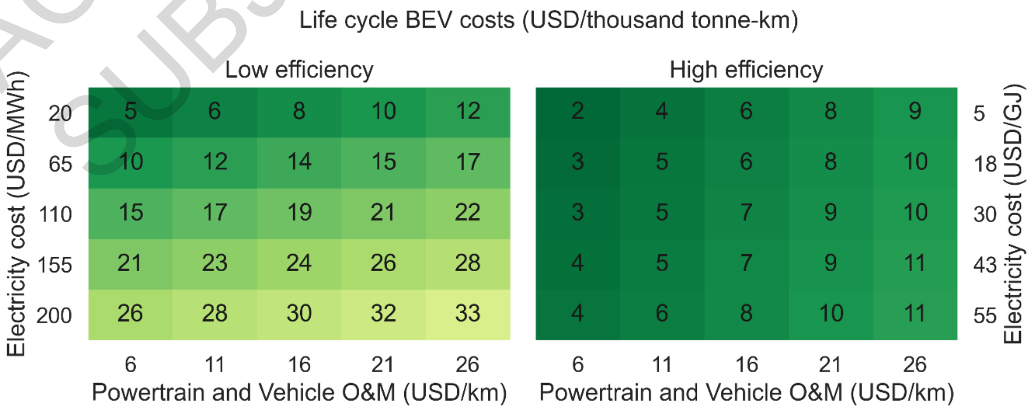
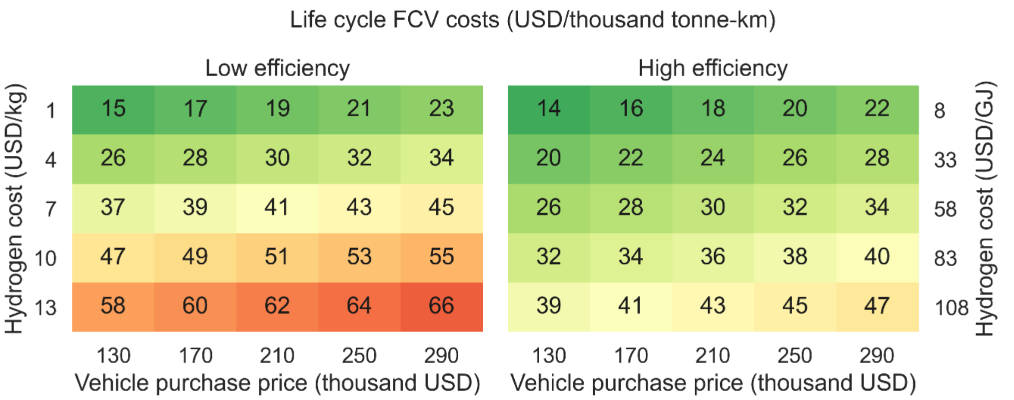
13
27
41
55
69
Diesel cost (USD/GJ)
1
1
Powertrain and Vehicle O&M (USD/km)


Life cycle BEV costs (USD/thousand tonne-km)
Low efficiency
High efficiency
Electricity cost (USD/MWh)
20
65
110
155
200
13 21 29 37 45
17 25 33 41 49
21 29 37 45 53
25 33 41 49 58
29 37 45 53 62
12 20 28 36 44
13 21 29 37 46
14 22 31 39 47
16 24 32 40 48
17 25 33 41 50
5
18
30
43
55
Electricity cost (USD/GJ)
120 285 450 615 780
Vehicle purchase price (thousand USD)
120 285 450 615 780
Vehicle purchase price (thousand USD)


Life cycle BEV costs (USD/thousand tonne-km)
Low efficiency
High efficiency
Electricity cost (USD/MWh)
20
65
110
155
200
5 6 8 10 12
10 12 14 15 17
15 17 19 21 22
21 23 24 26 28
26 28 30 32 33
2 4 6 8 9
3 5 6 8 10
3 5 7 9 10
4 5 7 9 11
4 6 8 10 11
5
18
30
43
55
Electricity cost (USD/GJ)
6 11 16 21 26
Powertrain and Vehicle O&M (USD/km)
6 11 16 21 26
Powertrain and Vehicle O&M (USD/km)



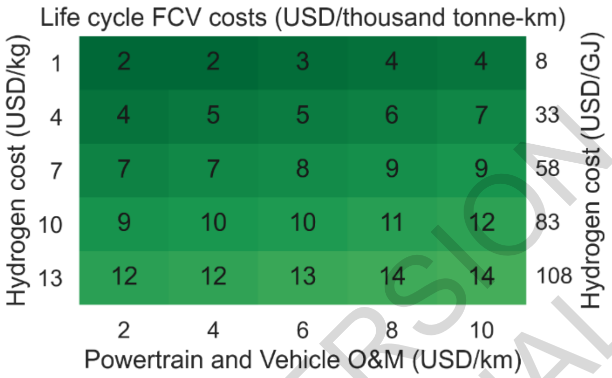


Figure 10.9 Life cycle costs for ICEV, BEV, and HFCV for heavy-duty trucks and freight rail. The range of efficiencies for each vehicle type are consistent with the range of efficiencies in Figure 10.8. The results for the ICEV can be used to evaluate the life cycle costs of ICE trucks and freight rail operated with any form of diesel, whether from petroleum, synthetic hydrocarbons, or biofuels, as the range of efficiencies of vehicles operating with all these fuels is similar. The secondary y-axis depicts the cost of the different of the energy carriers normalized in USD/GJ for easier cross-comparability.

10.4.4 Abatement costs

Taken together, the results in this section suggest a range of cost-effective opportunities to reduce GHG emissions from land-based transport. Mode shift from cars to passenger transit (bus or rail) can reduce GHG emissions while also reducing LCCs, resulting in a negative abatement cost. Likewise, increasing the utilization of vehicles (i.e., % occupancy for passenger vehicles or % payload for freight vehicles) simultaneously decreases emissions and costs per pkm or per tkm, respectively. Within a given mode, alternative fuel sources also show strong potential to reduce emissions at minimal added costs. For LDVs, BEVs can offer emission reductions with LCCs that are already approaching that for conventional ICEVs. For transit and freight, near-term abatement costs for the low-carbon BEV and FCV options relative to their diesel counterparts range from near 0 USD/tonne CO_2-eq (e.g., BEV buses and BEV passenger rail) into the hundreds or even low thousands of dollars per tonne CO_2-eq (e.g., for heavy duty BEV and FCV trucks at current vehicle and fuel costs). With projected future declines in storage, fuel cell, and low-carbon Hydrogen fuel costs, however, both BEV and FCV technologies can likewise offer GHG reductions at negative abatement costs across all land-transport modes in 2030 and beyond. Further information about costs and potentials is available in Chapter 12.

10.5 Decarbonisation of aviation

This section addresses the potential for reducing GHG emissions from aviation. The overriding constraint on developments in technology and energy efficiency for this sector is safety. Governance is complex in that international aviation comes under the International Civil Aviation Organization (ICAO), a specialised UN agency. The measures to reduce GHG emissions that are considered include both in-sector (technology, operations, fuels) and out of sector (market-based measures, high-speed rail modal shift/substitution). Demand management is not explicitly considered in this section, as it was discussed in 10.2. A limited range of scenarios to 2050 and beyond are available and assessed at the end of the section.

10.5.1 Historical and current emissions from aviation

Aviation is widely recognised as a 'hard-to-decarbonise' sector (Gota et al. 2019) having a strong dependency on liquid fossil fuels and an infrastructure that has long 'lock-in' timescales, resulting in slow fleet turnover times. The principal GHG emitted is CO_2 from the combustion of fossil fuel aviation kerosene ('JET-A'), although its non-CO_2 emissions can also affect climate (see section 10.5.2). International emissions of CO_2 are about 65% of the total emissions from aviation (Fleming and de Lépinay 2019), which totalled approximately 1 Gt of CO_2 in 2018. Emissions from this segment of the transport sector have been steadily increasing at rates of around 2.5% per year over the last two decades (see Figure 10.10), although for the period 2010 to 2018 the rate increased to roughly 4% per year. The latest available data (2018) indicate that aviation is responsible for approximately 2.4% of total anthropogenic emissions of CO_2 (including land use change) on an annual basis (using IEA data, IATA data and global emissions data of Le Quéré et al., 2018).

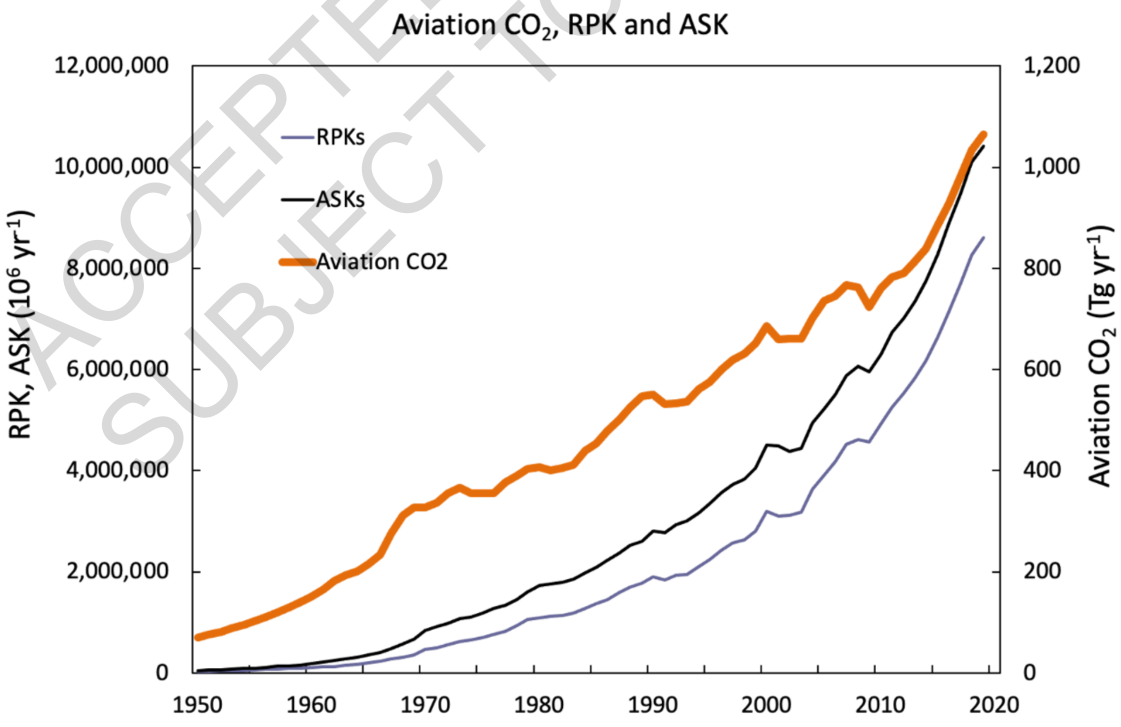


Figure 10.10 Historical global emissions of CO_2 from aviation, along with capacity and transport work (given in available seat kilometres, ASK; revenue passenger kilometres, RPK), Adapted from Lee et al. (2021) using IEA and other data

10.5.2 Short lived climate forcers and aviation

Aviation's net warming effect results from its historical and current emissions of CO_2, and non-CO_2 emissions of water vapour, soot, sulphur dioxide (from sulphur in the fuel), and nitrogen oxides (NO_x, = NO + NO_2) (Penner et al. 1999; Lee et al. 2021; Naik et al. 2021). Although the effective radiative forcing (ERF) of CO_2 from historic aviation emissions is not currently the largest forcing term, it is difficult to address because of the sector's current dependency on fossil-based hydrocarbon fuels and the longevity of CO_2. A residual of emissions of CO_2 today will still have a warming effect in many thousands of years (Archer et al. 2009; Canadell et al. 2021) whereas water vapour, soot, and NO_x emissions will have long ceased to contribute to warming after some decades. As a result, CO_2 mitigation of aviation to 'net zero' levels, as required in 1.5 ºC emission scenarios, requires fundamental shifts in technology, fuel types, or changes of behaviour or demand.

The non-CO_2 effects of aviation on climate fall into the category of short-lived climate forcers (SLCFs). Emissions of NO_x currently result in net positive warming from the formation of short-term ozone (warming) and the destruction of ambient methane (cooling). If the conditions are suitable, emissions of soot and water vapour can trigger the formation of contrails (Kärcher 2018), which can spread to form extensive contrail-cirrus cloud coverage. Such cloud coverage is estimated to have a combined ERF that is ~57% of the current net ERF of global aviation (Lee et al. 2021), although a comparison of cirrus cloud observations under pre- and post-COVID-19 pandemic conditions suggest that this forcing could be smaller (Digby et al. 2021). Additional effects from aviation from aerosol-cloud interactions on high-level ice clouds through soot (Chen and Gettelman 2013; Zhou and Penner 2014; Penner et al. 2018), and lower-level warm clouds through Sulphur (Righi et al. 2013; Kapadia et al. 2016) are highly uncertain, with no best estimates available (Lee et al. 2021). In total, the net ERF from aviation's non-CO_2 SLCFs is estimated to be approximately 66% of aviation's current total forcing. It is important to note that the fraction of non-CO_2 forcing to total forcing is not a fixed quantity and is dependent on the recent history of growth (or otherwise) of CO_2 emissions (Klöwer et al. 2021) The non-CO_2 effects from aviation are the subject of discussion for mitigation options (e.g., (Arrowsmith et al. 2020)). However, the issues are complex, potentially involving technological and operational trade-offs with CO_2.

10.5.3 Mitigation potential of fuels, operations, energy efficiency, and market-based measures

Technology options for engine and airframe: For every kg of jet fuel combusted, 3.16 kg CO_2 is emitted. Engine and airframe manufacturers' primary objective, after safety issues, is to reduce direct operating costs, which are highly dependent on fuel burn. Large investments have gone into engine technology and aircraft aerodynamics to improve fuel burn per km (Cumpsty et al. 2019). There have been major step changes in engine technology over time, from early turbojet engines, to larger turbofan engines. However, the basic configuration of an aircraft has remained more or less the same for decades and will likely remain at least to 2037 (Cumpsty et al. 2019). Airframes performance has improved over the years with better wing design, but large incremental gains have become much harder as the technology has matured. For twin-aisle aircraft, generally used for long ranges, fuel-burn is a pressing concern and there have been several all-new aircraft designs with improvements in their lift-to-drag ratio (Cumpsty et al. 2019). The principal opportunities for fuel reduction come from improvements in aerodynamic efficiency, aircraft mass reduction, and propulsion system improvements. In the future, Cumpsty et al. (2019) suggest that the highest rate of fuel burn reduction achievable for new aircraft is likely to be no more than about 1.3% per year, which is well short of ICAO's aspirational goal of 2% global annual average fuel efficiency improvement. Radically different aircraft shapes, like the blended wing body (where the wings are not distinct from the fuselage) are likely to use about 10% less fuel than future advanced aircraft of conventional form (Cumpsty et al. 2019). Such improvements would be "one-off" gains, do not compensate for growth in emissions of CO_2 expected to be in excess of 2% per annum, and would take a decade or more to penetrate the fleet completely. Thus, the literature does not support the idea that there are large improvements to be made in the energy efficiency of aviation that keep pace with the projected growth in air transport.

Operational improvements for navigation: From a global perspective, aircraft navigation is relatively efficient, with many long-haul routes travelling close to great circle trajectories, and avoiding headwinds that increase fuel consumption. The ICAO estimates that flight inefficiencies on a global basis are currently of the order 2–6% (ICAO 2019), while (Fleming and de Lépinay 2019) project operational improvements (air traffic management) of up to 13% on a regional basis by 2050. 'Intermediate stop operations' have been suggested, whereby longer-distance travel is broken into flight legs, obviating the need to carry fuel for the whole mission. (Linke et al. 2017) modelled this operational behaviour on a global basis and calculated a fuel savings of 4.8% over a base case in which normal fuel loads were carried. However, this approach increases the number of landing/take-off cycles at airports. 'Formation flying', which has the potential to reduce fuel burn on feasible routes has also been proposed (Xu et al. 2014; Marks et al. 2021).

Alternative biofuels, synthetic fuels, and liquid Hydrogen: As noted above, the scope for reducing CO_2 emissions from aviation through improved airplane technology or operations is limited and unable to keep up with the projected growth, let alone reduce beyond the present emission rate at projected levels of demand (assuming post-pandemic recovery of traffic). Thus, the literature outlined here suggests that the only way for demand for aviation to continue to grow without increasing CO_2 emissions is to employ alternative lower-carbon bio- or synthetic aviation fuels (Klöwer et al. 2021). For shorter ranges, flights of light planes carrying up to 50 passengers may be able to use electric power (Sahoo et al. 2020) but these planes are a small proportion of the global aviation fleet (Epstein and O'Flarity 2019; Langford and Hall 2020) and account for less than 12% of current aviation CO_2 emissions. Alternative lower-carbon footprint fuels have been certified for use over recent years, principally from bio-feedstocks, but are not yet widely available at economic prices (Kandaramath Hari et al. 2015; Capaz et al. 2021a). In addition, alternative fuels from bio-feedstocks have variable carbon footprints because of different life cycle emissions associated with various production methods and associated land-use change (de Jong et al. 2017; Staples et al. 2018; Capaz et al. 2021b; Zhao et al. 2021).

The development of 'sustainable aviation fuels' (referred to as 'SAFs') that can reduce aviation's carbon footprint is a growing area of interest and research. Alternative aviation fuels to replace fossil-based kerosene have to be certified to an equivalent standard as Jet-A for a variety of parameters associated with safety issues. Currently, the organisation responsible for aviation fuel standards, ASTM International, has certified seven different types of sustainable aviation fuels with maximum blends ranging from 10% to 50% (Chiaramonti 2019). Effectively, these blend requirements limit the amount of non-hydrocarbon fuel (e.g., Methanol) that can be added at present. While there currently is a minimum level of aromatic hydrocarbon contained in jet fuel to prevent 'O-ring' shrinkage in the fuel seals (Khandelwal et al. 2018), this minimum level can likely be lower in the medium- to long- term, with the added benefits of reduced soot formation and reduced contrail cirrus formation (Bier et al. 2017; Bier and Burkhardt 2019).

Bio-based fuels can be produced using a variety of feedstocks including cultivated feedstock crops, crop residues, municipal solid waste, waste fats, oils and greases, wood products and forestry residues (Staples et al. 2018). Each of these different sources can have different associated life cycle emissions, such that they are not net zero-CO_2 emissions but have associated emissions of CO_2 or other GHGs from their production and distribution (see Section 10.3 and Box 10.2). In addition, associated land use change emissions of CO_2 represent a constraint in climate change mitigation potential with biofuel

(Staples et al. 2017) and has inherent large uncertainties (Plevin et al. 2010). Other sustainability issues include food vs. fuel arguments, water resource use, and impacts on biodiversity. Cost-effective production, feedstock availability, and certification costs are also relevant (Kandaramath Hari et al. 2015). Nonetheless, bio-based SAFs have been estimated to achieve life cycle emissions reductions ranging between approximately 2% and 70% under a wide range of scenarios (Staples et al. 2018). For a set of European aviation demand scenarios, Kousoulidou and Lonza (2016) estimated that the fuel demand in 2030 would be ~100 Mtoe and biokerosene (HEFA/HVO) penetration would provide around 2% of the total fuel demand at that date. Several issues limit the expansion of biokerosene for aviation, the primary one being the current cost of fossil fuel compared to the costs SAF production (Capaz et al. 2021a). Other hybrid pathways e.g., the Hydrogenation of biofuels (the Hydrogen assumed to be generated with low carbon energy), could increase the output and improve the economic feasibility of bio-based SAF (Hannula 2016; Albrecht et al. 2017).

Costs remain a major barrier for bio-SAF, which cost around three times the price of kerosene by (Kandaramath Hari et al. 2015). Clearly, for SAFs to be economically competitive, large adjustments in prices of fossil fuels or the introduction of policies is required. Staples et al. (2018) estimated that in order to introduce bio-SAFs that reduce life cycle GHG emissions by at least 50% by 2050, prices and policies were necessary for incentivization. They estimate the need for 268 new biorefineries per year and capital investments of approximately USD 22 to 88 billion (2015 prices) per year between 2020 and 2050. Wise et al. (2017) suggest that carbon prices would help leverage production and availability.

Various pathways have been discussed for the production of non-bio SAFs such as power-to-liquid pathways (Schmidt et al. 2018), sometimes termed 'electro-fuels' (Goldmann et al. 2018), or more generalised power to 'x' pathways (Kober and Bauer 2019). This process would involve the use of low carbon energy electricity, CO_2, and water to synthesise jet fuel through the Fischer-Tropsch process or Methanol synthesis. Hydrogen would be produced via an electrochemical process, powered by low carbon energy and combined with CO_2 captured directly from the atmosphere or through BECCS. The energy requirement from photovoltaics has been estimated to be of the order 14 – 20 EJ to phase out aviation fossil fuel by 2050 (Gössling et al. 2021a). These synthetic fuels have potential for large life cycle emission reductions (Schmidt et al. 2016). In comparison to bio-SAF production, the implementation of the processes is in its infancy. However, assuming availability of low carbon energy electricity, these fuels have much smaller land and water requirements than bio-SAF. Low carbon energy supply, scalable technology, and therefore costs represent barriers. (Scheelhaase et al. 2019) review current estimates of costs, which are estimated to be approximately 4 to 6 times the price of fossil kerosene.

Liquid Hydrogen (LH_2) as a fuel has been discussed for aeronautical applications since the 1950s (Brewer 1991) and a few experimental aircraft have flown using such a fuel. Experimental, small aircraft have also flown using Hydrogen fuel cells. Although the fuel has an energy density per unit mass about 3 times greater than kerosene, it has a much lower energy density per unit volume (approximately factor 4, (McKinsey 2020)). The increased volume requirement makes the fuel less attractive for aviation since it would require the wings to be thickened or else fuel to take up space in the fuselage. Bicer and Dincer (2017) found that LH_2-powered aircraft compared favourably to conventional kerosene-powered aircraft on a life cycle basis, providing that the LH_2 was generated from low carbon energy sources (0.014 kg CO_2 per tonne km *cf* 1.03 kg CO_2 per tonne km, unspecified passenger aircraft). However, Ramos Pereira et al. (2014) also made a life cycle comparison and found much smaller benefits of LH_2-powered aircraft (manufactured from low carbon energy) compared with conventional fossil-kerosene. The two studies expose the sensitivities of boundaries and assumptions in the analyses. (Shreyas Harsha 2014; Rondinelli et al. 2017) conclude that there are many infrastructural barriers but that the environmental benefits of low carbon-based LH_2 could be considerable. Khandelwal et al. (2013) take a more optimistic view of the prospect of LH_2-powered aircraft but envisage them within a Hydrogen-oriented energy economy. A recently commissioned study by the European Union (EU)'s 'Clean Sky' (McKinsey 2020) addresses many of the aspects of the opportunities and obstacles in developing LH_2 powered aircrafts. The report provides an optimistic view of the feasibility of developing such aircraft for short to medium haul but makes clear that new aircraft designs (such as blended-wing body aircraft) would be needed for longer distances.

The non-CO_2 impacts of LH_2-powered aircrafts remain poorly understood. The emission index of water vapour would be much larger (estimated to be 2.6 times greater by Ström and Gierens (2002)) than for conventional fuels, and the occurrence of contrails may increase but have lower ERF because of the lower optical depth (Marquart et al. 2005). Moreover, contrails primarily form on soot particles from kerosene-powered aircraft, which would be absent from LH_2 exhaust (Kärcher 2018). The overall effect is currently unknown as there are no measurements. Potentially, NO_x emissions could be lower with combustor redesign (Khandelwal et al. 2013).

In conclusion, there are favourable arguments for LH_2-powered aircraft both on an efficiency basis (Verstraete 2013) and an overall reduction in GHG emissions, even on an life cycle basis. However, LH_2 requires redesign of the aircraft, particularly for long-haul operations. Similarly, there would be a need for expanded infrastructure for fuel manufacture, storage, and distribution at airports, which is likely to be more easily overcome if there is a more general move towards a Hydrogen-based energy economy.

Technological and operational trade-offs between CO_2 and non-CO_2 effects: Since aviation has additional non-CO_2 warming effects, there has been some discussion as to whether these can be addressed by either technological or operational means. For example, improved fuel efficiency has resulted from high overall pressure ratio engines with large bypass ratios. This improvement has increased pressure and temperature at the combustor inlet, with a resultant tendency to increase thermal NO_x formation in the combustor. Combustor technology aims to reduce this increase, but it represents a potential technology trade-off whereby NO_x control may be at the expense of extra fuel efficiency. Estimating the benefits or disbenefits of CO_2 (proportional to fuel burned) vs. NO_x in terms of climate is complex (Freeman et al. 2018).

Any GWP/GTP type emissions equivalency calculation always involves the user selection of a time horizon over which the calculation is made, which is a *subjective* choice (Fuglestvedt et al. 2010). In general, the longer the time horizon, the more important CO_2 becomes in comparison with a short-lived climate forcing agent. So, for example, a net (overall) aviation GWP for a 20-year time horizon is 4.0 times that of CO_2 alone, but only 1.7 over a 100-year time horizon. Correspondingly, a GTP for a 20-year time horizon is 1.3, but it is 1.1 for 100 years (Lee et al. 2021).

A widely discussed opportunity mitigation of non-CO_2 emissions from aviation is the avoidance of persistent contrails that can form contrail cirrus. Contrails only form in ice-supersaturated air below a critical temperature threshold (Kärcher 2018). It is therefore feasible to alter flight trajectories to avoid such areas conducive to contrail formation, since ice-supersaturated areas tend to be 10s to 100s of km in the horizontal and only a few 100 metres in the vertical extent (Gierens et al. 1997). Theoretical approaches show that avoidance is possible on a flight-by-flight basis (Matthes et al. 2017; Teoh et al. 2020). Case studies have shown that flight planning according to trajectories with minimal climate impact can substantially (up to 50%) reduce the aircraft net climate impacts despite small additional CO_2 emissions (e.g., (Niklaß et al. 2019)). However, any estimate of the net benefit or disbenefit depends firstly on the assumed magnitude of the contrail cirrus ERF effect (itself rather uncertain, assessed with a low confidence level;) and upon the choice of metric and time-horizon applied. While this is a potentially feasible mitigation option, notwithstanding the CO_2 percontrail trade-off question, meteorological models cannot currently predict the formation of persistent contrails with sufficient accuracy in time and space (Gierens et al. 2020) such that this mitigation option is speculated to take of the order of up to a decade to mature (Arrowsmith et al. 2020)

Market-based offsetting measures: The EU introduced aviation into its CO_2 emissions trading scheme (ETS) in 2012. Currently, the EU-ETS for aviation includes all flights within the EU as well as to and from EEA states. Globally, ICAO agreed in 2016 to commence, in 2020, the 'Carbon Offsetting and Reduction Scheme for International Aviation' (CORSIA). The pandemic subsequently resulted in the baseline being changed to 2019.

CORSIA has a phased implementation, with an initial pilot phase (2021–2023) and a first phase (2024–2026) in which states will participate voluntarily. The second phase will then start in 2026–2035, and all states will participate unless exempted. States may be exempted if they have lower aviation activity levels or based on their UN development status. As of September 2021, 109 ICAO Member States will voluntarily be participating in CORSIA starting in 2022. In terms of routes, only those where both States are participating are included. There will be a special review of CORSIA by the end of 2032 to determine the termination of the scheme, its extension, or any other changes to the scheme beyond 2035.

By its nature, CORSIA does not lead to a reduction in in-sector emissions from aviation since the program deals mostly in approved offsets. At its best, CORSIA is a transition arrangement to allow aviation to reduce its impact in a more meaningful way later. From 2021 onwards, operators can reduce their CORSIA offsetting requirements by claiming emissions reductions from 'CORSIA Eligible Fuels' that have demonstrably reduced life cycle emissions. These fuels are currently available at greater costs than the offsets (Capaz et al. 2021a). As a result, most currently approved CORSIA offsets are avoided emissions, which raises the issue of additionality (Warnecke et al. 2019) The nature of 'avoided emissions' is to prevent an emission that was otherwise considered to be going to occur, e.g. prevented deforestation. Avoided emissions are 'reductions' (over a counterfactual) and purchased from other sectors that withhold from an intended emission (Becken and Mackey 2017), such that if additionality were established, a maximum of 50% of the intended emissions are avoided. Some researchers suggest that avoided deforestation offsets are not a meaningful reduction, since deforestation continues to be a net source of CO_2 emissions (Mackey et al. 2013; Friedlingstein et al. 2020).

Modal shift to High-Speed Rail: Due to the limitations of the current suite of aviation mitigation strategies, the potential for high-speed rail (HSR) is of increasing interest (Givoni and Banister 2006; Chen 2017; Bi et al. 2019). The IEA's Net Zero by 2050 roadmap suggests significant behavioural change with more regional flights shifting to HSR in the NZE pathway (IEA 2021e). For HSR services to be highly competitive with air travel, the optimal distance between the departure and arrival points has been found to be in the approximate range of 400-800 km (Bows et al. 2008; Rothengatter 2010), although in the case of China's HSR operations, this range can be extended out to 1,000 km with corresponding air services having experienced significant demand reduction upon HSR service commencement (Lawrence et al. 2019). In some instances, negative effects on air traffic, air fare, and flight frequency have occurred at medium-haul distances such as HSR services in China on the Wuhan-Guangzhou route (1,069 km) and the Beijing-Shanghai route (1,318 km) (Fu et al. 2015; Zhang and Zhang 2016; Chen 2017; Li et al. 2019; Ma et al. 2019). This competition at medium-haul distances is contrary to that which has been experienced in European and other markets and may be attributable to China having developed a comprehensive network with hub stations, higher average speeds, and an integrated domestic market with strong patronage (Zhang et al. 2019a).

The LCA literature suggests that the GHG emissions associated with HSR vary depending on spatial, temporal, and operational specifics (Åkerman 2011; Baron et al. 2011; Chester and Horvath 2012; Yue et al. 2015; Hoyos et al. 2016; Jones et al. 2017; Robertson 2016, 2018; Lin et al. 2019). These studies found a wide range of approximately 10 - 110 grams CO_2 per pkm for HSR. This range is principally attributable to the sensitivity of operational parameters such as the HSR passenger seating capacity, load factor, composition of renewable and non-renewable energy sources in electricity production, rolling stock energy efficiency and patronage (i.e. ridership both actual and forecast), and line-haul infrastructure specifics (e.g. tunnelling and aerial structure requirements for a particular corridor) (Åkerman 2011; Chester and Horvath 2012; Yue et al. 2015; Newman et al. 2018; Robertson 2018) The prospect for HSR services providing freight carriage (especially on-line purchases) is also growing rapidly (Strale 2016; Bi et al. 2019; Liang and Tan 2019) with a demonstrated emission reduction potential from such operations (Hoffrichter et al. 2012). However, additional supportive policies will most likely be required (Strale 2016; Watson et al. 2019). Limiting emissions avoidance assessments for HSR modal substitution to account only for CO_2 emissions ignores aviation's non-CO_2 effects (see Section 10.5.2), and likely results in an under-representation of the climate benefits of HSR replacing flights.

HSR modal substitution can generate a contra-effect if the air traffic departure and arrival slots that become available as the result of the modal shift are simply reallocated to additional air services (Givoni and Banister 2006; Givoni and Dobruszkes 2013; Jiang and Zhang 2016; Cornet et al. 2018; Zhang et al. 2019a). Furthermore, HSR services have the potential to increase air traffic at a hub airport through improved networks but this effect can vary based on the distance of the HSR stations to airports (Jiang and Zhang 2014; Xia and Zhang 2016; Zhang et al. 2019b; Liu et al. 2019). Such rebound effects could be managed through policy interventions. For example, in 2021 the French government regulated that all airlines operating in France suspend domestic airline flights on routes if a direct rail alternative with a travel time of less than 2.5 hours is available. Other air travel demand reduction measures that have been proposed include regulations to ban frequent flyer reward schemes, mandates that all marketing of air travel declare flight emissions information to the prospective consumer (i.e., the carbon footprint of the nominated flight), the introduction of a progressive 'Air Miles Levy' as well as the inclusion of all taxes and duties that are presently exempt from air ticketing (Carmichael 2019). Moreover, China has the highest use of HSR in the world in part due to its network and competitive speeds and in part due to heavy regulation of the airline industry, in particular restrictions imposed on low-cost air carrier entry and subsidisation of HSR (Li et al. 2019). These air travel demand reduction strategies in addition to stimulating HSR ridership may induce shifts to other alternative modes.

Despite the risk of a rebound effect, and due to the probable reality of an incremental adoption of sustainable aviation fuel technology in the coming decades, the commencement of appropriate HSR services has the potential to provide, particularly in the short to medium-term, additional means of aviation emissions mitigation.

10.5.4 Assessment of aviation-specific projections and scenarios

The most recent projection from ICAO (prior to the COVID-19 pandemic) for international traffic (mid-range growth) is shown in Figure 10.11 (Fleming and de Lépinay 2019). This projection shows the different contributions of mitigation measures from two levels of improved technology, as well as improvements in air traffic management (ATM) and infrastructure use. The projections indicate an increase of CO_2 emissions by a factor of 2.2 in 2050 over 2020 levels for the most optimistic set of mitigation assumptions. The high/low traffic growth assumptions would indicate increases by factors of 2.8 and 1.1, respectively in 2050, over 2020 levels (again, for the most optimistic mitigation assumptions).

The International Energy Agency has published several long-term aviation scenarios since the AR5 within a broader scope of energy projections. Their first set of aviation scenarios include a 'reference technology scenario' (RTS), a '2° Scenario' (2DS) and a 'Beyond 2° Scenario' (B2DS). The scenarios are simplified in assuming a range of growth rates and technological/operational improvements (IEA 2017b) Mitigation measures brought about by policy and regulation are treated in a broad-brush manner, noting possible uses of taxes, carbon pricing, price and regulatory signals to promote innovation.

The IEA has more recently presented aviation scenarios to 2070 in their 'Sustainable Development Scenario' that assume some limited reduced post-COVID-19 pandemic demand, and potential technology improvements in addition to direct reductions in fossil kerosene usage from substitution of biofuels and synthetic fuels (IEA 2021b). There is much uncertainty in how aviation will recover from the COVID-19 pandemic but, in this scenario, air travel returns to 2019 levels in three years, and then continues to expand, driven by income. Government policies could dampen demand (12% lower by 2040 than the IEA 'Stated Policies Scenario,' which envisages growth at 3.4% per year, which in turn is lower than ICAO at 4.3%). Mitigation takes place largely by fuel substitution – lower-carbon biofuels and synthetic fuels, with a smaller contribution from technology. Approximately 85% of the actual cumulative CO_2 emissions (to 2070) are attributed to use of fuel at their lowest Technology Readiness Level of 'Prototype,' which is largely made up of biofuels and synthetic fuels, as shown in Figure 10.12. Details of the technological scenarios and the fuel availability/uptake assumptions are given in (IEA 2021b), which also makes clear that the relevant policies are not currently in place to make any such scenario happen.

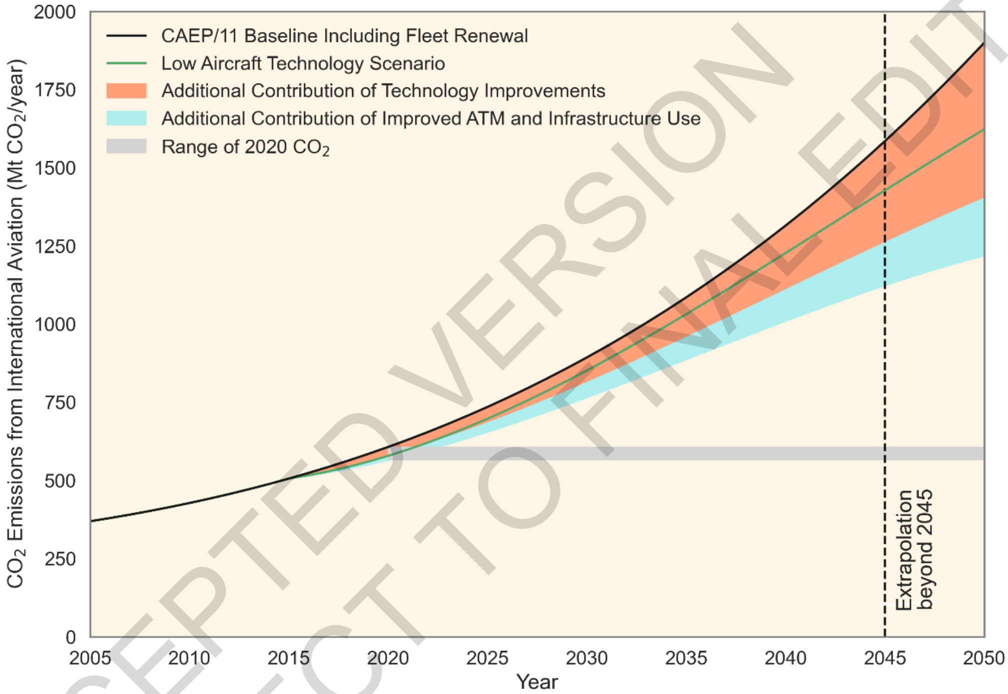


Figure 10.11 Projections of international aviation emissions of CO_2. Data in Mt yr-1, to 2050, showing contributions of improved technology, and air traffic management and infrastructure to emissions reductions to 2050.

Data from Fleming and de Lépinay (2019); projections made pre-COVID-19 global pandemic

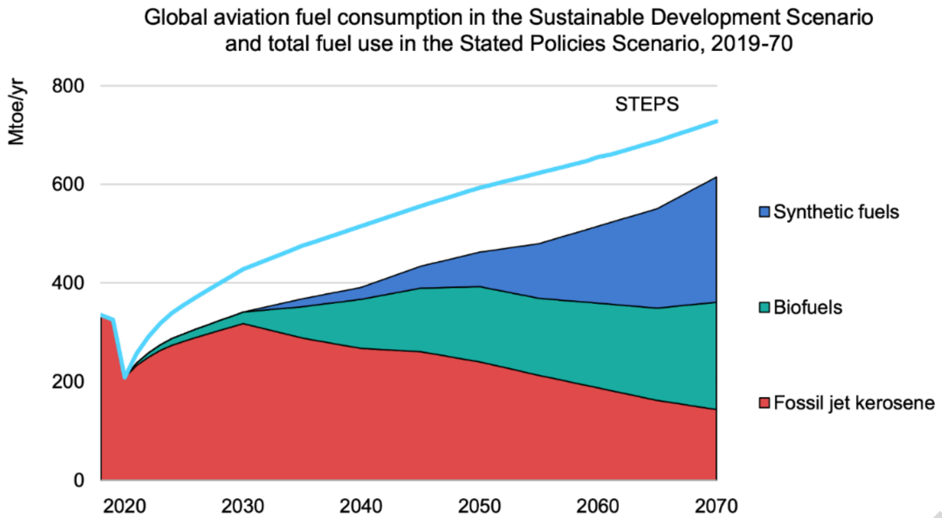


Figure 10.12 The International Energy Agency's scenario of future aviation fuel consumption for the States Policies Scenario ('STEPS') and composition of the Sustainable Development Scenario (from (IEA 2021b))

Within the Coupled Model Intercomparison Project Phase 6 (CMIP6) emissions database, a range of aviation emission scenarios for a range of SSP scenarios are available (see Figure 10.13). This figure suggests that by 2050, direct emissions from aviation could be 1.5 to 6.5 (5-95th percentile) times higher than in the 2020 model year under the scenarios without firm commitments to meet a long-term temperature target (i.e., C7-8 scenarios with temperature change above 2.5°C by 2100). In the C1-2 scenario group, which limit temperature change below 1.5°C, aviation emissions could still be up to 2.5 times higher in 2050 than emissions in the 2020 model year (95th percentile) but may need to decrease by 10% by 2050 (5th percentile).

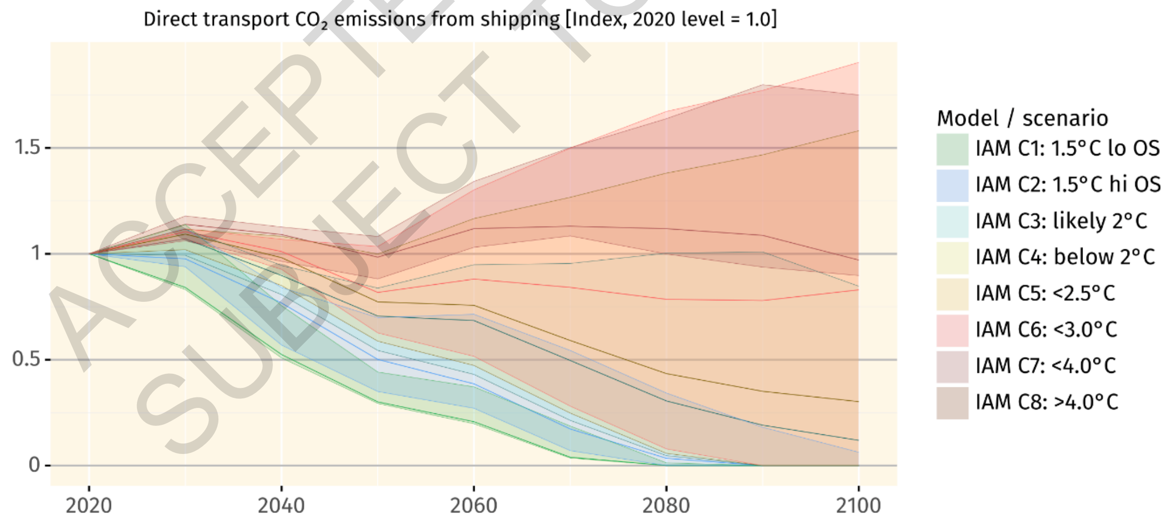


Figure 10.13 CO_2 emission from AR6 aviation scenarios indexed to 2020 modelled year. Data from the AR6 scenario database.

The COVID-19 pandemic of 2020 has changed many activities and consequentially, associated emissions quite dramatically (Le Quéré et al. 2018; Friedlingstein et al. 2020; Liu et al. 2020c; UNEP 2020). Aviation was particularly affected, with a reduction in commercial flights in April 2020 of ~74%

over 2019 levels, with some recovery over the following months, remaining at 42% lower as of October 2020 (Petchenik 2021). The industry is considering a range of potential recovery scenarios, with the International Air Transport Association (IATA) speculating that recovery to 2019 levels may take up until 2024 (see Box on COVID-19 and (Early and Newman 2021). Others suggest, however, that the COVID-19 pandemic and increased costs as a result of feed-in quotas or carbon taxes, could slow down the rate of growth of air travel demand, though global demand in 2050 would still grow 57%–187% between 2018 and 2050 (instead of 250% in a baseline recovery scenario) (Gössling et al. 2021a).

10.5.5 Accountability and governance options

Under Article 2.2 of the Kyoto Protocol, Annex I countries were called to *"...pursue limitation or reduction of emissions of GHGs not controlled by the Montreal Protocol from aviation and marine bunker fuels, working through the International Civil Aviation Organization and the International Maritime Organization, respectively.*" The Paris Agreement is different, in that ICAO (and the IMO) are not named. As a result, the Paris Agreement, through the NDCs, seemingly covers CO_2 emissions from domestic aviation (currently 35% of the global total) but does not cover international emissions. A number of states and regions, including the UK, France, Sweden, and Norway, have declared their intentions to include international aviation in their net zero commitments, while the EU, New Zealand, California, and Denmark are considering doing the same (Committee on Climate Change 2019). The Paris Agreement describes temperature-based goals, such that it is unclear how emissions of GHGs from international aviation would be accounted for. Clearly, this is a less than ideal situation for clarity of governance of international GHG emissions from both aviation and shipping. At its 40th General Assembly (October 2019) the ICAO requested its Council to "*...continue to explore the feasibility of a long-term global aspirational goal for international aviation, through conducting detailed studies assessing the attainability and impacts of any goals proposed, including the impact on growth as well as costs in all countries, especially developing countries, for the progress of the work to be presented to the 41st Session of the ICAO Assembly*". What form this goal will take is unclear until work is presented to the 41st Assembly (Autumn, 2022). It is likely, however, that new accountability and governance structures will be needed to support decarbonisation of the aviation sector.

10.6 Decarbonisation of Shipping

Maritime transport is considered one of the key cornerstones enabling globalisation (Kumar and Hoffmann 2002). But as for aviation, shipping has its challenges in decarbonisation, with a strong dependency on fossil fuels without major changes since AR5. At the same time, the sector has a range of opportunities that could help reduce emissions through not only changing fuels, but also by increasing the energy efficiency, optimising operations and ship design, reducing demand, improving regulations, as well as other options that will be reviewed in this section.

10.6.1 Historical and current emissions from shipping

Maritime transport volume has increased by 250% over the past 40 years, reaching an all-time high of 11 billion tons of transported goods in 2018 (UNCTAD 2019). This growth in transport volumes has resulted in continued growth in GHG emissions from the shipping sector, despite an improvement in the carbon intensity of ship operations, especially since 2014. The estimated total emissions from maritime transport can vary depending on data set and calculation method, but range over 600 – 1,100 Mt CO_2 per year over the past decade (Figure 10. 14), corresponding to 2 - 3% of total anthropogenic emissions. The legend in Figure 10.14 refers to the following data sources: (Endresen et al. 2003), (Eyring et al. 2005), (Dalsøren et al. 2009), DNV-GL (DNV GL 2019), CAMS-GLOB-SHIP (Jalkanen et al. 2014; Granier et al. 2019), EDGAR (Crippa et al. 2019), (Hoesly et al. 2018), (Johansson et al. 2017), ICCT (Olmer et al. 2017), the IMO GHG Studies; IMO 2nd (Buhaug et al. 2009), IMO 3rd (Smith et al. 2014), IMO 4th-vessel and IMO 4th-voyage (Faber et al. 2020), and (Kramel et al. 2021).

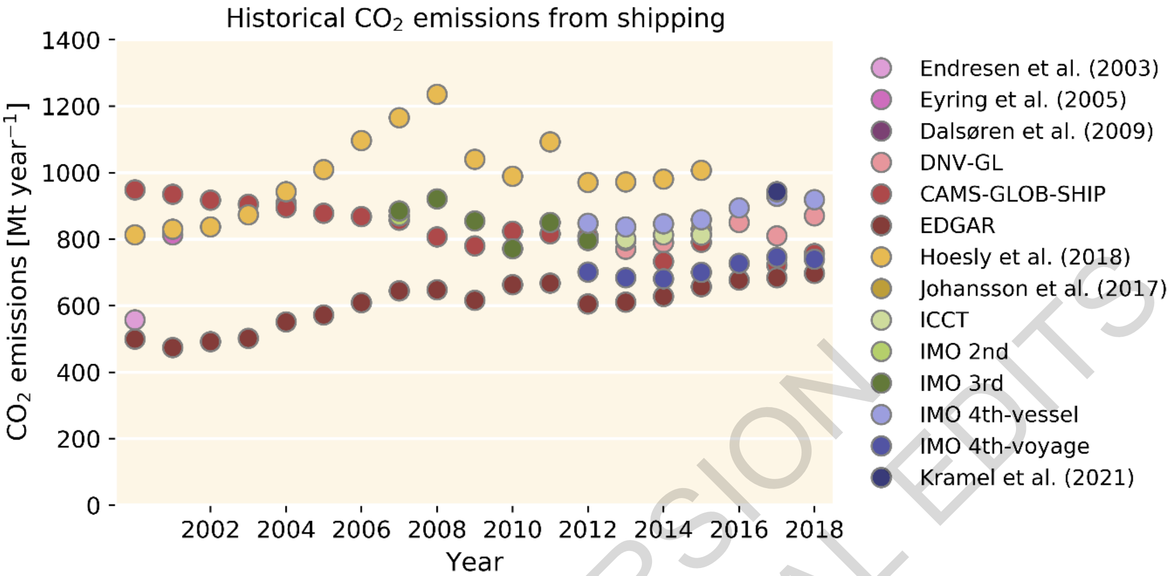


Figure 10.14 CO_2 emissions (Mt year-1) from shipping 2000 – 2018. Data from various inventories as shown in the label.

10.6.2 Short lived climate forcers and shipping

Like aviation, shipping is also a source of emissions of the SLCFs described in Section 10.5, including nitrogen oxides (NO_x), sulphur oxides (SO_2 and SO_4), carbon monoxide (CO), black carbon (BC), and non-methane volatile organic carbons (NMVOCs) (Naik et al. 2021). Though SLCF have a shorter lifetime than the associated CO_2 emissions, these short-lived forcers can have both a cooling effect (e.g., SO_x) or a warming effect (e.g., ozone from NO_x). The cooling from the SLCF from a pulse emission will decay rapidly and diminish after a couple of decades, whilst the warming from the long-lived substances lasts for centuries (Naik et al. 2021).

Emissions of SLCF from shipping not only affects the climate, but also the environment, air quality, and human health. Maritime transport has been shown to be a major contributor to coastal air quality degradation (Viana et al. 2014; Zhao et al. 2013; Jalkanen et al. 2014; Goldsworthy and Goldsworthy 2015; Goldsworthy 2017). Sulphur emissions may contribute towards acidification of the ocean (Hassellöv et al. 2013). Furthermore, increases in sulphur deposition on the oceans has also been shown to increase the flux of CO_2 from the oceans to the atmosphere (Hassellöv et al. 2013). To address the risks of SO_x emissions from shipping, there is now a cap on the on the amount of sulphur content permissible in marine fuels (IMO 2013). There is also significant uncertainty about the impacts of pollutants emitted from ships on the marine environment (Blasco et al. 2014).

Pollution control is implemented to varying degrees in the modelling of the SSP scenarios (Rao et al. 2017); for example, SSPs 1 and 5 assume that increasing concern for health and the environment result in more stringent air pollution policies than today (Naik et al. 2021). There is a downward trend in SO_x and NO_x emissions from shipping in all the SSPs, in compliance with regulations. The SLCF emission reduction efforts, within the maritime sector, are also contributing towards achieving the UN SDGs. In essence, while long lived GHGs are important for long term mitigation targets, accounting for short lived climate forcers is important both for current and near-term forcing levels as well as broader air pollution and SDG implications.

10.6.3 Shipping in the Arctic

Shipping in the Arctic is a topic of increasing interest. The reduction of Arctic summer sea ice increases the access to the northern sea routes (Melia et al. 2016; Smith and Stephenson 2013; Aksenov et al. 2017; Fox-Kemper et al. 2021). Literature and public discourse on the increased access sometimes has portrayed this trend as positive (Zhang et al. 2016b), as it allows for shorter shipping routes, e.g. between Asia and Europe with estimated travel time savings of 25 – 40% (Aksenov et al. 2017). However, the acceleration of Arctic cryosphere melt and reduced sea ice that enable Arcitc shipping reduce surface albedo and amplify climate warming (Eyring et al. 2021). Furthermore, local air pollutants can play different roles in the Arctic. For example, Black Carbon (BC) emissions reduce albedo and absorb heat in air, on snow and ice (Messner 2020; Browse et al. 2013; Kang et al. 2020; Eyring et al. 2021). Finally, changing routing from Suez to the north-eastern sea route may reduce total emissions for a voyage, but also shift emissions from low to high latitudes. Changing the location of the emissions adds complexity to the assessment of the climatic impacts of Arctic shipping, as the local conditions are different and the SLCF may have a different impact on clouds, precipitation, albedo and local environment (Marelle et al. 2016; Fuglestvedt et al. 2014; Dalsøren et al. 2013). Observations have shown that 5-25% of air pollution in the Arctic stem from shipping activity within the Arctic itself (Aliabadi et al. 2015). Emissions outside of the Arctic can affect Arctic climate, and changes within the Arctic may have global climate impacts. Both modelling and observations have shown that aerosol emissions from shipping can have a significant effect on air pollution, and shortwave radiative forcing (Peters et al. 2012; Roiger et al. 2014; Marelle et al. 2016; Dalsøren et al. 2013; Ødemark et al. 2012; Righi et al. 2015).

Increased Arctic shipping activity may also impose increased risks to local marine ecosystems and coastal communities from invasive species, underwater noise, and pollution (Halliday et al. 2017; IPCC 2019). Greater levels of Arctic maritime transport and tourism have political, as well as socio-economic implications for trade, and nations and economies reliant on the traditional shipping corridors. There has been an increase in activity from cargo, tankers, supply, and fishing vessels in particular (Zhao et al. 2015; Winther et al. 2014). Projections indicate more navigable Arctic waters in the coming decades (Smith and Stephenson 2013; Melia et al. 2016) and continued increases in transport volumes through the northern sea routes (Winther et al. 2014; Corbett et al. 2010; Lasserre and Pelletier 2011). Emission patterns and quantities, however, are also likely to change with future regulations from IMO, and depend on technology developments, and activity levels which may depend upon geopolitics, commodity pricing, trade, natural resource extractions, insurance costs, taxes, and tourism demand (Johnston et al. 2017). The need to include indigenous peoples' voices when shaping policies and governance of shipping activities in the high north is increasing (Dawson et al. 2020).

The Arctic climate and environment pose unique hazards and challenges with regards to safe and efficient shipping operations: low temperature challenges, implications for vessel design, evacuation and rescue systems, communications, oil spills, variable sea ice, and meteorological conditions (Buixadé Farré et al. 2014). To understand the total implications of shipping in the Arctic, including its climate impacts, a holistic view of synergies, trade-offs, and co-benefits is needed, with assessments of impacts on not only the physical climate, but also the local environment and ecosystems. To furthermore ensure safe operations in the Arctic waters, close monitoring of activities may be valuable.

10.6.4 Mitigation potential of fuels, operations and energy efficiency

A range of vessel mitigation options for the international fleet exist and are presented in this section. A variety of feedstocks and energy carriers can be considered for shipping. As feedstocks, fuels from biomass (advanced biofuels), fuels produced from renewable electricity and CO_2 capture from flue gas or the air (electro-, e-, or power-fuels), and fuels produced via thermochemical processes (solar fuels) can be considered. As energy carriers, synthetic fuels and the direct use of electricity (stored in batteries) are of relevance. The most prominent synthetic fuels discussed in literature are Hydrogen, Ammonia, Methane, Methanol, and synthetic hydrocarbon diesel. Figure 10.15 shows the emissions reductions potential for alternative energy carriers that have been identified as having the highest potential to mitigate operational emissions from the sector (Psaraftis 2015; DNV GL 2017; Hansson et al. 2019; Gilbert et al. 2018; Balcombe et al. 2019; Brynolf et al. 2014; Winebrake et al. 2019; Perčić et al. 2020; Bongartz et al. 2018; Biernacki et al. 2018; Faber et al. 2020; Sharafian et al. 2019; Seddiek 2015; ITF 2018b; Seithe et al. 2020; Xing et al. 2020; Czermański et al. 2020; Hua et al. 2018; Bicer and Dincer 2018a; Kim et al. 2020; Liu et al. 2020a; Hansson et al. 2020; Singh et al. 2018; Valente et al. 2021; Sadeghi et al. 2020; Nguyen et al. 2020; Stolz et al. 2021; Winkel et al. 2016; Chatzinikolaou and Ventikos 2013; Lindstad et al. 2015; Tillig et al. 2015; Traut et al. 2014; Teeter and Cleary 2014).

Low-carbon Hydrogen and Ammonia are seen to have a positive potential as a decarbonised shipping fuel. Hydrogen and Ammonia when produced from renewables or coupled to CCS, as opposed to mainly by fossil fuels with high life-cycle emissions (Bhandari et al. 2014), may contribute to significant CO_2-eq reductions of up to 70 - 80% compared to low-sulphur heavy fuel oil (Bicer and Dincer 2018b; Gilbert et al. 2018). These fuels have their own unique transport and storage challenges as Ammonia requires a pilot fuel due to difficulty in combustion, and Ammonia combustion could lead to elevated levels of NO_x, N_2O, or NH_3 emissions depending on engine technology used (DNV GL 2020). There is a need for the further development of technology and procedures for safe storage and handling of fuels such as Hydrogen and Ammonia both onboard and onshore for a faster rate of uptake of such shipping fuels (Hoegh-Guldberg et al. 2019), but they remain an encouraging decarbonisation option for shipping in the next decade.

While Methanol produced from fossil sources induces an emission increase of +7.5% (+44%), e-Methanol (via Hydrogen from electrolysis based on renewable energy and carbon from direct air capture) reduces emission by 80% (82%). In general, several synthetic fuels, such as synthetic diesel, methane, Methanol, ethanol, and dimethyl ether (DME) could in principle be used for shipping (Horvath et al. 2018). The mitigation potential of these is though fully dependent on the sourcing of the Hydrogen and carbon required for their synthesis.

As noted in Section 10.3, LNG has been found to have a relatively limited mitigation potential and may not be viewed as a low-carbon alternative, but has a higher availability than other fuel options (Gilbert et al. 2018). Emission reductions across the full fuel life cycle are found in the order of 10%, with ranges reported from -30% (reduction) to +8% (increase), if switching from heavy fuel oil to LNG, as indicated in Figure 10.15 (Bengtsson et al. 2011). Regardless of the production pathway, the literature points to the risk of methane slip (emissions of unburnt methane especially at low engine loads and from transport to ports) from LNG fuelled vessels, with no current regulation on emission caps (Ushakov et al. 2019; Anderson et al. 2015; Peng et al. 2020). Leakage rates are a critical point for the total climate impact of LNG as a fuel, where high pressure engines remedy this more than low pressure ones. As discussed in 10.3, some consider LNG as a transition fuel, whilst some literature point to the risk of stranded assets due to the increasing decarbonisation regulation from IMO and the challenge of meeting IMO's 2030 emissions reductions targets using this fuel.

In addition to fossil and e-fuels, advanced biofuels might play a role to provide the energy demand for future shipping. Biomass is presently used to produce alcohol fuels (such as ethanol and Methanol), liquid biogas, or biodiesel that can be used for shipping and could reduce CO_2 emissions from this segment. As explained in Box 10.2 and Chapter 7, the GHG footprint associated with biofuels is strongly dependent on the incurred land us and land use change emissions. Advanced biofuels from processing cellulose rather than sugar are likely to be more attractive in terms of the quantities required but are not commercially available Section 10.3. The estimates of emissions reductions from biofuels shown in Figure 10.15 rely on data from the Integrated Assessment Models –Energy Modelling Forum 33 (IAM EMF33), partial models assuming constant land cover (CLC), and partial models using natural growth (NRG). Box 10.2 and Section 10.4 include a more detailed description of the assumptions underlying these models and their estimates. The results based on IAM EMF33 and CLC suggests median mitigation potential of around 73% for advanced biofuels in shipping, while the NRG based results suggest increased emissions from biofuels. The EMF33 and CLC results rely on modelling approaches compatible with the scenarios in the AR6 database (see Chapters 6 and Box 7.7 for a discussion about emissions from bioenergy systems).

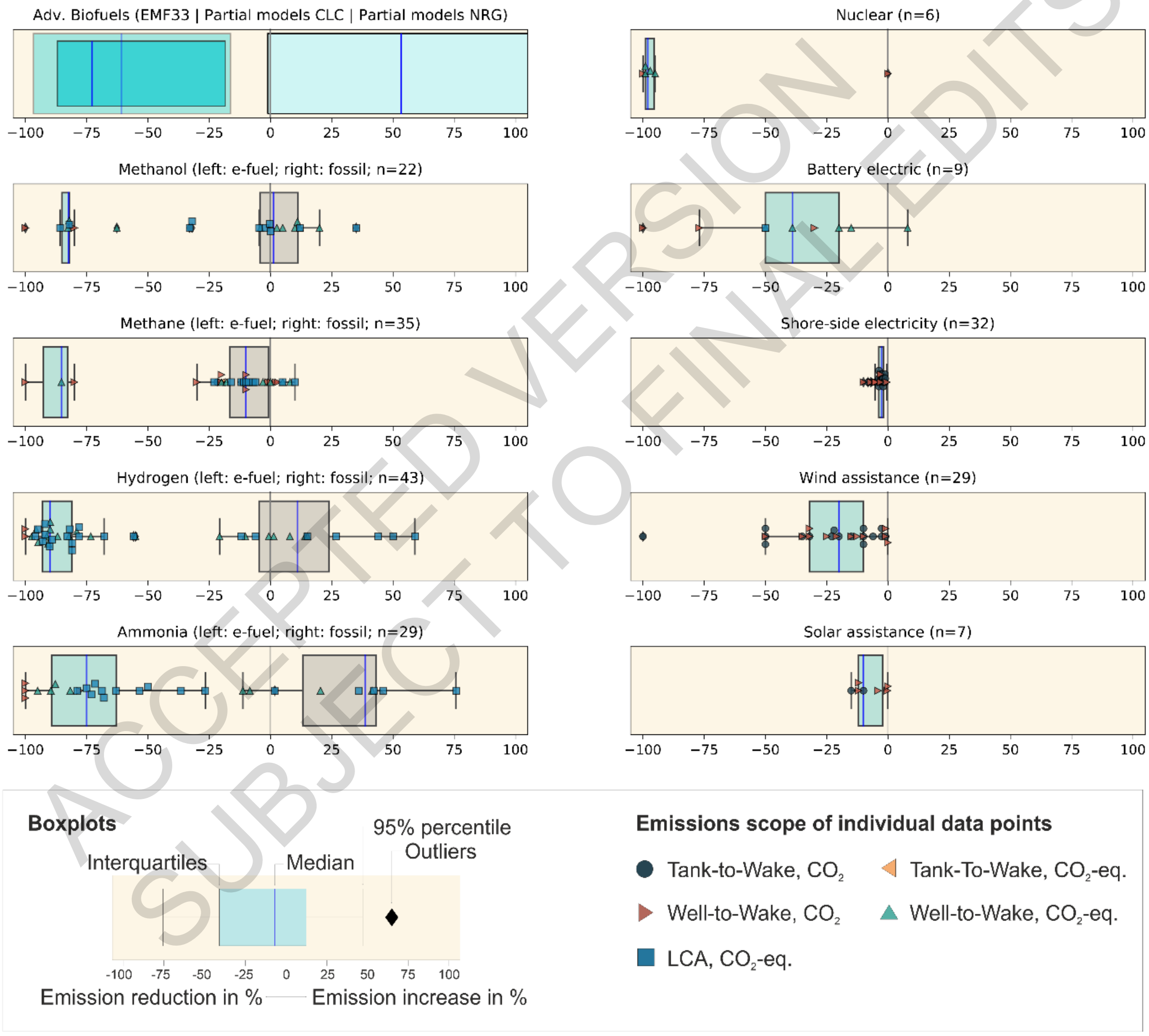


Figure 10.15 Boxplot of emission reductions potential compared to conventional fuels in the shipping sector. The x-axis is reported in %. Each individual marker represents a data point from the literature, where the blue square indicates a full LCA CO_2-eq value; light orange triangles tank – to – wake CO_2-eq.; light blue triangles well – to – wake CO_2-eq; dark orange triangles well – to – wake CO_2; and dark blue circle tank – to – wake CO_2 emission reduction potentials. The values in the figure rely on the 100-year GWP value embedded in the source data, which may differ slightly with the updated 100-year GWP values from WGI. 'n' indicates the number of data points per sub-panel. Grey shaded boxes represent

data where the energy comes from fossil resources, and turquoise from low carbon renewable energy sources. Advanced Biofuels EMF33 refers to emissions factors derived from simulation results from the integrated assessment models EMF33 scenarios (darkest coloured box in top left panel). Biofuels partial models CLC refers to partial models with constant land cover. Biofuels partial models NRG refers to partial models with natural regrowth. For ammonia and Hydrogen, low-carbon electricity is produced via electrolysis using low-carbon electricity, and 'fossil' refers to fuels produced via steam methane reforming of natural gas.

In addition to the fuels, there are other measures that may aid the low-carbon transition shipping. The amounts and speed of uptake of alternative low- or zero-carbon fuels in ports depend upon investments in infrastructure – including bunkering infrastructure, refinery readiness, reliable supply of the fuels, as well as sustainable production. The ship lifetime and age also play a role, whereupon retrofitting ships to accommodate engines and fuel systems for new fuel types may not be an option for older vessels. As such, operational efficiency becomes more important (Bullock et al. 2020). There is some potential to continue to improve the energy efficiency of vessels through operational changes (e.g., Traut et al. 2018), reducing the speed or 'slow steaming' (Bullock et al. 2020), and improved efficiency in port operations (Viktorelius and Lundh 2019; Poulsen and Sampson 2020). There is also a growing interest in onboard technologies for capturing carbon, with prototype ships underway showing 65-90% potential reduction in CO_2 emissions (Japan Ship Technology Reserach Association et al. 2020; Luo and Wang 2017; Awoyomi et al. 2020). Challenges identified include CO_2 capture efficiency (Zhou and Wang 2014), increased operating costs, and limited onboard power supply (Fang et al. 2019). Furthermore, designing CO_2 storage tanks for transport to shore may pose a challenge, as the volume and weight of captured CO_2 could be up to four times more than standard oil (Decarre et al. 2010).

Changes in design and engineering provide potential for reducing emissions from shipping through a range of measures, e.g., by optimizing hull design and vessel shape, power and propulsion systems that include wind or solar assisted propulsion, and through improved operations of vessels and ports. Figure 10.15 shows that such measures may decrease emissions by 5 - 40%, though with a broad range in potential (Bouman et al. 2017). Nuclear propulsion could decrease emissions from individual vessels by 98%. Battery- or hybrid-electric ships have been identified as a means to reduce emissions in short-sea shipping such as ferries and inland waterways (Gagatsi et al., 2016), which may also importantly reduce near-shore SLCF pollution (Nguyen et al. 2020). Figure 10.15 shows that the median emission from electric ships can be ~40% lower than equivalent fossil-based vessels but can vary widely. The wide reduction potential of battery-electric propulsion is due to different assumptions about the CO_2 intensity of the electricity used and the levels of CO_2 footprints associated with battery production.

Although projections indicate continued increase in freight demand in the future, demand-side reductions could contribute to mitigation. The development of autonomous systems may play a role (Colling and Hekkenberg 2020; Liu et al. 2021) while 3-D printing can reduce all forms of freight as parts and products can be printed instead of shipped (UNCTAD 2018). As more than 40% of transported freight is fossil fuels, a lessened demand for such products in low emission scenarios should contribute to reduce the overall maritime transport needs and hence emissions in the future (Sharmina et al. 2017). An increase in alternative fuels on the other hand, may increase freight demand (Mander et al. 2012). Potentials for demand-side reduction in shipping emissions may arise from improving processes around logistics and packaging, and further taxes and charges could serve as leverage for reducing demand and emissions.

The coming decade is projected to be costly for the shipping sector, as it is preparing to meet the 2030 and 2050 emission reduction targets set by the IMO (UNCTAD 2018). With enough investments, incentives, and regulation, substantial reductions of CO_2 emissions from shipping could be achieved through alternative energy carriers. The literature suggests that their cost could be manyfold higher than for conventional fuels, which in itself could reduce demand for shipping, and hence its emissions, but make the transition difficult. Hence R&D may help reduce these costs. The literature points to the need for developing technology roadmaps for enabling the maritime transport sector to get on to pathways for decarbonisation early enough to reach global goals (Kuramochi et al. 2018). Accounting for the full life cycle of emissions of the vessels and the fuels is required to meet the overall long-term objectives of cutting GHG and SLCF emissions. The urgency of implementing measures for reducing emissions is considered to be high, considering the lifetime of vessels is typically 20 years, if not more.

10.6.5 Accountability and governance options

Regulatory frameworks for the shipping sector have been developed over time and will continue to do so through bodies such as the IMO, which was established by the UN to manage international shipping. The IMO strategy involves a 50% reduction in GHG emissions from international shipping by 2050 compared to 2008 (IMO 2018). The strategy includes a reduction in carbon intensity of international shipping by at least 40% by 2030, and 70% by 2050, compared to 2008. IMO furthermore aims for the sectoral phase out of GHG emissions as soon as possible this century.

In 2020, the IMO approved the short-term goal-based measure to reduce the carbon intensity of existing international vessels. This measure addresses both technical and operational strategies. The operational element is represented by a Carbon Intensity Indicator (CII), and the technical element is represented by the Energy Efficiency Existing Ship Index (EEXI), which will apply to ships from 2023. The EEXI builds upon the Energy Efficiency Design Index (EEDI), which is a legally binding mitigation regulation for newbuild ships, established as a series of baselines for the amount of fuel ships may burn for a particular cargo-carrying capacity. The EEDI differs per ship segment. E.g., ships built in 2022 and beyond should be 50% more energy efficient than in 2013. This legislation aims to reduce GHG emissions in particular. Energy efficiency may be improved by several of the mitigation options outlined above. The ship energy efficiency management plan (SEEMP) is seen as the international governance instrument to improve energy efficiency and hence emissions from ships. SEEMP is a measure to enable changes to operational measures and retrofits (see Johnson et al., 2013). The combination of EEXI, EEDI, and SEEMP may reduce emissions by 23% by 2030 compared to a 'no policy' scenario (Sims et al. 2014). With regards to accountability, it is mandatory for ships of ≥5,000 gross tonnage to collect fuel consumption data, as well as specified data for e.g. transport work. Similarly, the EU MRV (Monitoring, Reporting, Verification) requires mandatory reporting of a vessel's fuel consumption when operating in European waters.

Policy choices may enable or hinder changes, and gaps in governance structures may, to some degree, hinder the objectives of mechanisms like SEEMP to improve energy efficiency and emissions. Policies may be developed to incentivize investments in necessary changes to the global fleet and related infrastructures. The literature argues that regulations and incentives that motivates mitigation through speed optimisation, ship efficiency improvements, and retrofits with lower-carbon technologies at a sub-global scale may contribute to immediate reductions in CO_2 emissions from the sector (Bows-Larkin 2015). The role of the financial sector through initiatives such as the Poseidon Principle, whereupon financial institutions limit lending to companies that fail to uphold environmental standards, could also become increasingly important (Sumaila et al. 2021).

It has been proposed to make shipping corporations accountable for their emissions by making it mandatory to disclose their vessel's emissions reductions (Rahim et al. 2016). Market based mechanisms may increasingly encourage ship operators to comply with IMO GHG regulations. Development of policies such as carbon pricing / taxing to enable a business case for adopting low carbon fuels could be a near term priority for acceleration of transformation of the sector (Hoegh-Guldberg et al. 2019). The EU is considering including shipping in its carbon trading system, with the details still to be agreed upon but expected to come into force in 2023, along with the CII. The proposition is that shipowners who conduct voyages within Europe, or start or end at an EU port, will have to pay for carbon permits to cover the CO_2 emitted by their vessel.

Regulations exist also to limit emissions of air pollution from shipping with the aim to improve environment and health impacts from shipping in ports and coastal communities. In sulphur emission control areas (SECAS), the maximum permissible sulphur content in marine fuels is 0.10% m/m (mass/mass). These are further tightened by the IMO legislation on reducing marine fuel sulphur content to a maximum of 0.5% in 2020 outside of SECAS, compared to 3.5% permissible since 2012 (MARPOL Convention). The MARPOL Annex VI also limits the emissions of ozone depleting substances and ozone precursors; NO_x, and VOCs from tankers (Mertens et al. 2018). The implementation of the emission control areas have been shown to reduce the impacts on health and the environment (Viana et al. 2015).

While there are many governance and regulatory initiatives that help reduce emissions from the shipping sector, few are transformative on their own, unless zero carbon fuels can become available at a reasonable cost as suggested in 10.3 and in scenarios outlined next.

10.6.6 Transformation trajectories for the maritime sector

Figure 10.16 shows CO_2 emissions from shipping in scenarios from the AR6 database and the 4th GHG study by the IMO (Faber et al., 2020). Panel (a) shows that CO_2 emissions from shipping go down by 33-70% (5-95% percentile) by 2050 in the scenarios limiting warming to 1.5°C (C1-C2). By 2080, median values for the same set of scenarios reach net zero CO_2 emissions. IAMs often do not report emission pathways for shipping transport and the sector is underrepresented in most IAMs (Esmeijer et al. 2020). Hence pathways established outside of IAMs can be different for the sector. Indeed, the IMO projections for growth in transport demand (Faber et al. 2020) indicate increases by 40 - 100 % by 2050 for the global fleet. Faber and et al. (2020), at the same time predict, reductions in trade for fossil fuels dependent on decarbonisation trajectories. The energy efficiency improvements of the vessels in these scenarios are typically of 20 - 30%. This offsets some of the increases from higher demand in the future scenarios. Fuels assessed by the 4th IMO GHG study were limited to HFO, MGO, LNG, and Methanol, with a fuels mix ranging from 91 - 98% conventional fuel use and a small remainder of alternative fuels (primarily LNG, and some Methanol). Panel (b) in Figure 10.16 shows average fleetwide emissions of CO_2 emissions based on these aggregate growth and emission trajectories from the IMO scenarios. In these scenarios, CO2 emissions from shipping remain stable or grow compared to 2020 modelled levels. These results contrast with the low emission trajectories in the C1-C2 bin in panel (a) of Figure 10.16. It seems evident that the scenarios in the AR6 database explore a broader solutions space for the sector, than the 4th GHG study by IMO. However, the 1.5°C - 2°C warming goal has led to an IMO 2050 target of 40% reductions in carbon intensity by 2030, which would require emission reduction efforts to begin immediately. Results from global models, suggest the solutions space for deep emission reductions in shipping is available.

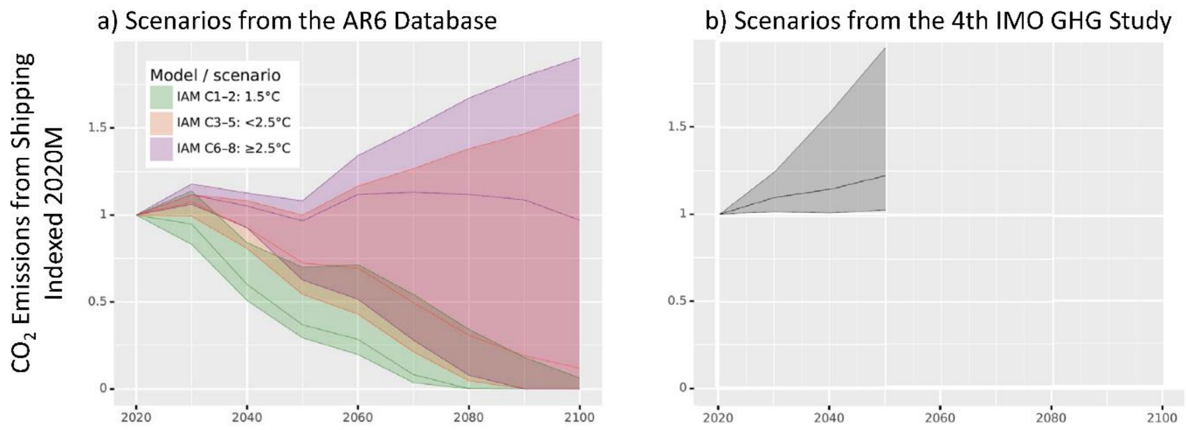


Figure 10.16 CO_2 emission from shipping scenarios indexed to 2020 Modelled year. Panel a) Scenarios from the AR6 database. Panel b) Scenarios from the 4th IMO GHG Study (Faber et al., 2020). Figures show median, 5th and 95th percentile (shaded area) for each scenario group.

Combinations of measures are likely needed for transformative transitioning of the shipping sector to a low-carbon future, particularly if an expected increase in demand for shipping services is realised (Smith et al. 2014; Faber et al. 2020). Both GHG and SLCF emissions decrease significantly in SSP1-1.9, where mitigation is achieved in the most sustainable way (Rao et al. 2017). Conversely, there are no emissions reductions in the scenarios presented by the IMO 4th GHG study, even though these scenarios incorporate some efficiency improvements and a slight increase in the use of LNG.

Options outlined in this chapter suggest a combination of policies to reduce demand, increase investments by private actors and governments, and develop the TRL of alternative fuels and related infrastructure (especially synthetic fuels). Some literature suggests that battery electric-powered short distance sea shipping could yield emission reductions given access to low carbon electricity. For deep sea shipping, advanced biofuels, Hydrogen, Ammonia, and synthetic fuels hold potential for significant emission reductions, depending on GHG characteristics of the fuel chain and resource base. Other options, such optimisation of speed and hull design and wind-assisted ships could also combine to make significant contributions in 2050 to further bring emissions down. In total a suite of mitigation options exists or is on the horizon for the maritime sector.

10.7 Scenarios from integrated, sectoral, and regional models

10.7.1 Transport scenario modelling

This section reviews the results of three types of models that systemically combine options to assess different approaches to generate decarbonisation pathways for the transport system: (1) integrated assessment models (IAMs); (2) global transport energy sectoral models (GTEM); and (3) national transport/energy models (NTEMs) (Yeh et al. 2017; Edelenbosch et al. 2017). Common assumptions across the three model types include trajectories of socioeconomic development, technological development, resource availability, policy, and behavioural change. The key differences underlying these models are their depth of technological and behavioural detail versus scope in terms of sectoral and regional coverage. In very general terms, the narrower the scope in terms of sectors and regions, the more depth on spatial, technological, and behavioural detail. A large set of scenarios from these models were collected in a joint effort led by Chapter 3 and supported by Chapter 10 and others. The outcomes from over 100 models have been analysed for this chapter with the methodologies set out in Annex III for the whole report.

GHG emissions from transport are a function of travel demand, travel mode, transport technology, GHG intensity of fuels, and energy efficiency. These drivers can be organized around a group of levers that can advance the decarbonisation of the transport system. The levers thus include reducing travel activity, increasing use of lower-carbon modes, and reducing modal energy intensity and fuel carbon content. This section explores each lever's contributions to the decarbonisation of the transport sector by reviewing the results from the three model types IAM and G-/NTEMs.

IAMs integrate factors from other sectors that interact with the transport system endogenously, such as fuel availability and costs. IAMs minimize mitigation costs to achieve a temperature goal *across all sectors of the economy* over a long-time horizon (typically to 2100). IAMs typically capture mitigation options for energy and carbon intensity changes with greater technology/fuel details and endogeneity linked to the other sectors. In the scenarios with very large-scale electrification of the transport sector, the coupling with the other sectors in fuel production, storage, and utilization becomes more important. G-/NTEMs and related regional transport sectoral models have more details in transport demand, technology, behaviours, and policies than IAMs, but treat the interactions with the other sectors exogenously, potentially missing some critical interactions, such as the fuel prices and carbon intensity of electricity. National models have detailed representation of national policies related to transport and energy, sometimes with greater spatial resolution. Compared with IAMs, G-/NTEMs typically have greater detailed representation to explore mitigation options along the activity and mode dimensions where spatial, cultural, and behavioural details can be more explicitly represented. The appendix in Annex III provides more details about these types of models. Scenarios for shipping and aviation are handled in more detail in sections 10.5 and 10.6, respectively.

This section applies the following categorization of scenarios (see table 3.1 in Chapter 3 for more details): C1 (1.5°C with no or limited Overshoot (OS)), C2 (1.5°C with high OS), C3 (>67% below 2°C), C4 (>50% below 2°C), C5 (below 2.5°C), C6 (below 3°C), C7 (above 3°C). A large share of the scenarios was developed prior to 2020. Results from such the scenario are indexed to a modelled (non-covid) year 2020, referred to as 2020Mod.

10.7.2 Global emission trajectories

In 2018, transport emitted 8.5 Gt CO_2eq, reaching a near doubling from 1990 levels after two decades of 2% per year emissions growth (see Section 10.1). Assessing future trajectories, Figure 10.17 provides an overview of direct CO_2 emissions estimates from the transport sector across IAMs (colour bars) and selected global transport models (grey bars). The results from the IAMs are grouped in bins by different temperature goal. Global energy transport models (GTEMs) are grouped into reference and policy bins, since the transport sector cannot by itself achieve fixed global temperature goals. The policy scenarios in G-/NTEMs cover a wide range of "non-reference" scenarios, which include, for example, assumptions based on the "fair share action" principles. In these scenarios, transport emissions reach emissions reductions consistent with the overall emission trajectories aligning with warming levels of 2°C. These scenarios may also consider strengthening existing transport policies such as increasing fuel economy standards or large-scale deployments of electric vehicles. In most cases, these Policy scenarios are not necessarily in line with the temperature goals explored by the IAMs.

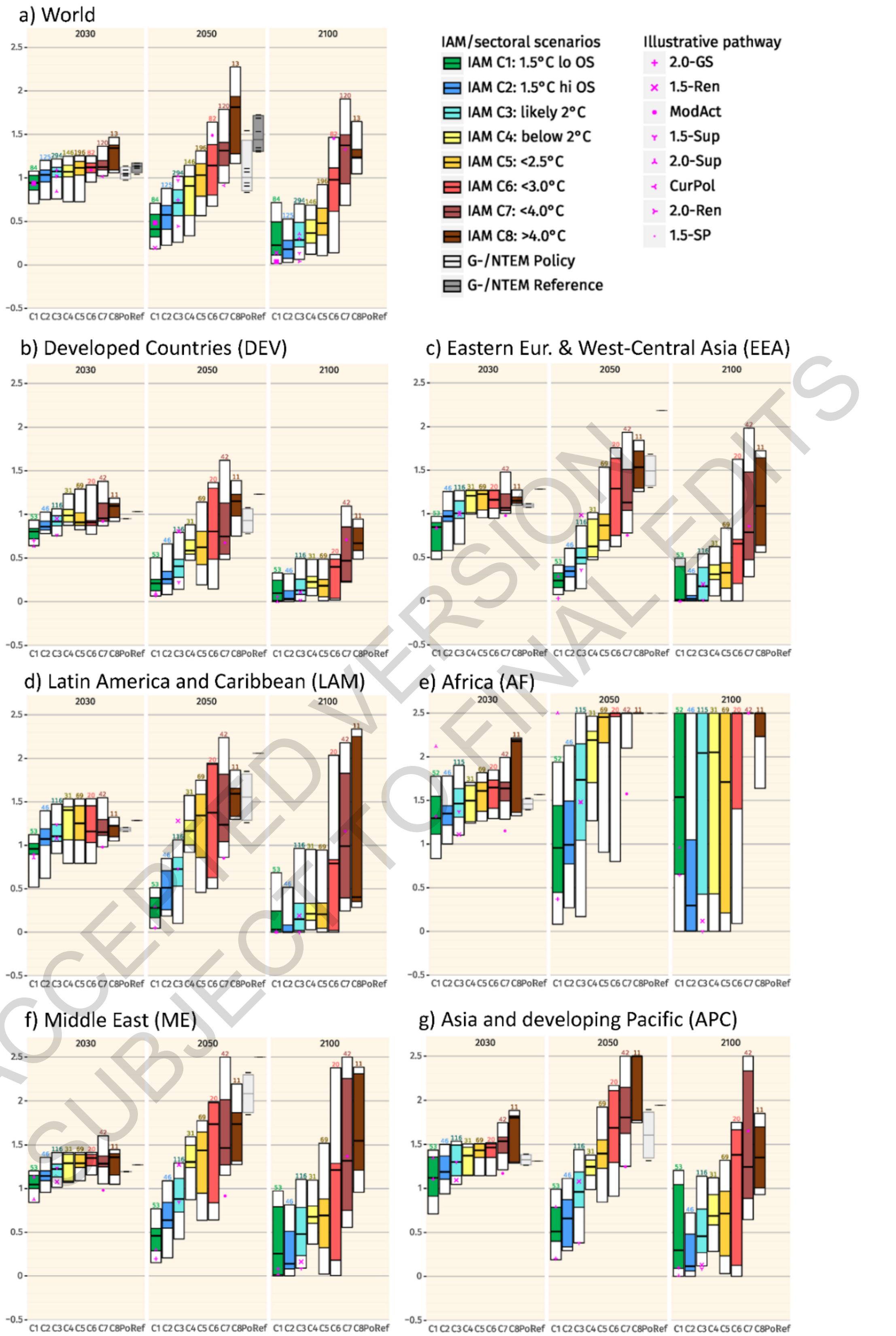


Figure 10.17 Direct CO_2 emissions in 2030, 2050, and 2100 indexed to 2020 modelled year across R6 Regions and World. IAM results are grouped by temperature targets. Sectoral studies are grouped by reference and policy categories. Plots show 5th/95th percentile, 25th/75th percentile, and median. Numbers above the bars indicate the number of scenarios. Data from the AR6 scenario database.

According to the collection of simulations from the IAM and GTEM models shown in Figure 10.17, global transport emissions could grow up to 2–47% (5–95th percentile) by 2030 and -6–130% by 2050 under the scenarios without firm commitments to meet a long-term temperature goal (i.e., C7-8 scenarios with temperature change above 3.0°C by 2100). Population and GDP growth and the secondary effects, including higher travel service demand per capita and increased freight activities per GDP, drive the growth in emissions in these scenarios (see Section 10.7.3). Though transport efficiencies (energy use per pkm travelled and per ton-km of delivery) are expected to continue to improve in line with the historical trends (see Section 10.7.4), total transport emissions would grow due to roughly constant carbon intensity (Section 10.7.5) under the C7-8 (>3.0°C) scenarios. Significant increases in emissions (> 150% for the medium values by 2050) would come from Asia and developing Pacific (APC), the Middle East and (ME), and Africa (AF), whereas Developed Countries (DEV) would have lower transport emissions (medium value -25% for C7 and 15% for C8) than the estimated 2020 level in 2050.

To meet temperature goals, global transport emissions would need to decrease by 17% (67–+23% for the 5–95th percentile) below 2020Mod levels in the C3-5 scenario group (1.5 - 2.5°C, orange bars), and 47% (14–80% for the 5–95th percentile) in the C1-2 scenario group (below 1.5°C, green bars) by 2050. However, transport-related emission reductions may not happen uniformly across regions. For example, transport emissions from the Developed Countries (DEV), and Eastern Europe and West-Central Asia (EEA) would decrease from 2020 levels by 2050 across all C1-2 scenarios, but could increase in Africa (AF), Asia and developing Pacific (APC), Latin America and Caribbean (LAM) and the Middle East (ME), in some of these scenarios. In particular, the median transport emissions in India and Africa could increase by 2050 in C1-2 scenarios, while the 95th percentile emissions in Asia and developing Pacific (APC), Latin America and Caribbean (LAM), and the Middle East (ME), could be higher in 2050 than in 2020.

The Reference scenario emission pathways from GTEMs described in Figure 10.17 have similar ranges as C7-8 scenario groups in 2050. The Policy scenarios are roughly in line with C6-7 scenarios for the world region. The results suggest that the majority of the Policy scenarios examined by the GTEMS reviewed here are in the range of the 2-3°C temperature goal scenarios examined by the IAMs (Gota et al. 2016; Yeh et al. 2017; IEA 2017b; Fisch-Romito and Guivarch 2019). The NDCs in the transport sector include a mix of measures targeting efficiency improvements of vehicles and trucks; improving public transit services; decarbonising fuels with alternative fuels and technologies including biofuels, fossil- or bio-based natural gas, and electrification; intelligent transport systems; and vehicle restrictions (Gota et al. 2016). Because of the long lag-time for technology turnover, these measures are not expected to change 2030 emissions significantly. However, they could have greater impacts on 2050 emissions.

Several GTEMs not included in AR6 scenario database have examined ambitious CO_2 mitigation scenarios. For example, a meta-analysis of scenarios suggests that global transport emissions consistent with warming levels of 2°C, would peak in 2020 at around 7-8 $GtCO_2$ and decrease to 2.5-9.2 Gt for 2°C with an average of 5.4 Gt by 2050 (Gota et al. 2019). For comparison, the IEA's Sustainable Development Scenario (SDS) suggests global transport emissions decrease to 3.3 Gt (or 55% reduction from 2020 level) by 2050 (IEA 2021f). In the latest IEA Net Zero by 2050 report proposes transport emissions to be close to zero by 2050 (IEA 2021e). The latter is lower than the interquartile ranges of the C1 group of scenarios from the AR6 database analysed here.

Low carbon scenarios are also available from national models (Latin America, Brazil, Canada, China, France, Germany, Indonesia, India, Italy, Japan, Mexico, South Africa, UK, US) with a good representation of the transport sector. The low carbon scenarios are either defined with respect to a global climate stabilization level of e.g., 2°C /1.5°C Scenario (Dhar et al. 2018), or a CO_2 target that is more stringent than what has been considered in the NDCs, such as the net zero emissions pathways (Bataille et al. 2020; IEA 2021e). These studies have generally used bottom-up models (see Annex III) for the analysis, but in some cases, they are run by national teams using global models (e.g., GCAM for China and India). National studies show that transport CO_2 emissions could decline significantly in low-carbon scenarios in all the developed countries reviewed (Bataille et al. 2015; Kainuma et al. 205AD; Virdis et al. 2015; Pye et al. 2015; Criqui et al. 2015; Kemfert et al.; Williams et al. 2015; Zhang et al. 2016a) in 2050 from the emissions in 2010 and reductions vary from 65% to 95%. However, in developing countries reviewed (Altieri et al. 2015; Buira and Tovilla 2015; Teng et al. 2015; Rovere et al. 2015; Siagian et al. 2015; Shukla et al. 2015; Di Sbroiavacca et al. 2014; Dhar et al. 2018), emissions could increase in 2050 in the range of 35% - 83% relative to 2010 levels. Transport CO_2 emissions per capita in the developing countries were much lower in 2010 (vary from 0.15 to 1.39 tCO_2 per capita) relative to developed countries (vary from 1.76 to 5.95 tCO_2 per capita). However, results from national modelling efforts suggest that, by 2050, the CO_2 emissions per capita in developed countries (vary from 0.19 to 1.04 tCO_2 per capita) could be much lower than in developing countries (vary from 0.21 to 1.7 tCO_2 per capita).

The transport scenario literature's mean outcomes suggest that the transport sector may take a less steep emission reduction trajectory than the cross-sectoral average and still be consistent with the 2°C goal. For example, most of the 1.5°C pathway scenarios (C1-2) reach zero-emission by 2060, whereas transport sector emissions are estimated in the range of 20% of the 2020Mod level (4-65% for the 10^{th} – 90^{th} percentiles) by 2100. This finding is in line with perspectives in the literature suggesting that transport is one of the most difficult sectors to decarbonise (Davis et al. 2018). There is, however, quite a spread in the results for 2050. Since temperature warming levels relate to global emissions from all sectors, modelling results from IAMs tend to suggest that in the short and medium-term, there might be lower cost mitigation options outside the transport sector. On the other hand, compared with G-/NTEMs, some IAMs may have limited mitigation options available including technology, behavioural changes, and policy tools especially for aviation and shipping. The models therefore rely on other sectors and/or negative emissions elsewhere to achieve the overall desired warming levels. This potential shortcoming should be kept in mind when interpreting the sectoral results from IAMs.

10.7.3 Transport activity trajectories

Growth in passenger and freight travel demand is strongly dependent on population growth and GDP. In 2015, transport activities were estimated at around 35-50 trillion pkm or 5,000-7,000 pkm per person per year, with significant variations among studies (IEA 2017b; ITF 2019). The number of passenger cars in use has grown 45% globally between 2005-2015, with the most significant growth occurring in the developing countries of Asia and the Middle East (119%), Africa (79%) and, South and Central America (80%), while the growth in Europe and North America is the slowest (21% and 4% respectively) (IOMVM 2021). On the other hand, car ownership levels in terms of vehicles per 1,000 people in 2015 were low in developing countries of Asia and the Middle East (141), Africa (42), South and Central America (176), while in Europe and North America they are relatively high (581 and 670 respectively) (IOMVM 2021). The growth rate in commercial vehicles (freight and passenger) was 41% between 2005 and 2015, with a somewhat more even growth across developed and developing countries (IOMVM 2021).

Figure 10.18 shows activity trajectories for both freight and passenger transport based on the AR6 database for IAMs. According to demand projections from the IAMs, global passenger and freight transport demand could increase relative to a modelled year 2020 across temperature goals. The median transport demand from IAMs for all the scenarios in line with warming levels below 2.5°C (C1-C5) suggests the global passenger transport demand could grow by 1.14-1.3 times in 2030 and by 1.5-1.8 times in 2050 (1.27-2.33 for the 5^{th} – 95^{th} percentile across C1-C5 scenarios) relative to modelled 2020 level. Developed regions including North America and Europe exhibit lower growth in passenger demand in 2050 compared to developing countries across all the scenarios. In 2030, most of the global passenger demand growth happens in Africa (AF) (44%% growth relative to 2020), and Asia and developing Pacific (APC) (57%% growth in China and 59% growth in India relative to 2020) in the below 2.5 scenario (C5). These regions start from a low level of per capita demand. For example, in India, demand may grow by 84%. However, the per capita demand in 2010 was under 7,000 km per person per year (Dhar and Shukla 2015). Similarly, in China, demand may grow by 52%, starting from per capita demand of 8,000 km per person per year in 2010 (Pan et al. 2018). The per capita passenger demand in these regions was lower than in developed countries in 2010, but it converges towards the per capita passenger transport demand of advanced economies in less stringent climate scenarios (C6-7). Demand for passenger travel would grow at a slower rate in the stricter temperature stabilization scenarios (< 2.5 and 1.5 scenarios, C1-C5) compared to the scenarios with higher warming levels (C7-C8). The median global passenger demand in the scenarios with warming levels below 1.5°C scenarios (C1-C2) are 27% lower in 2050 relative to C8.

Due to limited data availability, globally consistent freight data is difficult to obtain. In 2015, global freight demand was estimated to be 108 trillion tkm, most of which was transported by sea (ITF 2019). The growth rates of freight service demand vary dramatically among different regions: over the 1975–2015 period, road freight activity in India increased more than 9-fold, 30-fold in China, and 2.5-fold in the US (Mulholland et al. 2018). Global freight demand continues to grow but at a slower rate compared to passenger demand across all the scenarios in 2050 compared to modelled 2020 values. Global median freight demand could increase by 1.17 -1.28 times in 2030 and 1.18-1.7 times in 2050 in all the scenarios with warming level below 2.5°C (C1-C5). Like passenger transport, the models suggest that a large share of growth occurs in Africa (AF) and Asian regions (59% growth in India and 50% growth in China in 2030 relative to a modelled year 2020) in C5 scenario. Global median freight demand grows slower in the stringent temperature stabilization scenarios, and is 40% and 22% lower in 2050 in the below 1.5°C scenarios (C1-C2) and below 2.5°C scenarios (C3-C4), respectively, compared to scenarios with warming levels of above 4°C (C8).

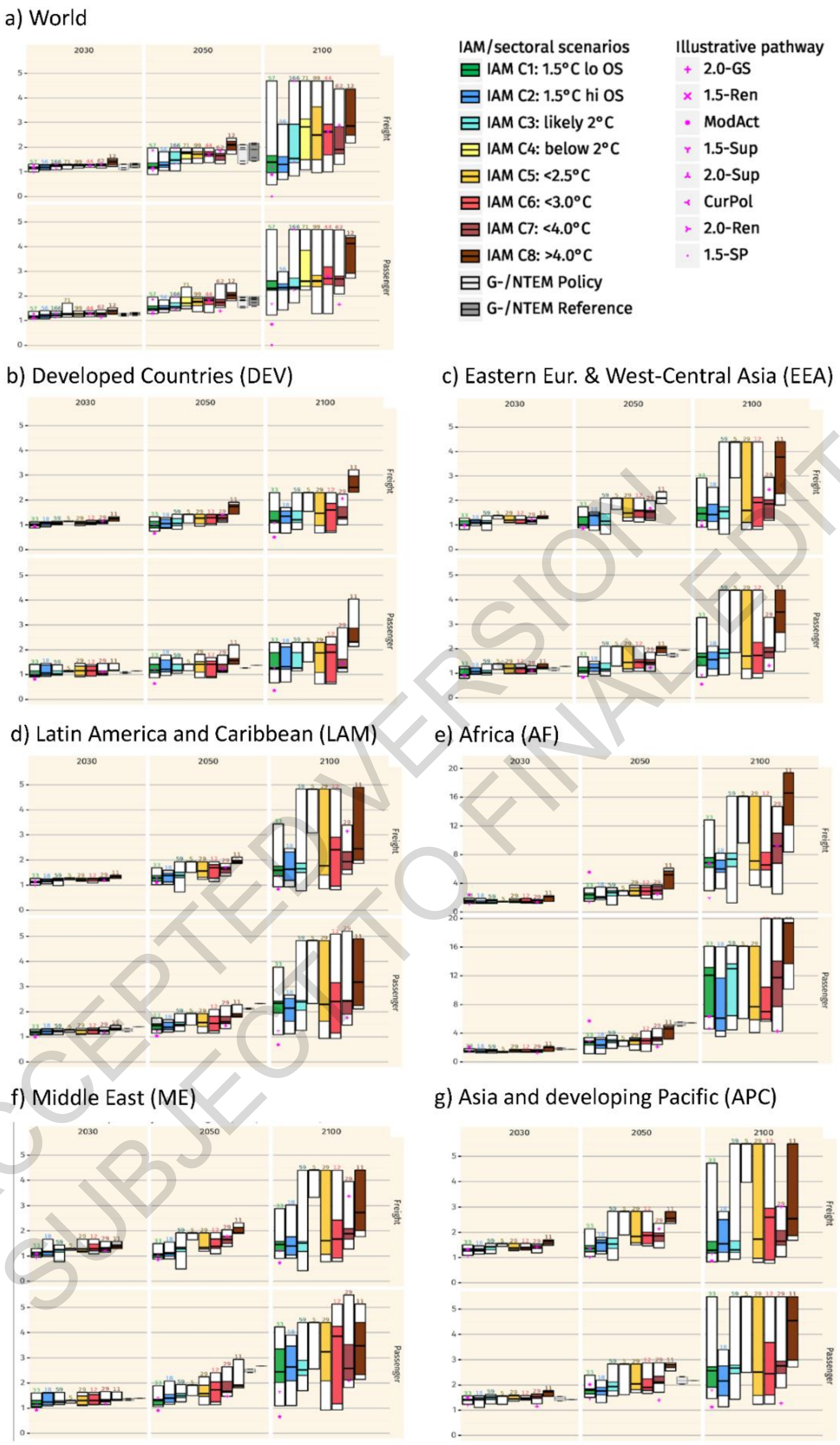


Figure 10.18 Transport activity trajectories for passenger (bottom panel) and freight (top panel) in 2030, 2050, and 2100 indexed to 2020 modelled year across R6 Regions and World. Plots show 5-95% percentile, 25th/75th percentile, and median. Numbers above the bars indicate the number of scenarios. Data from the AR6 scenario database.

GTEMs show broad ranges for future travel demand, particularly for the freight sector. These results show more dependency on models than on baseline or policy scenarios. According to ITF Transport Outlook (ITF 2019) , global passenger transport and freight demand could more than double by 2050 in a business-as-usual (BAU) scenario. Mulholland et al. (2018) suggest the freight sector could grow by 2.4-fold over 2015–2050 in the reference scenario, with the majority of growth attributable to developing countries. The IEA suggests a more modest increase in passenger transport, from 51 trillion pkm in 2014 to 110 trillion pkm in 2060, in a reference scenario without climate policies and a climate scenario that would limit emissions below 2ºC. The demand for land-based freight transport in 2060 is, however, slightly lower in the climate scenario (116 trillion tkm) compared to the reference scenario (130 trillion tkm) (IEA 2017b)The ITF, however, suggests that ambitious decarbonisation policies could reduce global demand for passenger transport by 13-20% in 2050, compared to the business-as-usual scenario (ITF 2019, 2021). The reduction in vehicle travel through shared mobility could reduce emissions from urban passenger transport by 30% compared to the BAU scenario. Others suggest reductions larger than 25%, on average, for both passenger and freight in 2030 and 2050 may be needed to achieve very low carbon emission pathways (Fisch-Romito and Guivarch 2019). In absence of large-scale carbon dioxide removal, few global studies highlight the need for significant demand reduction in critical sectors (aviation, shipping and road freight) in well below 2ºC scenarios (van Vuuren et al. 2018; Grant et al. 2021; Sharmina et al. 2021).

Many models find small differences in passenger transport demand across temperature goals because IAM models rely on historical relationships between population, GDP, and demand for services to estimate future demand. This assumption poses a limitation to the modelling efforts, as mitigation efforts would likely increase travel costs that could result in lower transport demand (Zhang et al. 2018). In most models, demand is typically an exogenous input. These models often assume mode shifts of activities from the most carbon-intensive modes (driving and flying for passenger travel and trucking for freight) to less carbon-intensive modes (public transit and passenger rails, and freight rail) to reduce emissions.

Traditionally there is a disconnection between IAM models and bottom-up sectoral or city-based models due to the different scale (both spatial and temporal) and focus (climate mitigation vs. urban pollutions, safety (Creutzig 2016)). The proliferation of shared and on-demand mobility solutions are leading to rebound effects for travel demand (Chen and Kockelman 2016; Coulombel et al. 2019) and this is a new challenge for modelling. Some IAM studies have recently begun to explore demand-side solutions for reducing transport demand to achieve very low-carbon scenarios through a combination of culture and low-carbon lifestyle (Creutzig et al. 2018; van Vuuren et al. 2018); urban development (Creutzig et al. 2015a); increased vehicle occupancy (Grubler et al. 2018); improved logistics and streamline supply chains for the freight sector (Mulholland et al. 2018); and disruptive low-carbon innovation, described as technological and business model innovations offering "novel value propositions to consumers and which can reduce GHG emissions if adopted at scale" (Wilson et al. 2019). In the literature from national models, demand has been differentiated between conventional and sustainable development scenarios through narratives built around policies, projects, and programs envisaged at the national level (Shukla et al. 2015; Dhar and Shukla 2015) and price elasticities of travel demand (Dhar et al. 2018). However, a greater understanding of the mechanisms underlying energy-relevant decisions and behaviours (Brosch et al. 2016), and the motivations for sustainable behaviour (Steg et al. 2015) are critically needed to realize these solutions in reality.

Overall, passenger and freight activity are likely to continue to grow rapidly under the C7 (>3.0°C) scenarios, but most growth would occur in developing countries. Most models treat travel demand exogenously following the growth of population and GDP, but they have limited representation of responses to price changes, policy incentives, behavioural shifts, nor innovative mobility solutions that can be expected to occur in more stringent mitigation scenarios Chapter 5 provides a more detailed discussion of the opportunities for demand changes that may results from social and behavioural interventions.

10.7.4 Transport modes trajectories

Globally over the last century, shares of faster transport modes have generally increased with increasing passenger travel demand (Schafer and Victor 2000; Schäfer 2017). For short- to medium-distance travel, private cars have displaced public transit, particularly in OECD countries, due to a variety of factors, including faster travel times in many circumstances (Liao et al. 2020); increasing consumers' value of time and convenience with GDP growth; and broader transport policies, e.g. provision of road versus public transit infrastructure (Mattioli et al. 2020). For long-distance travel, travel via aviation for leisure and business has increased (Lee et al. 2021). These trends do not hold in all countries and cities, as many now have rail transit that is faster than driving (Newman et al. 2015a). For instance, public transport demand rose from 1990 through 2016 in France, Denmark, and Finland (eurostat 2019). In general, smaller and denser countries and cities with higher or increasing urbanization rates tend to have greater success in increasing public transport share. However, other factors, like privatisation of public transit (Bayliss and Mattioli 2018) and urban form (ITF 2021), also play a role. Different transport modes can provide passenger and freight services, affecting the emissions trajectories for the sector.

Figure 10.19 shows activity trajectories for freight and passenger transport through 2100 relative to a modelled year 2020 across different modes based on the AR6 database for IAMs and global transport models. Globally, climate scenarios from IAMs, and policy and reference scenarios from global transport models indicate increasing demand for freight and passenger transport via most modes through 2100 (Yeh et al. 2017; Zhang et al. 2018; Mulholland et al. 2018; Khalili et al. 2019). Road passenger transport exhibits a similar increase (roughly tripling) through 2100 across scenarios. For road passenger transport, scenarios that limit warming to 1.5 °C (C1-C2) have a smaller increase from modelled 2020 levels (median increase of 2.4 times modelled 2020 levels) than do scenarios with higher warming levels (C3-C8) (median increase of 2.7-2.8 times modelled 2020 levels). There are similar patterns for passenger road transport via light-duty vehicle, for which median increases from modelled 2020 levels are smaller for C1-2 (3 times larger) than for C3-5 (3.1 times larger) or C6-7 (3.2 times larger). Passenger transport via aviation exhibits a 2.2 times median increase relative to modelled 2020 levels under C1-2 and C3-5 scenarios but exhibits a 6.2 times increase under C6-C8. The only passenger travel mode that exhibits a decline in its median value through 2100 according to IAMs is walking/bicycling, in C3-5 and C6-8 scenarios. However, in C1-2 scenarios, walking/bicycling increases by 1.4 times relative to modelled 2020 levels. At the 5th percentile of IAM solutions (lower edge of bands in Figure 10.19), buses and walking/bicycling for passenger travel both exhibit significant declines.

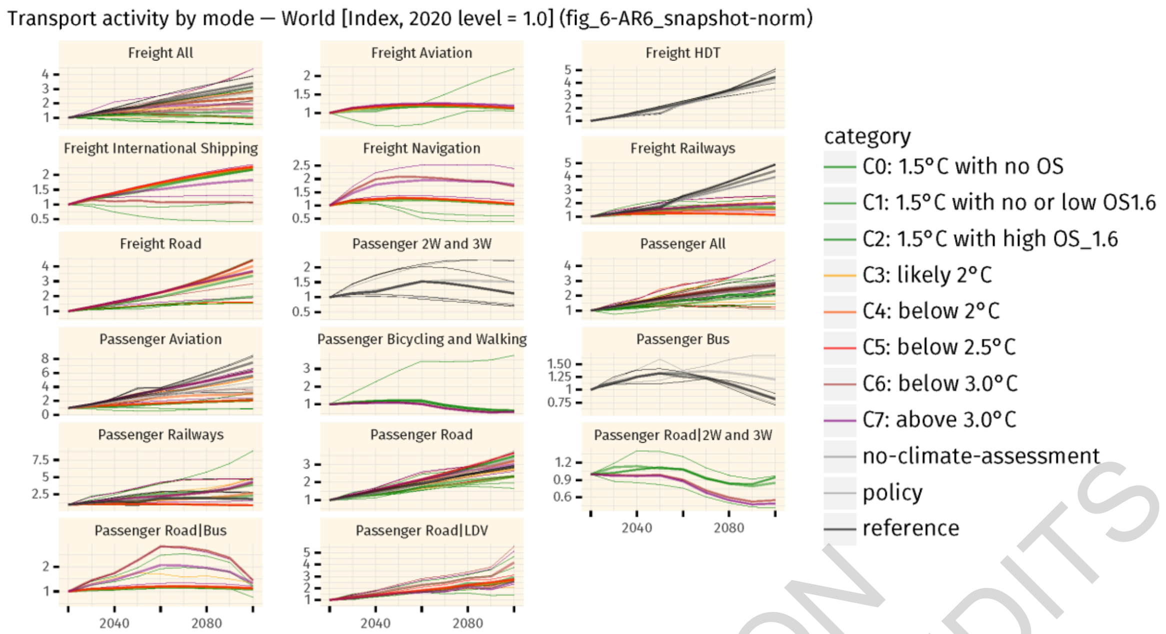


Figure 10.19 Transport activity trajectories for passenger and freight across different modes. Global passenger (billion pkm per year) and freight (billion tkm per year) demand projections relative to a modelled year 2020 index. Results for IAM for selected stabilization temperatures by 2100. Also included are global transport models Ref and Policy scenarios. Data from the AR6 scenario database. Trajectories span the 5th/95th percentiles across models with a solid line indicating the median value across models.

For freight, Figure 10.19 shows that the largest growth occurs in transport via road (Mulholland et al. 2018). By 2100, global transport models suggest a roughly 4 times increase in median- heavy-duty trucking levels relative to modelled 2020 levels, while IAMs suggest a 2-4 times increase in freight transport by road by 2100. Notably, the 95th percentile of IAM solutions see up to a 4.7 times increase in road transport through 2100 relative to modelled 2020 levels, regardless of warming level. Other freight transport modes – aviation, international shipping, navigation, and railways – exhibit less growth than road transport. In scenarios that limit warming to 1.5 °C (C1-C2), navigation and railway remain largely unchanged and international shipping roughly doubles by 2100. Scenarios with higher warming (i.e., moving from C1-2 to C6-8) generally lead to more freight by rail and less freight by international shipping.

Relative to global trajectories, upper-income regions – including North America, Europe, and the Pacific OECD – generally see less growth in passenger road via light-duty vehicle and passenger aviation, given more saturated demand for both. Other regions like China exhibit similar modal trends as the global average, whereas regions such as the African continent and Indian subcontinent exhibit significantly larger shifts, proportionally, in modal transport than the globe. In particular, the African continent represents the starkest departure from global results. Freight and passenger transport modes exhibit significantly greater growth across Africa than globally in all available scenarios. Across Africa, median freight and passenger transport via road from IAMs increases by 5-16 times and 4-28 times, respectively, across warming levels by 2100 relative to modelled 2020 levels. Even C1 has considerable growth in Africa via both modes (3-16 times increase for freight and 4-29 times increase for passenger travel at 5th and 95th percentiles of IAM solutions by 2100).

As noted in Section 10.2, commonly explored mitigation options related to mode change include a shift to public transit, shared mobility, and demand reductions through various means, including improved urban form, teleconferences that replace passenger travel (Creutzig et al. 2018; Grubler et al. 2018;

Wilson et al. 2019), improved logistics efficiency, green logistics, and streamlined supply chains for the freight sector (Mulholland et al. 2018). NDCs often prioritize options like bus improvements and enhanced mobility that yield pollution, congestion, and urban development co-benefits, especially in medium and lower-income countries (Fulton et al. 2017). Conversely, high-income countries, most of which have saturated and entrenched private vehicle ownership, typically focus more on technology options, e.g., electrification and fuel efficiency standards (Gota et al. 2016). Available IAM and regional models are limited in their ability to represent modal shift strategies. As a result, mode shifts alone do not differentiate climate scenarios. While this lack of representation is a limitation of the models, it is unlikely that such interventions would completely negate the increases in demand the models suggest. Therefore, transport via light-duty vehicle and aviation, freight transport via road, and other modes will likely continue to increase through end-of-century. Consequently, fuel and carbon efficiency and fuel energy and technology will probably play crucial roles in differentiating climate scenarios, as discussed in the following sub-sections.

10.7.5 Energy and Carbon efficiency trajectories

This section explores what vehicle energy efficiencies and fuel carbon intensity trajectories, from the data available in AR6 database from IAMs and GTEMs, could be compatible with different temperature goals. Figure 10.20 shows passenger and freight energy intensity, and fuel carbon intensity indexed relative to 2020Mod values. The top panel shows passenger energy intensity across all modes. LDVs constitute a major share of this segment. (Yeh et al. 2017) report 2.5-2.75 MJ vkm^{-1} in 2020 across models for the LDV segment, which is also very close to the IEA estimate of 2.5 MJ vkm^{-1} for the global average fuel consumption for LDVs in 2017 (IEA 2020d). For reference, these numbers correspond to 1.6-1.7 MJ pkm^{-1} for an occupancy rate of 1.5. The following results of the AR6 database are conditional on the corresponding reductions in fuel carbon intensity. Figure 10.20 shows that the scenarios suggest that passenger transport's energy intensity drops to between 10%-23% (interquartile ranges across C1-C4) in 2030 for the scenarios in line with warming levels below 2°C. In 2050, the medians across the group of 1.5°C scenarios (C1-C2) and 2°C scenarios (C2-C3) suggest energy intensity reductions of 51% and 45-46% respectively. These values correspond to annual average energy efficiency improvement rates of 2.3-2.4% and 2.0-2.1%, respectively, from 2020 to 2050. For reference, the IEA reports an annual energy efficiency improvement rate of 1.85% per year in 2005-16 (IEA 2020d). In contrast, the results from GTEMs suggest lower energy efficiency improvement, with median values for policy scenarios of 39% reduction in 2050, corresponding to annual energy efficiency improvement rates close to 1.6%. The IAM scenarios suggest median energy intensity reductions of passenger transport of 57-61% by the end of the century would align with warming levels of both 1.5°C and 2°C (C1-C4) given the corresponding decarbonisation of the fuels.

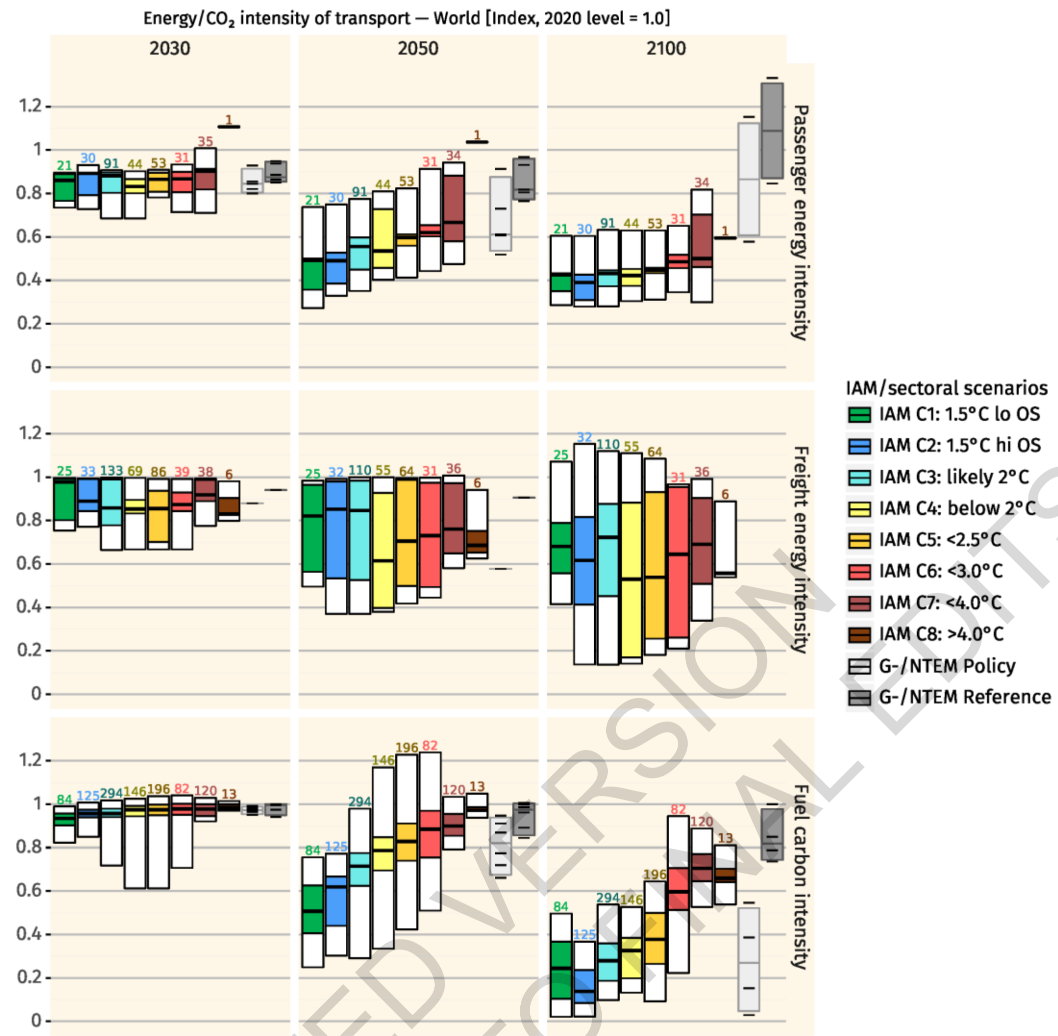


Figure 10.20 Energy efficiency and carbon intensity in 2030, 2050, and 2100 indexed to 2020 modelled year across scenarios. Plots show 5th/95th percentile, 25th/75th percentile, and median. Numbers above the bars indicate the number of scenarios. Data from the AR6 scenario database.

The scenarios in line with warming levels of 1.5°C or 2°C goals show different trends for freight's energy intensity. The amount of overshoot and differences in demand for freight services and, to some extent, fuel carbon intensities contribute to these differences. For the two scenarios aligning with the warming levels of 1.5°C, the trajectories in 2030 and 2050 are quite different. The median scenario in the high overshoot bin (C2) takes a trajectory with lower energy intensity improvements in the first half of the century. In contrast, the limited overshoot scenario (C1) takes on a more steadily declining trajectory across the means. The IAMs provide a less clear picture of required energy intensity improvements for freight than for passenger associated with different temperature targets. As for the carbon intensity of direct energy used across both passenger and freight, the modelling scenarios suggest very moderate reductions by 2030. The interquartile ranges for the C1 scenarios suggest global average reductions in carbon intensity of 5%-10%. Across the other scenarios compatible with warming levels of 1.5°C or 2°C (C2-4), the interquartile ranges span from 1%-6% reductions in carbon intensity of direct energy used for transport. For 2050 the scenarios suggest that dependence on fuel decarbonisation increases with more stringent temperature targets. For the 1.5°C scenarios (C1), global carbon intensity of energy used for transport decreases by 37%-60% (interquartile range) by 2050 with a mean of 50% reduction. The IAM scenarios in the AR6 database do not suggest full decarbonisation of transport fuels by 2100. The interquartile ranges across the C1-C4 set of scenarios, compatible with warming levels of 2°C and less, span from 61%-91% reduction from 2020Mod levels.

Increasing occupancy rate of passenger transport (Grubler et al. 2018) and reducing empty miles or increasing payload in freight deliveries (Gucwa and Schäfer 2013; McKinnon 2018) via improved logistics efficiency or streamlined supply chains (Mulholland et al. 2018), can present significant opportunities to effectively improve energy efficiency and decrease GHG emissions in transport. However, the recent trends of consumer behaviours have shown a declining occupancy rate of light-duty vehicles in industrialized countries (Schäfer and Yeh 2020), and the accelerating growing preference for SUVs challenges emissions reductions in the passenger car market (IEA 2019d). These trends motivate a strong focus on demand-side options.

Based on the scenario literature, a 51% reduction in median energy intensity of passenger transport and a corresponding reduction of 38%-50% reduction in median carbon intensity by 2050 would be aligned with transition trajectories yielding warming levels below 1.5°C by the end of the century. For comparison, the LCA literature suggests a switch from current ICEs to current BEVs would yield a reduction in energy intensity well beyond 45% and up to 70%, for a mid-sized vehicle (see Sections 10.4). Correspondingly, a switch from diesel or gasoline to low-carbon electricity or low-carbon Hydrogen would yield carbon intensity reduction beyond the median scenario value. Thus, the LCA literature suggests technologies exist today that would already match and exceed the median energy and carbon intensities values that might be needed by 2050 for low warming levels.

10.7.6 Fuel energy and technology trajectories

Two mechanisms for reducing carbon emissions from the transport sector are fuel switching for current vehicle technologies and transitioning to low carbon vehicle technologies. Figure 10.21 combines data from IAMs and GTEMs on shares of transport final energy by fuel. These shares account for fuels uses across modes - road, aviation, rail, and shipping- and both passenger and freight transport. Since the technologies have different conversion efficiencies, these shares of final energy by fuel are necessarily different from the shares of service (passenger- or ton-km) by fuel and shares of vehicle stock by fuel. For example, a current battery-electric LDV powertrain is roughly 3 times more energy-efficient than a comparable ICE powertrain (see Section 10.3, and Table 10.9 in Appendix 10.1); thus, fuel shares of 0.25 for electricity and 0.75 for oil could correspond to vehicle stock shares of 0.5 and 0.5, respectively. In general, while models may project that EVs constitute a greater share of road vehicle stock, and provide a greater share of road passenger-kilometres, their share of transport final energy (shown in Figure 10.21) can still remain lower than the final energy share of fuels used in less-efficient (e.g. ICE) vehicles. Thus, the shares of transport final energy by fuel presented in Figure 10.21 should be interpreted with care.

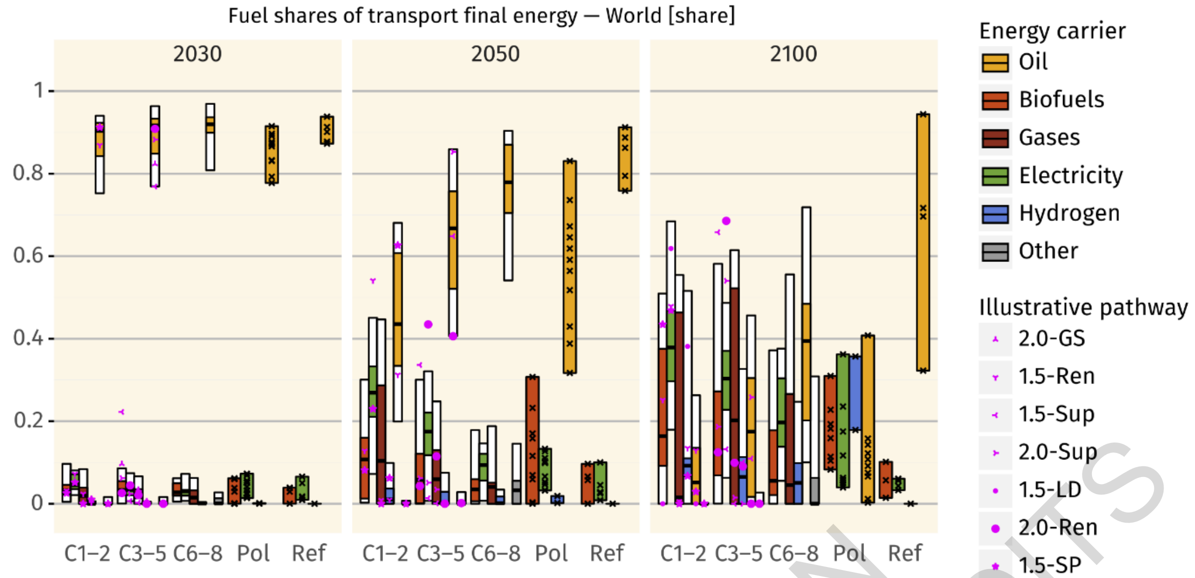


Figure 10.21 Global shares of final fuel energy in the transport sector in 2030, 2050, and 2100 for freight and passenger vehicles. Plots show 10th/90th percentile, 25th/75th percentile, and median. Data from the AR6 scenario database.

IAM and GTEM scenarios indicate that fuel and technology shifts are crucial to reduce carbon emissions to achieve lower levels of warming (Edelenbosch et al. 2017; IEA 2017b). Across the transport sector, a technology shift towards advanced fuel vehicles is the dominant driver of decarbonisation in model projections. This trend is consistent across climate scenarios, with larger decreases in the final energy share of oil in scenarios that achieve progressively lower levels of warming. Due to efficiency improvements; the higher efficiency of advanced fuel vehicles; and slower progress in the freight sector, the final energy share of oil decreases more rapidly after 2030. By 2050, the final energy shares of electricity, biofuels, and alternative gaseous fuels increase, with shares from electricity generally about twice as high (median values from 10%–30% across warming levels) as the shares from biofuels and gases (median values from 5%–10%). While IAMs suggest that the final energy share of hydrogen will remain low in 2050, by 2100 the median projections include 5%–10% hydrogen in transport final energy.

While only few IAMs report final energy shares by transport mode or passenger/freight, several relevant studies provide insights into fuel share trends in passenger LDVs and freight. The IEA suggests that full LDV electrification would be the most promising low-carbon pathway to meet a 1.75°C goal (IEA 2017b). The MIT Economic Projection and Policy Analysis (EPPA) model focuses on the future deployment of gasoline versus EV technologies in the global LDV stock (Ghandi and Paltsev 2019). These authors estimate that the global stock of vehicles could increase from 1.1 billion vehicles in 2015 up to 1.8 billion by 2050, with a growth in EVs from about 1 million vehicles in 2015 up to 500 million in 2050. These changes are driven primarily by cost projections (mostly in battery cost reductions). Similarly, the International Council on Clean Transport (ICCT) indicates that EV technology adoption in the light-duty sector can lead to considerable climate benefits. Their scenarios reach nearly 100% electrification of LDVs globally, leading to global GHG emissions ranging from 0% to -50% of 2010 LDV levels in 2050 (Lutsey 2015). Khalili *et al* (2019) estimate transport stocks through 2050 under aggressive climate mitigation scenarios that nearly eliminate road transport emissions. They find the demand for passenger transport could triple through 2050, but emissions targets could be met through widespread adoption of BEVs (80% of LDVs) and, to a lesser extent, fuel cell and plug-in hybrid electric vehicles. Contrary to these estimates, the US Energy Information Administration (EIA) finds small adoption of electrification for LDVs and instead identifies diffusion of natural gas-fuelled LDVs in OECD and, to a greater extent, non-OECD countries through 2040. This trend occurs in a reference and a "low liquids" case, which lowers LDV ownership growth rates and increases preferences for alternative fuel vehicles. A comprehensive overview of regional technology adoption models across many methodological approaches can be found in (Jochem et al. 2018).

In freight transport, studies indicate a shift toward alternative fuels would need to be supplemented by efficiency improvements. The IEA suggests efficiency improvements would be essential for decarbonisation of trucks, aviation, and shipping in the short-to-medium term. At the same time, the IEA suggests that fuel switching to advanced biofuels would be needed to decarbonise freight in the long-term (IEA 2019d). Mulholland et al. (2018) investigated the impacts of decarbonising road freight in two scenarios: countries complying with COP21 pledges and a second more ambitious reduction scenario in line with limiting global temperature rise to 1.75ºC. Despite the deployment of logistics improvements, high-efficiency technologies, and low carbon fuels, activity growth leads to a 47% increase in energy demand for road freight while overall GHG emissions from freight increase by 55% (4.8 $GtCO_2eq$) in 2050 (relative to 2015) in the COP21 scenario. In the 1.75ºC scenario, decarbonisation happens primarily through a switch to alternative fuels (hybrid electric and full battery-electric trucks), which leads to a 60% reduction in GHG emissions from freight in 2050 relative to 2015. Khalili et al. (2019) also find substantial shifts to alternative fuels in HDVs under aggressive climate mitigation scenarios. Battery electricity, Hydrogen fuel cell, and plug-in hybrid electric vehicles constitute 50%, 30%, and 15% of heavy-duty vehicles, respectively, in 2050. They also find 90% of buses would be electrified by 2050.

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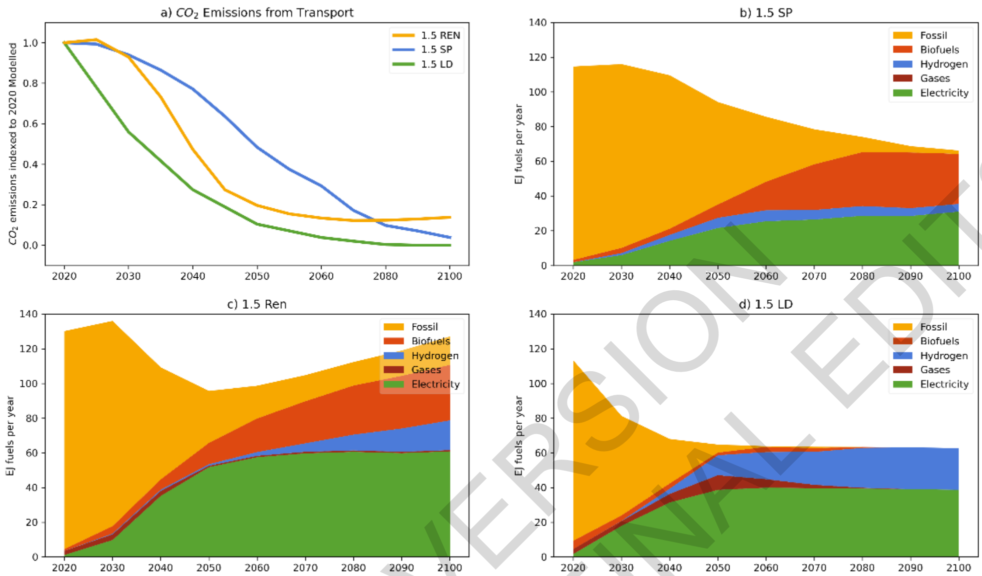
Box 10.4 Three Illustrative Mitigation Pathways.

Section 10.7 presents the full set of scenarios in the AR6 database and highlight the broader trends of how the transport sector may transform in order to be compliant with different warming levels. This box elaborates on three illustrative mitigation pathways (IMPs) to exemplify a few different ways the sector may transform. A total of 7 illustrative pathways are introduced in section 3.2.5 of chapter 3. In this box we focus on three of the IMPs: (1) focus on deep renewable energy penetration and electrification (IMP-Ren), (2) low demand (IMP-LD) and (3) pathways that align with both sustainable development goals as well as climate policies (IMP-SP). In particular, the variants of these three scenarios limit warming to 1.5°C with no or limited overshoot (C1). All of the three selected pathways reach global net zero CO_2 emissions across all sectors between 2060 and 2070, but not all reach net zero GHG emissions (see Figure 3.4 Chapter 3). Panel (a) in Box 10.4, Figure 1 below shows the CO_2 trajectories for the transport sector for the selected IMPs. Please note that the year 2020 is modelled in these scenarios. Therefore, the scenarios do not reflect the effects of the COVID-19 pandemic. For the low demand scenarios IMP-LD and renewables pathway IMP-Ren, CO_2 emissions from the transport sectors decrease to 10% and 20% of modelled 2020 levels by 2050, respectively. In contrast, the IMP-SP has a steady decline of transport sector CO_2 emissions over the century. By 2050, this scenario has a 50% reduction in emissions compared to modelled 2020 levels. Panels (b), (c) and (d) show energy by different fuels for the three selected IMPs. The IMPs-SP yields a drop in energy for transport of about 40% by the end of the century. CO_2 emission reductions are obtained through a phase-out of fossil fuels with electricity and biofuels, complemented by a minor share of Hydrogen by the end of the century. In IMP Ren, the fuel energy demand at the end of the century is in par with the 2020 levels, but the fuel mix has shifted towards a larger share of electricity complimented by biofuels and a minor share of Hydrogen. For the IMP-LD scenario, the overall fuel demand decreases by 45% compared to 2020 levels by the end of the century. Oil is largely phased out by mid-century, with electricity and Hydrogen becoming the major fuels in the second half of the century. Across the three IMPs, electricity plays a major role, in combination with biofuels, Hydrogen, or both.



Box 10.4, Figure 1 Three Illustrative mitigation pathways for the Transport sector. Panel (a) shows CO_2 emissions from the transport sector indexed to simulated non-COVID 2020 levels. Panels (b), (c), and (c) show fuels mix for 1.5 (IMP-SP), 1.5 REN (IMP-Ren) and 1.5 LD (IMP-LD), respectively. All data from IPCC AR6 Scenario database.

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10.7.7 Insights from the modelling literature

This section provides an updated, detailed assessment of future transport scenarios from IAM and G-/NTEMs given a wide range of assumptions and under a set of policy targets and conditions. The scenario modelling tools are necessary to aggregate individual options and understand how they fit into mitigation pathways from a systems perspective. The scenarios suggest that 43% (30-63% for the inter quartile ranges) reductions in CO_2 emissions from the transport emissions CO_2 (below modelled 2020 levels) by 2050 would be compatible with warming levels of 1.5°C (C1-C2 group). While the global scenarios suggest emissions reductions in energy supply sectors at large precede those in the demand sectors (see section 3.4.1), a subset of the scenarios also demonstrate that more stringent emission reductions in the transport sector are feasible. For example, the illustrative mitigation pathways IMP-REN and IMP-LD suggest emission reductions of respectively 80% and 90% are feasible by 2050 en-route to warming levels of 1.5°C (C1-C2) with low or no overshoot by the end of the century.

The scenarios from the different models project continued growth in demand for freight and passenger services, particularly in developing countries. The potential of demand reductions is evident, but the specifics of demand reduction measures remain less explored by the scenario literature. This limitation not-withstanding, the IAM and GTEMs suggest interventions that reduce the energy and fuel carbon intensity are likely crucial to successful mitigation strategies.

The scenario literature suggests that serious attempts at carbon mitigation in the transport sector must examine the uptake of alternative fuels. The scenarios described in the IAMs and GTEMs literature decarbonise through a combination of fuels. Across the scenarios, electrification plays a key role, complemented by biofuels and Hydrogen. In general terms, electrification tends to play the key role in passenger transport while biofuels and Hydrogen are more prominent in the freight segment. The three illustrative mitigation pathways in Box 10.4 exemplify different ways these technologies may be combined and still be compatible with warming levels of 1.5°C with low or no overshoot. Shifts towards alternative fuels must occur alongside shifts towards clean technologies in other sectors, as all alternative fuels have upstream impacts. Without considering other sectors, fuel shifts would not yield their full mitigation potentials. These collective efforts are particularly important for the electrification of transport, as the transformative mitigation potential is strongly dependent on the decarbonisation of the power sector. In this regard, the scenario literature is well aligned with the LCA literature reviewed in Section 10.4.

The models reviewed in this section would all generally be considered to have a good representation of fuels, technologies, and costs, but they often better represent land transport modes than shipping and aviation. While these models have their strengths in some areas, they have some limitations in other areas, like behavioural aspects. Analogously, these models are also limited in their ability to account for unexpected technological innovation such as a breakthrough in heavy vehicle fuels, AI, autonomy and big data, even the extent of digital communications replacing travel (see Section 10.2). As a result of these type of limitations, the models cannot yet provide a fully exhaustive set of options for decarbonising the transport sectors. These limitations not-withstanding, the models can find solutions encompassing the transport sector and its interactions with other sectors that are compatible with stringent emissions mitigation efforts. The solution space of transportation technology trajectories is therefore wider than explored by the models, so there is still a need to better understand how all options in combination may support the transformative mitigation targets.

10.8 Enabling conditions

10.8.1 Conclusions across the chapter

This final section draws some conclusions from the chapter, provides an overview-based feasibility assessment of the major transport mitigation options, as well as a description of emerging issues. The section ends by outlining an integrated framework for enabling the transformative changes that are emerging and required to meet the potential transformative scenarios from Section 10.7.

Transport is becoming a major focus for mitigation as its GHG emissions are large and growing faster than for other sectors, especially in aviation and shipping. The scenarios literature suggests that without mitigation actions, transport emissions could grow by up to 65% by 2050. Alternatively, successful deployment of mitigation strategies could reduce sectoral emissions by 68%, which would be consistent with the goal of limiting temperature change to 1.5°C above pre-industrial levels. This chapter has reviewed the literature on all aspects of transport and has featured three special points of focus: (1) A survey of life cycle analysis from the academic and industry community that uses these tools; (2) A similar exercise of surveying the modelling community for top-down and bottom-up approaches to identify decarbonisation pathways for the transport sector, and (3) For the first time in the IPCC, separate sections on shipping and aviation. The analysis of the literature suggests three crucial components for the decarbonisation of the transport sector: demand and efficiency strategies, electromobility, and alternative fuels for shipping and aviation.

The challenge of decarbonisation requires a transition of the socio-technical system, which in turn depends on the combination of technological innovation and societal change (Geels et al. 2017). A socio-technical system includes technology, regulation, user practices and markets, cultural meaning, infrastructure, maintenance networks, and supply networks (Geels 2005) (see Cross Chapter Box 12 in Chapter 16). The multi-level perspective (MLP) is a framework that provides insights to assist policymakers when devising transformative transition policies (Rip and Kemp 1998; Geels 2002). Under the MLP framework, strategies are grouped into three different categories. The Micro level (niche) category includes strategies where innovation differs radically to that of the incumbent socio-technical system. The niche provides technological innovations a protected space during development and usually requires considerable R&D and demonstrations. In the Meso level (regime) state, demonstrations begin to emerge as options that can be adopted by leading groups who begin to overcome lock-in barriers from previous technological dependence. Finally, in the Macro level (Landscape) stage, main-streaming happens, and the socio-technical system enables innovations to breakthrough. Figure 10.22 maps the MLP stage for the major mitigation strategies identified in this chapter.

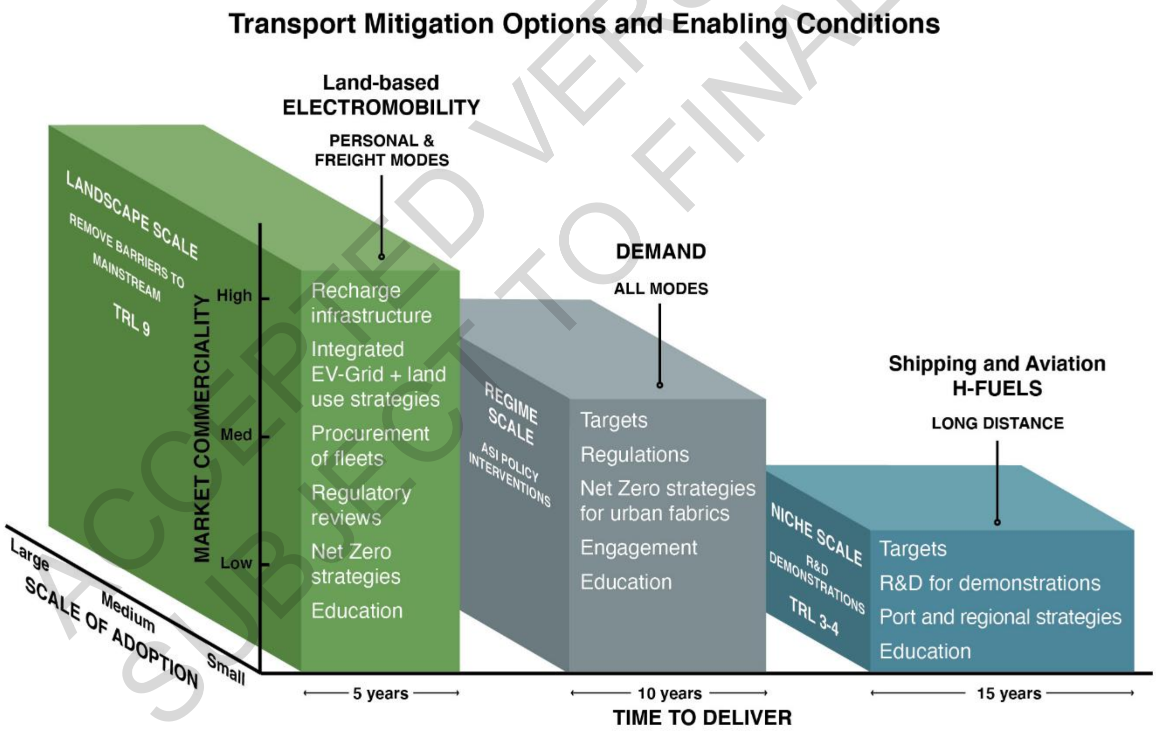

Figure 10.22 Mitigation Options and Enabling Conditions for Transport. Niche scale includes strategies that still require innovation.

Demand and behaviour. While technology options receive substantial attention in this chapter, there are many social and equity issues that cannot be neglected in any transformative change to mitigate climate change. Transport systems are socio-economic systems that include systemic factors that are developing into potentially transformative drivers of emissions from the sector. These systemic drivers include, for example, changes in urban form that minimises automobile dependence and reduces stranded assets; behaviour change programs that emphasise shared values and economies; smart technologies that enable better and more equitable options for transit and active transport as well as integrated approaches to using autonomous vehicles; new ways of enabling electric charging systems to fit into electricity grids creating synergistic benefits to grids, improving the value of electric transit, and reducing range anxiety for EV users; and, new concepts for the future economy such as circular economy, dematerialisation, shared economy that have the potential to affect the structure of the transport sector. The efficacy of demand reductions and efficiency opportunities depends on the degree of prioritisation and focus by government policy. Figure 10.22 suggests that innovative demand and efficiency strategies are at the regime scales. While these strategies are moving beyond R&D, they are not mainstreamed yet and have been shown to work much more effectively if combined with technology changes as has been outlined in the transformative scenarios from Section 10.7 and in Chapter 5.

Electromobility in Land-based Transport. Since AR5, there has been a significant breakthrough in the opportunities to reduce transport GHG emissions in an economically efficient way due to electrification of land-based vehicle systems, which are now commercially available. EV technologies are particularly well-established for light duty passenger vehicles, including micro mobility. Furthermore, there are positive developments to enable EV technologies for buses, light and medium-duty trucks, and some rail applications (though advanced biofuels and hydrogen may also contribute to the decarbonisation of these vehicles in some contexts). In developing countries, where micro mobility and public transit account for a large share of travel, EVs are ideal to support mitigation of emissions. Finally, demand from critical materials needed for batteries has become a focus of attention, as described in Box 10.6.

Electromobility options are moving from regime to landscape levels. This transition is evident in the trend of incumbent automobile manufacturers producing an increasing range of EVs in response to demand, policy, and regulatory signals. EVs for light-duty passenger travel are largely commercial and likely to become competitive with ICE vehicles in the early 2020's (Dia 2019; Bond et al. 2020; Koasidis et al. 2020). As these adopted technologies increase throughout cities and regions, governments and energy suppliers will have to deploy new supporting infrastructure to support them, including reliable low-carbon grids and charging stations (Sierzchula et al. 2014). In addition, regulatory reviews will be necessary to ensure equitable transition and achievement of SDG's, addressing the multitude of possible barriers that may be present due to the incumbency of traditional automotive manufacturers and associated supporting elements of the socio-technical system (Newman 2020b); and Chapter 6). Similarly, new partnership between government, industry, and communities will be needed to support the transition to electromobility. These partnerships could be particularly effective at supporting engagement and education programs ((Newman 2020b); and Chapter 8).

Deployment of electromobility is not limited to developed countries. The transportation sector in low- and middle-income countries includes millions of gas-powered motorcycles within cities across Africa, Southeast Asia, and South America (Ampersand 2020; Ehebrecht et al. 2018; Posada et al. 2011). Many of these motorcycles function as taxis. In Kampala, Uganda, estimates place the number of motorcycle taxis, known locally as boda-bodas, at around 40,000 (Ehebrecht et al. 2018). The popularity of the motorcycle for personal and taxi use is due to many factors including lower upfront costs, lack of regulation, and mobility in highly congested urban contexts (UNECE 2018; Posada et al. 2011). While motorcycles are often seen as a more fuel-efficient alternative, emissions can be worse from 2-wheelers than cars, particularly nitrogen oxides (NOx), carbon monoxide (CO), and hydrocarbon (HC) emissions (Vasic and Weilenmann 2006; Ehebrecht et al. 2018). These 2-wheeler emissions contribute to dangerous levels of air pollution across many cities in low- and middle-income countries. In Kampala, for example, air pollution levels frequently exceed levels deemed safe for humans by the World Health Organization (WHO) (Airqo 2020; World Health Organization 2018; Kampala Capital City Authority 2018). To mitigate local and environmental impacts, electric boda boda providers are emerging in many cities, including Zembo in Kampala and Ampersand in Kigali, Rwanda.

Bulawayo, the capital city of Zimbabwe, is also looking at opportunities for deploying electromobility solutions. The city is now growing again after a difficult recent history, and there is a new emphasis on achieving the Sustainable Development Goals (City of Bulawayo 2020a,b). With this goal in mind, Bulawayo is seeking opportunities for investment that can enable leapfrogging private, fossil fuel vehicle ownership. In particular, trackless trams, paired with solar energy, have emerged as a potential pathway forward (Kazunga 2019). Trackless trams are a new battery-based mid-tier transit system that could enable urban development around stations that use solar energy for powering both transit and the surrounding buildings (Newman et al. 2019). The new trams are rail-like in their capacities and speed, providing a vastly better mobility system that is decarbonised and enable low transport costs (Ndlovu and Newman 2020). While this concept is only under consideration in Bulawayo, climate funding could enable the wider deployment of such projects in developing countries.

Fuels for Aviation and Shipping. Despite technology improvements for land-based transport, equivalent technologies for long distance aviation and shipping remain elusive. Alternative fuels for use in long range aviation and shipping are restricted to the niche level. The aviation sector is increasingly looking towards synthetic fuels using low-carbon combined with CO_2 from direct air capture, while shipping is moving towards Ammonia produced using low-carbon Hydrogen. Biofuels are also of interest for these segments. To move out of the niche level, there is a need to set deployment targets to support breakthroughs in these fuels. Similarly, there is a need for regulatory changes to remove barriers in new procurement systems that accommodate uncertainty and risks inherent in the early adoption new technologies and infrastructure (Borén 2019; Sclar et al. 2019; Marinaro et al. 2020). R&D programs and demonstration trials are the best focus for achieving fuels for such systems. Finally, there is a need for regulatory changes. Such regulatory changes need to be coordinated through ICAO and IMO as well as with national implementation tools related to the Paris Agreement (see Box 10.5). Long-term visions, including creative exercises for cities and regions will be required providing a protected space for the purpose of trialling new technologies (Borén 2019; Geels 2019).

10.8.2 Feasibility Assessment

Figure 10.23 sets out the feasibility of the core mitigation options using the six criteria created for the cross-sectoral analysis. This feasibility assessment outlines how the conclusions outlined in Section 10.8.1 fit into the broader criteria created for feasibility in the whole AR6 report and that emphasise the SDGs. Figure 10.23 highlights that there is high confidence that demand reductions and mode shift can be feasible as the basis of a GHG emissions mitigation strategy for the transport sector. However, demand-side interventions work best when integrated with technology changes. The technologies that can support such changes have a range of potential limitations as well as opportunities. EV have a reliance on renewable resources (wind, solar, and hydro) for power generation, which could pose constraints on geophysical resources, land use, water use. Furthermore, expanding the deployment of EVs requires a rapid deployment of new power generation capacity and charging infrastructure. The overall feasibility of electric vehicles for land transport is likely high and their adoption is accelerating. HFCVs for land transport would also have constraints related to land geophysical resource needs, land use, and water use. These constraints are likely higher than for EVs, since producing Hydrogen with electricity reduces the overall efficiency of meeting travel demand. Furthermore, the infrastructure to produce, transport, and deliver Hydrogen is under-developed and would require significant R&D and a rapid scale-up. Thus, the feasibility of HFCV is likely lower than for EVs. Biofuels could be used in all segments of the transport sector, but there may be some concerns about their feasibility. Specifically, there are concerns about land use, water use, impacts on water quality and eutrophication, and biodiversity impacts. Advanced biofuels could mitigate some concerns and the feasibility of using these fuels likely varies by world region. The feasibility assessment for alternative fuels for shipping and aviation suggests that Hydrogen-based fuels like Ammonia and synthetic fuels have the lowest technology readiness of all mitigation options considered in this chapter. Reliance on electrolytic Hydrogen for the production of these fuels poses concerns about land and water use. Using Ammonia for shipping could pose risks for air quality and toxic discharges to the environment. The DAC/BECCS infrastructure that would be needed to produce synthetic fuel does not yet exist. Thus, the feasibility suggests that the technologies for producing and using these Hydrogen-based fuels for transport are in their infancy.

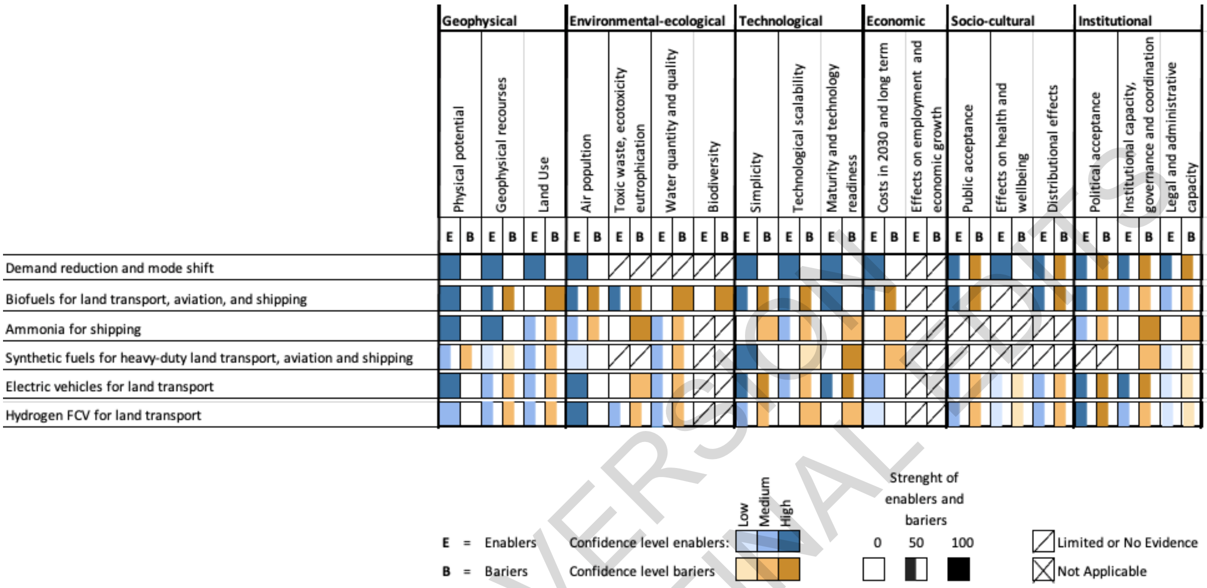

Figure 10.23 Summary of the extent to which different factors would enable or inhibit the deployment of mitigation options in Transport. Blue bars indicate the extent to which the indicator enables the implementation of the option (E) and orange bars indicate the extent to which an indicator is a barrier (B) to the deployment of the option, relative to the maximum possible barriers and enablers assessed. An 'X' signifies the indicator is not applicable or does not affect the feasibility of the option, while a forward slash indicates that there is no or limited evidence whether the indicator affects the feasibility of the option. The shading indicates the level of confidence, with darker shading signifying higher levels of confidence. Appendix 10.3 provides an overview of the extent to which the feasibility of options may differ across context (e.g., region), time (e.g., 2030 versus 2050), and scale (e.g., small versus large), and includes a line of sight on which the assessment is based. The assessment method is explained in Annex II.11.

10.8.3 Emerging Transport Issues

Planning for integration with the power sector: Decarbonising the transport sector will require significant growth in low-carbon electricity to power EVs, and more so for producing energy-intensive fuels, such as Hydrogen, Ammonia and synthetic fuels. Higher electricity demand will necessitate greater expansion of the power sector and increase land use. The strategic use of energy-intensive fuels, focussed on harder-to-decarbonise transport segments, can minimise the increase in electricity demand. Additionally, integrated planning of transport and power infrastructure could enable sectoral synergies and reduce the environmental, social, and economic impacts of decarbonising transport and energy. For example, smart charging of EVs could support more efficient grid operations. Hydrogen production, which is likely crucial for the decarbonisation of shipping and aviation, could also serve as storage for electricity produced during low-demand periods. Integrated planning of transport and power infrastructure would be particularly useful in developing countries where "greenfield" development doesn't suffer from constraints imposed by legacy systems.

Shipping and aviation governance: Strategies to deliver fuels in sufficient quantity for aviation and shipping to achieve transformative targets are growing in intensity and often feature the need to review international and national governance. Some literature suggests that the governance of the international transport systems could be included the Paris Agreement process (Gençsü and Hino 2015; Traut et al. 2018; Lee 2018). Box 10.6 sets out these issues.

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Box 10.5 Governance Options for shipping and aviation

Whenever borders are crossed, the aviation and shipping sector creates international emissions that are not assigned to states' Nationally Declared Contributions in the Paris Agreement. Emissions from these segments are rapidly growing (apart from COVID affecting aviation) and are projected to grow between 60% to 220% by 2050 (IPCC 2018; UNEP 2020). Currently, the International Civil Aviation Organization (ICAO) and the International Marine Organization (IMO), specialised UN Agencies, are responsible for accounting and suggesting options for managing these emissions.

Transformational goals?

ICAO has two global aspirational goals for the international aviation sector: 2% annual fuel efficiency improvement through 2050; and carbon neutral growth from 2020 onwards. To achieve these goals, ICAO has established CORSIA – Carbon Offsetting and Reduction Scheme for International Aviation, a market-based program.

In 2018, IMO adopted an 'Initial Strategy' on the reduction of GHG emissions from ships. This strategy calls for a reduction of the carbon intensity of new ships through implementation of further phases of the energy efficiency design index (EEDI). Similarly, the IMO calls for a 40% reduction of the carbon intensity of international shipping by 2030, and is striving for a 70% reduction by 2050. Such reductions in carbon intensity would result in an overall decline in emissions of 50% in 2050 (relative to 2008).

These goals are likely insufficiently transformative for the decarbonisation of aviation or shipping, though they are moving towards a start of decarbonisation at a period in history where the options are still not clear, as set out in Sections 10.5 and 10.6.

Regulations?

The ICAO is not a regulatory agency, but rather produces standards and recommended practices that are adopted in national/international legislation. IMO does publish 'regulations' but does not have power of enforcement. Non-compliance can be regulated by nation states if they so desire, as a ship's 'MARPOL' certificate, issued by the flag state of the ship, means there is some responsibility for states with global shipping fleets.

Paris?

Some commentators have suggested that emissions from international aviation and shipping should be part of the Paris Agreement (Gençsü and Hino 2015; Traut et al. 2018; Lee 2018; Rayner 2021) argue that the shipping and aviation industries would prefer emissions to be treated under an international regime rather than a national-oriented regime. If international aviation and shipping emissions were a part of the Paris Agreement, it may remove something of the present ambiguity of responsibilities. However, inclusion in the Paris agreement is unlikely to fundamentally change emissions trends unless targets and enforcement mechanisms are developed either by ICAO and IMO or by nation states through global processes.

Individual nations?

If international regulations do not occur, then the transformation of aviation and shipping will be left to individual nations like Switzerland. In 2020, Switzerland approved a new CO_2 tax on flights (The Swiss Parliament 2020) with part of its revenues earmarked for the development of synthetic aviation fuels, to cover up to 80% of their additional costs compared to fossil jet fuel (Energieradar 2020). Hence, appropriate financing frameworks will be a key to the large-scale market adoption of these fuels. Egli et al. (2019) suggest that the successful design of renewable energy investment policies for solar and wind power over the past 20 years could serve as a model for future synthetic aviation fuels production projects "attracting a broad spectrum of investors in order to create competition that drives down financing cost", and with state investment banks building "investor confidence in new technologies." These national investment policies would provide the key enablers for successful deployments.

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Managing critical minerals: Critical minerals are required to manufacture LIB's and other renewable power technologies. There has been growing awareness that critical minerals may face challenges related to resource availability, labour rights, and costs. Box 10.6, below, sets out the issues showing how emerging national strategies on critical minerals, along with requirements from major vehicle manufacturers, are addressing the need for rapid development of new mines with a more balanced geography, less use of cobalt through continuing LIB innovations, and a focus on recycling batteries. The standardisation of battery modules and packaging within and across vehicle platforms, as well as increased focus on design for recyclability are important. Given the high degree of potential recyclability of LIBs, a near closed-loop system in the future would be a feasible opportunity to minimise critical mineral issues.

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Box 10.6 Critical Minerals and The Future of Electro-Mobility and Renewables

The global transition towards renewable energy technologies and battery systems necessarily involves materials, markets, and supply chains on a hitherto unknown scale and scope. This has raised concerns regarding mineral requirements central to the feasibility of the energy transition. Constituent materials required for the development of these low carbon technologies are regarded as "critical" materials (US Geological Survey 2018; Commonwealth of Australia 2019; Lee et al. 2020; Marinaro et al. 2020; Sovacool et al. 2020). 'Critical materials' are critical because of their economic or national security importance, or high risk of supply disruption (UK Government 2019). describes many of these materials and rare earth elements (REEs) as "technologically critical" not only due to their strategic or economic importance but the risk of short supply or price volatility (Marinaro et al. 2020). In addition to these indicators, production growth and market dynamics are also incorporated into screening tools to assess emerging trends in material commodities that are deemed as fundamental to the well-being of the nation (NSTC 2018).

The critical materials identified by most nations are: REEs Neodymium and Dysprosium for permanent magnets in wind turbines and electric motors; Lithium and Cobalt, primarily for batteries though many other metals are involved (see figure below); and, Cadmium, Telluriam, Selenium, Gallium and Indium for solar PV manufacture (Valero et al. 2018; Giurco et al. 2019). Predictions are that the transition to a clean energy world will be significantly energy intensive (World Bank Group 2017; Sovacool et al. 2020) putting pressure on the supply chain for many of the metals and materials required.

Governance of the sustainability of mining and processing of many of these materials, in areas generally known for their variable environmental stewardship, remains inadequate and often a source for conflict. (Sovacool et al. 2020) propose four holistic recommendations for improvement to make these industries more efficient and resilient: diversification of mining enterprises for local ownership and livelihood benefit; improve the traceability of material sources and transparency of mining enterprise; exploration of alternative resources; and the incorporation of minerals into climate and energy planning by connecting to the NDCs under the Paris Accord.

Resource Constraints?

Valero et al. (2018) highlights that the demand for many of the REEs and other critical minerals will, at the current rate of RE infrastructure growth, increase a multiple of 3,000 times or more by 2050. Some believe this growth may reach constraints in supply (Giurco et al. 2019). Others suggest that the minerals involved are not likely to physically run out (Sovacool et al. 2020) if well managed, especially as markets are found in other parts of the world (for example the transition away from Lithium in brine lakes to hard rock sources). Lithium hydroxide, more suitable for batteries, now competes well, in terms of cost, when extracted from rock sources (Azevedo et al. 2018) due to the ability to more easily create high quality Lithium Hydroxide from rock sources, even though brines provide a cheaper source of Lithium *per se* (Kavanagh et al. 2018). Australia has proven resources for all the Li-ion battery minerals and has a strategy for their ethical and transparent production (Commonwealth of Australia 2019). Changes in the technology have also been used to create less need for certain critical minerals (Månberger and Stenqvist 2018). Recycling of all the minerals is not yet well developed but is likely to be increasingly important (Habib and Wenzel 2014; Golroudbary et al. 2019; World Bank Group 2017; Giurco et al. 2019).

International Collaboration

There have been many instances since the 1950's when the supply of essential minerals has been restricted by nations in times of conflict and world tensions, but international trade has continued under the framework of the World Trade Organization. Keeping access open to critical minerals needed for a low-carbon transition will be an essential role of the international community as the need for local manufacture of such renewable and electro-mobility technologies will be necessary for local economies. shows that the trend over the past 30 years has been for the US to move from being self-sufficient in REEs to being 100% reliant on imports, predominantly from China, Japan, and France. In terms of heavy REEs, essential for permanent magnets for wind turbines, China has a near-monopoly on REE processing though other mines and manufacturing facilities are now responding to these constrained markets (Stegen 2015; Gulley et al. 2018, 2019; Yan et al. 2020). China, on the other hand, is reliant on other nations for the supply of other critical metals, particularly cobalt and lithium for batteries.

A number of Critical Materials Strategies have now been developed by nations developing the manufacturing-base of new power and transport technologies. Some of these strategies pay particular attention to the supply of lithium (Martin et al. 2017; Hache et al. 2019). For example, Horizon 2020, a substantial EU Research and Innovation program, couples research and innovation in science, industry, and society to foster a circular economy in Europe thus reducing these bottlenecks in the EU nations. Similarly CREEN (Canada Rare Earth Elements Network) is supporting the US-EU-Japan resource partnership with Australia (Klossek et al. 2016).

As renewables and electromobility-based development leapfrogs into the developing world it will be important to ensure the critical minerals issues are managed for local security of supply as well as participation in the mining and processing of such minerals to develop their own employment around renewables and electro-mobility (Sovacool et al. 2020).

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Enabling creative foresight: Human culture has always had a creative instinct that enables the future to be better dealt with through imagination (Montgomery 2017). Science and engineering have often been preceded by artistic expressions such as Jules Verne, who first dreamed of the Hydrogen future in 1874 in his novel The Mysterious Island. Autonomous vehicles have regularly occupied the minds of science fiction authors and filmmakers (Braun 2019). Such narratives, scenario building, and foresighting are increasingly seen as a part of the climate change mitigation process (Lennon et al. 2015; Muiderman et al. 2020) and can 'liberate oppressed imaginaries' (Luque-Ayala 2018). (Barber 2021) have emphasised the important role of positive images about the future instead of dystopian visions and the impossibility of business-as-usual futures.

Transport visions can be a part of this cultural change as well as the more frequently presented visions of renewable energy (Wentland 2016; Breyer et al. 2017). There are some emerging technologies like Maglev, Hyperloop, and Drones that are likely to continue the electrification of transport even further (Daim 2021) and which are only recently at the imagination stage. Decarbonised visions for heavy vehicle systems appear to be a core need from the assessment of technologies in this chapter. Such visioning or foresighting requires deliberative processes and the literature contains a growing list of transport success stories based on such processes (Weymouth and Hartz-Karp 2015). Ultimately, reducing GHG emissions from the transport sector would benefit from creative visions that integrate a broad set of ideas about technologies, urban and infrastructure planning (including transport, electricity, and telecommunication infrastructure), and human behaviour and at the same time can create opportunities to achieve the SDGs.

Enabling transport climate emergency plans, local pledges and net zero strategies: National, regional and local governments are now producing transport plans with a climate emergency focus (e.g. (Jaeger et al. 2015; Pollard 2019)). Such plans are often grounded in the goals of the Paris Agreement, based around Local Low Carbon Transport Roadmaps that contain targets for and involve commitments or pledges from local stakeholders, such as workplaces, local community groups, and civil society organisations. Pledges often include phasing out fossil-fuel based cars, buses, and trucks (Plötz et al. 2020), strategies to meet the targets through infrastructure, urban regeneration and incentives, and detailed programs to help citizens adopt change. These institution-led mechanisms could include bike-to-work campaigns, free transport passes, parking charges, or eliminating car benefits. Community-based solutions like solar sharing, community charging, and mobility as a service can generate new opportunities to facilitate low-carbon transport futures. Cities in India and China have established these transport roadmaps, which are also supported by the UNCRD's Environmentally Sustainable Transport program (Baeumler et al. 2012; Pathak and Shukla 2016; UNCRD 2020). There have been concerns raised that these pledges may be used to delay climate action in some cases (Lamb et al. 2020) but but such pledges can be calculated at a personal level and applied through every level of activity from individual, household, neighbourhood, business, city, nation or groups of nations (Meyer and Newman 2020) and are increasingly being demonstrated through shared communities and local activism (Bloomberg and Pope 2017; Sharp 2018; Figueres and Rivett-Carnac 2020). Finally, the world's major financing institutions are also engaging in decarbonisation efforts by requiring their recipients to commit to Net Zero Strategies before they can receive their funding (COVID Box, Chapter 1; Chapter 15; (Robins 2018; Newman 2020a)). As a result, transparent methods are emerging for calculating what these financing requirements mean for transport by companies, cities, regions, and infrastructure projects (see Chapters 8, 15). The continued engagement of financial institutions may, like in other sectors, become a major factor in enabling transformative futures for transport as long as governance and communities continue to express the need for such change.

10.8.4 Tools and Strategies to Enable Decarbonisation of the Transport Sector

Using the right tools and strategies is crucial for the successful deployment of mitigation options. Table 10.7 summarises the tools and strategies to enable electromobility, new fuels for aviation and shipping, and the more social aspects of demand efficiency.

Table 10.7 Tools and Strategies for enabling mitigation options to achieve transformative scenarios

Tools and Strategies	Travel Demand Reductions and Fuel/Vehicle Efficiency	Light Vehicle Electromobility Systems	Alternative Fuel Systems for Shipping and Aviation
Education and R&D	TDR can be assisted with digitalisation, connected autonomous vehicle, EVs and Mobility as a Service (Marsden et al. 2018; Shaheen et al. 2018). Knowledge gaps on TDR exist for longer distance travel (intercity); non-mandatory trips (leisure; social trips), and travel by elder people. Travel demand foresighting tools can be open source (Marsden 2018).	Behaviour change programs help EV's become more mainstream. R&D will help on the socio-economic structures that impede adoption of EV's and the urban structures that enable reduced car dependence and how EV's can assist grids (Newman 2010; Taiebat and Xu 2019; Seto et al. 2021).	R&D is critical for new fuels and to test the full life cycle costs of various heavy vehicle options (Marinaro et al. 2020).
Access and Equity	TDR programs in cities can be inequitable. To avoid such inequities, there is a need for better links to spatial and economic development (Marsden et al, 2018), mindful of diverse local priorities, personal freedom and personal data (See Box on Smart Technologies in Section 10.2)	Significant equity issues with EV's in the transition period can be overcome with programs that enable affordable electric mobility, especially transit. (IRENA 2016)	Shipping is mostly freight and is less of a problem but aviation has big equity issues (Bows-Larkin 2015)
Financing Economic Incentives and Partnerships	Carbon budget implications of different demand futures should be published and used to help incentivize net zero projects (Marsden 2018). Business and community pledges for net zero can be set up in partnership agreements (see Section 10.8.3).	Multiple opportunities for financing, economic incentives, and partnerships with clear economic benefits can be assured especially using the role of value capture in enabling such benefits. The nexus between EV's and the electricity grid needs opportunities to demonstrate positive partnership projects (Zhang et al. 2014; Mahmud et al. 2018; Newman et al. 2018; Sovacool et al. 2018; Sharma and Newman 2020)	Taking R&D into demonstration projects is the main stage for heavy vehicle options and these are best done as partnerships. Government assistance will greatly assist in such projects as well as an R&D levy. Abolishing fossil fuel subsidies and imposing carbon taxes are likely to help in the early stages of heavy vehicle transitions (Sclar et al. 2019)
Co-benefits and Overcoming Fragmentation	A focus on people-centred solutions for future mobility with more pluralistic and feasible sets of outcomes for all people can be achieved	The SDG benefits in zero carbon light vehicle transport systems are being demonstrated and can now be quantified as nations	Heavy vehicle systems can also demonstrate SDG co-benefits if formulated with this in mind. Demonstrations of how innovations can also help

	when they focus on more than simple benefit cost ratios but include well-being and livelihoods, considering transport as a system, rather than loosely connected modes as well as behaviour change programs (Barter and Raad 2000; Newman 2010; Martens 2020).	mainstream this transition. Projects with transit and sustainable housing are more able to show such benefits. New Benefit Cost Ratio methods that focus on health benefits in productivity are now favouring transit and active transport (Buonocore et al. 2019; UK DoT 2019; Hamilton et al. 2021).	SDGs will attract more funding. Such projects need cross-government consideration (Pradhan et al. 2017).
Regulation and Assessment	Implementing a flexible regulatory framework is needed for most TDR (Li and Pye 2018). Regulatory assessment can help with potential additional (cyber) security risk due to digitalization, AVs, IoT, and big data (Shaheen and Cohen 2019). Assessment tools and methods need to take account of greater diversity of population, regions, blurring of modes, and distinct spatial characteristics (Newman and Kenworthy 2015).	With zero carbon light vehicle systems rapidly growing the need for a regulated target and assessment of regulatory barriers can assist each city and region to transition more effectively. Regulating EV's for government fleets and recharge infrastructure can establish incentives (Bocken et al. 2016).	Zero carbon heavy vehicle systems need to have regulatory barrier assessments as they are being evaluated in R&D demonstrations (Sclar et al. 2019).
Governance and Institutional Capacity	TDR works better if adaptive decision-making approaches focus on more inclusive and whole of system benefit-cost ratios (Yang et al. 2020; Marsden 2018)	Governance and institutional capacity can now provide international exchanges and education programs based on successful cities and nations enabling light vehicle decarbonisation to create more efficient and effective policy mechanisms towards self-sustaining markets (Greene et al. 2014; Skjølsvold and Ryghaug 2019)..	Governance and institutional capacity can help make significant progress if targets with levies for not complying. Carbon taxes would also affect these segments. A review of international transport governance is likely (Makan and Heyns 2018)
Enabling infrastructure	Ensuring space for active transport and urban activities is taken from road space where necessary (Gössling et al. 2021b). Increasing the proportion infrastructure that supports walking in urban areas will structurally enable reductions in car use (Section 10.2 and	Large-scale electrification of LDVs requires expansion of low-carbon power systems, while charging or battery swapping infrastructure is needed for some segments (Gnann et al. 2018; Ahmand et al. 2020)	In addition to increasing the capabilities to produce low or zero-carbon fuels for shipping and aviation, there is a need to invest in supporting infrastructure including low carbon power generation. New Hydrogen delivery and refuelling infrastructure may be needed (Maggio et al. 2019). For zero-carbon

	(Newman and Kenworthy 2015). Creating transit activated corridors of TOD-based rail or mid-tier transit using value capture for financing will create inherently less car dependence (McIntosh et al. 2017; Newman et al. 2019)		synthetic fuels, infrastructure is needed to support carbon capture and CO_2 transport to fuel production facilities (Edwards and Celia 2018).

Frequently Asked Questions (FAQs)

FAQ 10.1 -How important is electro-mobility in decarbonising transport and are there major constraints in battery minerals?

Electromobility is the biggest change in transport since AR5. When powered with low-carbon electricity, electric vehicles (EVs) provide a mechanism for major GHG emissions reductions from the largest sources in the transport sectors, including cars, motor-bikes, tuk tuks, buses and trucks. The mitigation potential of EVs depends on the decarbonization of the power system. EVs can be charged by home or business renewable power before or in parallel to the transition to grid-based low-carbon power.

Electromobility is happening rapidly in micro-mobility (e-autorickshaws, e-scooters, e-bikes) and in transit systems, especially buses. EV adoption is also accelerating for personal cars. EVs can be used in grid stabilization through smart charging applications.

The state-of-the-art Lithium-Ion Batteries (LIBs) available in 2020 are superior to alternative cell technologies in terms of battery life, energy density, specific energy, and cost. The expected further improvements in LIBs suggest these chemistries will remain superior to alternative battery technologies in the medium-term, and therefore LIBs will continue to dominate the electric vehicle market.

Dependence on LIB metals will remain, which may be a concern from the perspective of resource availability and costs. However, the demand for such metals is much lower than the reserves available, with many new mines starting up in response to the new market particularly in a diversity of places.

Recycling batteries will significantly reduce long-term resource requirements. The standardisation of battery modules and packaging within and across vehicle platforms, as well as increased focus on design for recyclability are important. Many mobility manufacturers and governments are considering battery recycling issues to ensure the process is mainstreamed.

The most significant enabling condition in electro-mobility is to provide electric recharging opportunities and a strategy to show they can be helping the grid.

FAQ 10.2 - How hard is it to decarbonise heavy vehicles in transport like long haul trucks, ships and planes?

Unlike for land transport vehicles, there are few obvious solutions to decarbonizing heavy vehicles like international ships and planes. The main focus has been increased efficiency, which so far has not prevented these large vehicles from becoming the fastest growing source of GHG globally. These vehicles likely need alternative fuels that can be fitted to the present propulsion systems. Emerging demonstrations suggest that ammonia, advanced biofuels, or synthetic fuels could become commercial.

Electric propulsion using hydrogen fuel cells or Li-ion batteries could work with short-haul aviation and shipping, but the large long-lived vessels and aircraft likely need alternative liquid fuels for most major long-distance functions.

Advanced biofuels, if sourced from resources with low GHG footprints, offer decarbonisation opportunities. As shown in Chapters 2, 6, and 12, there are multiple issues constraining traditional biofuels. Sustainable land management and feedstocks, as well as R&D efforts to improve lignocellulosic conversion routes are key to maximise the mitigation potential from advanced biofuels.

Synthetic fuels made using CO_2 captured with DAC/BECCS and low-carbon hydrogen can subsequently be refined to a net zero jet fuel or marine fuel. These fuels may also have less contrails-based climate impacts and low emissions of local air pollution. However, these fuels still require significant R&D and demonstration.

The deployment of low-carbon aviation and shipping fuels that support decarbonisation of the transport sector will likely require changes to national and international governance structures

FAQ 10.3 - How can governments, communities and individuals reduce demand and be more efficient in consuming transport energy?

Cities can reduce their transport-related fuel consumption by around 25% through combinations of more compact land use and less car dependent transport infrastructure.

More traditional programs for reducing unnecessary high-energy travel through behaviour change programs (i.e., taxes on fuel, parking, and vehicles or subsidies for alternative low-carbon modes), continue to be evaluated with mixed results due to the dominance of time savings in an individual's decision-making.

The circular economy, the shared economy, and digitalisation trends can support systemic changes that lead to reductions in demand for transport services or expands the use of more efficient transport modes

COVID-19-based lockdowns have confirmed the transformative value of telecommuting replacing significant numbers of work and personal journeys as well as promoting local active transport. These changes may not last and impacts on productivity and health are still to be fully evaluated.

Solutions for individual households and businesses involving pledges and shared communities that set new cultural means of reducing fossil fuel consumption, especially in transport, are setting out new approaches for how climate change mitigation can be achieved.

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Appendix 10.1: Data and methods for life cycle assessment

IPCC LCA Data Collection Effort

In mid-2020, the IPCC, in collaboration with the Norwegian University of Science and Technology, released a request for data from the life cycle assessment community, to estimate the life cycle greenhouse (GHG) emissions of various passenger and freight transport pathways. The data requested included information about vehicle and fuel types, vintages, vehicle efficiency, payload, emissions from vehicle and battery manufacturing, and fuel cycle emissions factors, among others.

Data submissions were received from approximately 20 research groups, referencing around 30 unique publications. These submissions were supplemented by an additional 20 studies from the literature. While much of this literature was focused on LDVs and trucks, relatively few studies referenced bus and rail pathways.

Harmonization method

First, the datapoints were separated into categories based on the approximate classification (e.g., heavy-duty vs medium-duty trucks), powertrain (i.e., ICEV, HEV, BEV, FCV), and fuel combination. For each category of vehicle/powertrain/fuel, a simplified LCA that harmonizes values from across the reviewed studies was constructed, using the following basic equation:

$$Life\ cycle\ GHG\ intensity = \frac{FC}{P} * EF + \frac{VC}{P * LVKT}$$

Where:

- Life cycle GHG intensity represents the normalized life cycle GHG emissions associated with each transportation mode, measured in g CO_2-eq/passenger-km or g CO_2-eq/tonne-km
- FC is the fuel consumption of the vehicle in MJ or kWh per km
- P represents the payload (measured in tonnes of cargo) or number of passengers, at a specified utilization capacity (e.g., 50% payload or 80% occupancy)
- EF is an emissions factor representing the life cycle GHG intensity of the fuel used, measured in g CO_2-eq/MJ or g CO_2-eq/kWh. A single representative EF value is selected for each fuel type. When a given fuel type can be generated in different ways with substantially different upstream emissions factors (e.g., H_2 from methane steam reforming vs H_2 from water electrolysis), these are treated as two different fuel categories. The fuel emissions factors that were used are presented in Table 10.8
- VC are the vehicle cycle emissions of the vehicle, measured in g CO_2-eq /vehicle. This may include vehicle manufacturing, maintenance and end-of-life, or just manufacturing.
- LVKT is the lifetime vehicle kilometres travelled

Note: for PHEVs, the value of FC/P*EF is a weighted sum of this aggregate term for each of battery and diesel/gasoline operation.

Fuel emissions factors used are presented in Table 10.8. Note that the fuel emissions factors were compiled from several studies that used different global warming potential (GWP) values in their underlying assumptions, and therefore the numbers reported here may be slightly different if GWP_{100} from the AR6 had been used. This difference would be small given the small contribution from non-CO_2 gases to the total life cycle emissions. For example, methane emissions exist in the life cycle of natural gas supply chains or natural gas dependent supply chains such as Hydrogen from SMR. Recent data from the U.S. suggests emissions of approximately 0.2-0.3 g CH_4/MJ natural gas (Littlefield et al. 2017, 2019), which would range by no more than 1-2 g CO_2-eq/MJ natural gas (<3% of natural gas life cycle emissions) when converting from a GWP_{100} of 25 (AR4) or 36 (AR5) to the current (AR6) GWP_{100} of 29.8.

For LDVs, the entire distribution of estimated life cycle emissions is presented for each vehicle/powertrain/fuel category (as a boxplot). For trucks, rail and buses, only the low and high estimates are presented (as solid bars) since the number of datapoints were not sufficient to present as a distribution. Table 10.9 presents the low and high estimates of fuel efficiency for each category. The references used are reported in the main text.

Table 10.8 Fuel emissions factors used to estimate life cycle greenhouse gas (GHG) emissions of passenger and freight transport pathways

Fuel	Emissions factor	Units	Source
Gasoline	92	g CO_2-eq MJ^{-1}	Submissions to IPCC data call (median)
Diesel	92	g CO_2-eq MJ^{-1}	Submissions to IPCC data call (median)
Diesel, high	110	g CO_2-eq MJ^{-1}	Diesel from oil sands: average of in-situ pathways (Guo et al. 2020)
Biofuels, IAM EMF33	25	g CO_2-eq MJ^{-1}	From Chapter 7
Biofuels, partial models CLC	36	g CO_2-eq MJ^{-1}	From Chapter 7
Biofuels, partial models NG	141	g CO_2-eq MJ^{-1}	From Chapter 7
Compressed natural gas	71	g CO_2-eq MJ^{-1}	Submissions to IPCC data call (median)
Liquefied natural gas	76	g CO_2-eq MJ^{-1}	Submissions to IPCC data call (median)
Liquefied petroleum gas	78	g CO_2-eq MJ^{-1}	Submissions to IPCC data call (median)
DAC FT-Diesel, wind electricity	12	g CO_2-eq MJ^{-1}	From electrolytic Hydrogen produced using low-carbon electricity (Liu et al. 2020a)
DAC FT-Diesel, natural gas electricity	370	g CO_2-eq MJ^{-1}	From electrolytic Hydrogen produced using natural gas electricity; extrapolated from (Liu et al. 2020a)
Ammonia, low carbon renewable	3.2	g CO_2-eq MJ^{-1}	From electrolytic Hydrogen produced using low-carbon electricity via Haber-Bosch (Gray et al. 2021)
Ammonia, natural gas SMR	110	g CO_2-eq MJ^{-1}	From H_2 derived from natural gas steam methane reforming; via Haber-Bosch (Frattini et al. 2016)
Hydrogen, low carbon renewable	10	g CO_2-eq MJ^{-1}	From electrolysis with low-carbon electricity (Valente et al. 2021)
Hydrogen, natural gas SMR	95	g CO_2-eq MJ^{-1}	From steam-methane reforming (SMR) of fossil fuels (Valente et al. 2021)
Wind electricity	9.3	g CO_2-eq kWh^{-1}	Submissions to IPCC data call (median)
Natural gas electricity	537	g CO_2-eq kWh^{-1}	Submissions to IPCC data call (median)
Coal electricity	965	g CO_2-eq kWh^{-1}	Submissions to IPCC data call (median)

For transit and freight, the life cycle harmonization exercise allows two aggregate parameters to vary from the low to high among submitted values within each category: FC/P and VC/P. Aggregate parameters are used to capture internal correlations (e.g., fuel consumption and payload both depend heavily on vehicle size) and are presented in Table 10.10 to Table 10.14. The references used are reported in the main text.

Table 10.9 Range of fuel efficiencies for light duty vehicles by fuel and powertrain category, per vehicle kilometre

Fuel	Powertrain	Fuel efficiency (MJ/vehicle-km)		Electric efficiency (kWh/vehicle-km)	
		Low	High	Low	High
Compression ignition	ICEV	1.34	2.6		
Spark ignition	ICEV	1.37	2.88		
Spark ignition	HEV	1.22	2.05		
Compression ignition	HEV	1.15	1.51		
Electricity	BEV			0.12	0.242
Hydrogen	FCV	1.14	1.39		

Table 10.10 Range of fuel efficiencies for buses by fuel and powertrain category, at 80% occupancy

Fuel	Powertrain	Fuel efficiency (MJ/passenger-km)		Electric efficiency (kWh/passenger-km)	
		Low	High	Low	High
Diesel	ICEV	0.16	0.52		
CNG	ICEV	0.25	0.61		
LNG	ICEV	0.27	0.37		
Biodiesel	ICEV	0.16	0.52		
DAC FT-Diesel	ICEV	0.16	0.52		
Diesel	HEV	0.11	0.37		
Electricity	BEV			0.01	0.04
Hydrogen	FCV	0.11	0.31		

Table 10.11 Range of fuel efficiencies for passenger rail by fuel and powertrain category, at 80% occupancy

Fuel	Powertrain	Fuel efficiency (MJ/passenger-km)		Electric efficiency (kWh/passenger-km)	
		Low	High	Low	High
Diesel	ICEV	0.36	0.40		
Biofuels	ICEV	0.36	0.40		

DAC FT-Diesel	ICEV	0.36	0.40		
Diesel	HEV	0.33	0.33		
Electricity	BEV			0.03	0.03
Hydrogen[a]	FCV	0.18	0.18		

[a] *Occupancy corresponds to average European occupancy rates* (IEA 2019e)

Table 10.12 Range of fuel efficiencies for heavy-duty truck by fuel and powertrain category, at 100% payload

Fuel	Powertrain	Fuel efficiency (MJ/tonne-km)		Electric efficiency (kWh/tonne-km)	
		Low	High	Low	High
Diesel	ICEV	0.38	0.93		
CNG	ICEV	0.48	1.45		
LNG	ICEV	0.43	1.00		
Biofuels	ICEV	0.38	0.93		
Ammonia[a]	ICEV	0.38	0.93		
DAC FT-Diesel	ICEV	0.38	0.93		
Diesel	HEV	0.34	0.59		
LNG	HEV	0.46	0.51		
Electricity	BEV			0.03	0.09
Hydrogen	FCV	0.25	0.43		
Ammonia[b]	FCV	0.25	0.43		

[a]*Ammonia ICEV trucks are assumed to have the same fuel economy as diesel ICEVs due to lack of data.*

[b]*Ammonia FCV trucks are assumed to have the same fuel economy as Hydrogen FCVs due to lack of data.*

Table 10.13 Range of fuel efficiencies for medium-duty truck by fuel and powertrain category, at 100% payload

Fuel	Powertrain	Fuel efficiency (MJ/tonne-km)		Electric efficiency (kWh/tonne-km)	
		Low	High	Low	High
Diesel	ICEV	0.85	2.30		
CNG	ICEV	1.08	2.54		
LNG	ICEV	1.05	1.41		
Biofuels	ICEV	0.85	2.30		
Ammonia[a]	ICEV	0.85	2.30		
DAC FT-Diesel	ICEV	0.85	2.30		
Diesel	HEV	0.81	1.54		

Electricity	BEV			0.12	0.22
Hydrogen	FCV	0.65	0.99		
Ammonia[b]	FCV	0.65	0.99		

[a]*Ammonia ICEV trucks are assumed to have the same fuel economy as diesel ICEVs due to lack of data.*

[b]*Ammonia FCV trucks are assumed to have the same fuel economy as Hydrogen FCVs due to lack of data.*

Table 10.14 Range of fuel efficiencies for freight rail by fuel and powertrain category, at an average payload

Fuel	Powertrain	Fuel efficiency (MJ/tonne-km)		Electric efficiency (kWh/tonne-km)	
		Low	High	Low	High
Diesel	ICEV	0.11	0.78		
Biodiesel	ICEV	0.11	0.78		
DAC FT-Diesel	ICEV	0.11	0.78		
Electricity	BEV			0.01	0.12
Hydrogen	FCV	0.10	0.10		

Appendix 10.2: Data and assumptions for life cycle cost analysis

Fuel cost ranges

For diesel, a range of 0.5-2.5 USD/L is used based on historic diesel costs across all OECD countries reported in the IEA Energy Prices and Taxes Statistics database (IEA 2021c) since 2010. The lower end of this range is consistent with the minimum projected value from the 2021 U.S. Annual Energy Outlook (low oil price scenario, 0.55 USD/L) (U.S. Energy Information Administration 2021). The upper end of the range encompasses both the maximum diesel price observed in the 2021 U.S. Annual Energy Outlook projections (high oil price scenario, 1.5 USD/L) (U.S. Energy Information Administration 2021), and the diesel price that would correspond to the 2020 IEA World Energy Outlook crude oil price projections (Stated Policies scenario) (IEA 2020b), assuming the historical price relationship between crude oil and diesel is maintained (1.5 USD/L). For reference, the IEA reports current world-average automotive diesel costs to be around 1 USD/L (IEA 2021d). The selected range also captures the current range of production costs for values for bio-based and synthetic diesels (51-144 Eur/MWh, corresponding to 0.6-1.70 USD/L), which are generally still higher than wholesale petroleum diesel costs (30-50 Eur/MWh corresponding to 0.35-0.6 USD/L), as reported by IEA (IEA 2020c). This range also encompasses costs for synthesized electro-fuels from electrolytic Hydrogen as reported in Chapter 6 (1.6 USD/L).

The range of electricity costs used here are consistent with the range of levelized cost of electricity estimates presented in Chapter 6 (20-200 USD/MWh).

For Hydrogen, a range of 1-13 USD/kg is used. The upper end of this range corresponds approximately to reported retail costs in the US (Burnham et al. 2021; Eudy and Post 2018b; Argonne National Laboratory 2020). Despite the high upper bound, lower costs (6-7 USD/kg) are already consistent with recent cost estimates of Hydrogen produced via electrolysis from Chapter 6 and current production cost estimates from IRENA (IRENA 2020). The lower end of the range (1 USD/kg) corresponds to projected future price decreases for electrolytic Hydrogen (BNEF 2020; Hydrogen Council 2020; IRENA 2020), and is consistent with projections from Chapter 6 for the low end of long-term future prices for fossil Hydrogen with CCS.

Vehicle efficiencies

The vehicle efficiencies used in developing the life cycle cost estimates were derived from the harmonized ranges used to develop life cycle GHG estimates and are presented in Table 10.9 to Table 10.14.

Other inputs to bus cost model

For buses, a 40-ft North American transit bus with a passenger capacity of 50, lifetime of 15 years, and an annual mileage of 72,400 km based on data in the ANL AFLEET model (Argonne National Laboratory 2020) is assumed. Maintenance costs were assumed to be 1 USD/mile for ICEV buses and 0.6 USD/mile for BEV and ICEV buses, also based on data from the AFLEET model (Argonne National Laboratory 2020). For ICEV and BEV purchase costs, data from the National Renewable Energy Laboratory (Johnson et al. 2020) is used for bounding ranges (430,000 to 500,000 USD for ICEV and 579,000 to 1,200,000 USD for BEV), which encompass the default values from AFLEET model (Argonne National Laboratory 2020). Note that wider ranges are available in the literature (e.g., as low as USD120,000 per bus in (Burnham et al. 2021) and (Harris et al. 2020)); but these are not included in the sensitivity analysis to avoid conflating disparate vehicles. For FCV buses, the upper bound of the purchase price range (1,200,000 USD) represents current costs in the U.S. (Argonne National Laboratory 2020; Eudy and Post 2020), and the lower bound represents the target future value from the U.S Department of Energy (Eudy and Post 2020).

Other inputs to rail cost model

For freight and passenger rail, powertrain and vehicle O&M costs in USD/km from the IEA Future of Rail report (IEA 2019e) (IEA Figure 2.14 for passenger rail and IEA Figure 2.15 for freight rail) are used as a proxy for non-fuel costs. The ranges span conservative and forward-looking cases. In addition, the range for BEV rail ranges encompass short and long-distance trains – corresponding to 100-200 km for passenger rail, and 400-750 km for freight rail. Note that all values exclude the base vehicle costs, but they are expected not to be significant as they are amortized over the lifetime-km travelled. For freight rail, a network that is representative of North America is assumed, with a payload of 2800 tonnes per train (IEA Figure 1.17), assumed to be utilized at 100%, with a lifetime of 10 years, and an average mileage of 120,000 km/year. For BEV freight rail, the range in powertrain costs are driven by battery costs of 250-600 USD/kWh, while for FCV freight rail, the range in powertrain costs are driven by fuel cell stack costs of 50-1000 USD/kW. For passenger rail, a network that is representative of Europe is assumed, with an average occupancy of 180 passengers per train (IEA Figure 1.14), with a lifetime of 10 years, and an average mileage of 115,000 km/year.

Other inputs to truck cost model

Capital cost ranges vary widely in the literature depending on the exact truck model, size and other assumptions. For ICEVs in this analysis, the lower bound (90,000 USD) corresponds to the 2020 estimate for China from (Moultak et al. 2017), and the upper bound (250,000 USD) corresponds to the 2030 projection for the US from the same study. These values encompass the full range reported by Argonne (Burnham et al. 2021). The lower bound BEV cost (120,000 USD) is taken from 2030 projections for China (Moultak et al. 2017) and the upper bound (780,000 USD) is taken from 2020 cost estimates in the US (class 8 sleeper cab tractor) (Burnham et al. 2021). The lower bound for FCV trucks (130,000 USD) corresponds to the 2050 estimate for class 8 sleeper cab tractors from Argonne National Laboratory and the upper bound (290,000 USD) corresponds the 2020 estimate from the same study (Burnham et al. 2021). These values span the full range reported by (Moultak et al. 2017) for the US, Europe and China from 2020-2030.

The analysis uses a truck lifetime of 10 years and annual mileage of 140,000 km based on (Burnham et al. 2021). An effective payload of 17 tonnes (80% of maximum payload of 21 tonnes) is assumed based on reported average effective payload submitted by Argonne National Laboratory in response to the IPCC LCA data collection call. A discount rate of 3% is used, based on (Burnham et al. 2021) and consistent with the social discount rate from Chapter 3. Maintenance costs are assumed to be 0.15 USD/km for ICEV trucks and 0.09 USD/km for BEV and FCV trucks, as reported in (Burnham et al. 2021).

Appendix 10.3: Line of sight for feasibility assessment

	Geophysical		
	Physical potential	**Geophysical recourses**	**Land Use**
Demand reduction and mode shift	+	+	+
Role of contexts	Adoption of Avoid Shift Improve approach along with improving fuel efficiency will have negligible physical constraints; they can be implemented across the countries.	Reduction in demand, fuel efficiency and demand management measures such as Clean Air Zones/ Parking Policy will reduce negative impact on land use and resource consumption - without any constraints in terms of available resources	Reduction in demand, increase in fuel efficiency and demand management measures will have a positive impact on land use as compared to 'without' them - no likely adverse constraints in terms of limited land use (such decline in biofuel)
Line of sight	Holguín-Veras, J., & Sánchez-Díaz, I. (2016). Freight demand management and the potential of receiver-led consolidation programs. Transportation Research Part A: Policy and Practice, 84, 109-130. Creutzig, F., Roy, J., Lamb, W. F., Azevedo, I. M., De Bruin, W. B., Dalkmann, H., ... & Hertwich, E. G. (2018). Towards demand-side solutions for mitigating climate change. Nature Climate Change, 8(4), 260. Rajé, F. (2017). Transport, demand management and social inclusion: The need for ethnic perspectives. Routledge. Dumortier, J., Carriquiry, M., & Elobeid, A. Where does all the biofuel go? Fuel efficiency gains and its effects on global agricultural production. Energy Policy, 148, 111909.		
Biofuels for land transport, aviation, and shipping	+	±	-
Role of contexts	Climate conditions are an important factor for bioenergy viability. Land availability constrains might be expected for bioenergy deployment	Land and synthetic fertilizers are examples of limited resources to deploy large-scale biofuels, however the extent of this restrictions will depend on local and context specific conditions	Implementing biofuels may require additional land use. However, it will depend on context and local specific conditions.
Line of sight	Daioglou, Vassilis, Jonathan C. Doelman, Birka Wicke, Andre Faaij, and Detlef P. van Vuuren. "Integrated assessment of biomass supply and demand in climate change mitigation scenarios." Global Environmental Change 54 (2019): 88-101. Roe, S., Streck, C., Beach, R., Busch, J., Chapman, M., Daioglou, V., Deppermann, A., Doelman, J., Emmet-Booth, J., Engelmann, J. and Fricko, O., 2021. Land-based measures to mitigate climate change: Potential and feasibility by country. Global Change Biology.		
Ammonia for shipping	+	+	±
Role of contexts	A global ammonia supply chain is already established; the primary requirement for delivering greater carbon emission reductions will be through the production of ammonia using green hydrogen or CCS.	The use of ammonia would reduce reliance of fossil fuels for shipping and is expected to reduce reliance on natural resources when produced using green hydrogen. The primary resource requirements will be the supply of renewable electricity and clean water to produce green hydrogen, from which ammonia can be produced.	No major changes in land use for the vehicle. Increases may occur if the hydrogen is produced through electrolysis and renewable energy sources or hydrogen production with CCS.
Line of sight	Bicer, Y., and I. Dincer, 2018: Clean fuel options with hydrogen for sea transportation: A life cycle approach. International Journal of Hydrogen Energy, 43, 1179–1193, https://doi.org/https://doi.org/10.1016/j.ijhydene.2017.10.157 Gilbert, P., C. Walsh, M. Traut, U. Kesieme, K. Pazouki, and A. Murphy, 2018: Assessment of full life-cycle air emissions of alternative shipping fuels. Journal of Cleaner Production, 172, 855–866, https://doi.org/10.1016/j.jclepro.2017.10.165.		

Synthetic fuels for heavy-duty land transport, aviation, and shipping (e.g., DAC-FT)	±	±	±
Role of contexts	Fischer Tropsch chemistry is well established; pilot scale direct air capture (DAC) plants are already in operation; - does not qualify as a mitigation option except in regions with very low carbon electricity	+ Gasification can use a wide range of feedstocks; DAC can be applied in wide range of locations - Limited information available on potential limits related to large input energy requirements, or water use and required sorbents for DAC	No major changes in land use for the vehicle. Potential increases in land use for electricity generation (especially solar, wind or hydropower) for CO2 capture and fuel production; likely lower land use than crop-based biofuels
Line of sight	Realmonte, G., Drouet, L., Gambhir, A. et al. An inter-model assessment of the role of direct air capture in deep mitigation pathways. Nat Commun 10, 3277 (2019). https://doi.org/10.1038/s41467-019-10842-5 Liu, C. M., N. K. Sandhu, S. T. McCoy, and J. A. Bergerson, 2020: A life cycle assessment of greenhouse gas emissions from direct air capture and Fischer-Tropsch fuel production. Sustain. Energy Fuels, https://doi.org/10.1039/c9se00479c. Ueckerdt, F., C. Bauer, A. Dirnaichner, J. Everall, R. Sacchi, and G. Luderer, 2021: Potential and risks of hydrogen-based e-fuels in climate change mitigation. Nat. Clim. Chang., https://doi.org/10.1038/s41558-021-01032-7.	Realmonte, G., Drouet, L., Gambhir, A. et al. An inter-model assessment of the role of direct air capture in deep mitigation pathways. Nat Commun 10, 3277 (2019). https://doi.org/10.1038/s41467-019-10842-5	
Electric vehicles for land transport	+	±	±
Role of contexts	Electromobility is being adopted across a range of land transport options including light-duty vehicles, trains and some heavy-duty vehicles, suggesting no physical constraints	Current dominant battery chemistry relies on minerals that may face supply constraints, including lithium, cobalt, and nickel. Regional supply/availability varies. Alternative chemistries exist; recycling may likewise alleviate critical material concerns. Similar supply constraints may exist for some renewable electricity sources (e.g., solar) required to support EVs. May reduce critical materials required for catalytic converters in ICEVs (e.g., platinum, palladium, rhodium)	No major changes in land use for the vehicle. Potential increases in land use for electricity generation (especially solar, wind or hydropower) and mineral extraction, but may be partially offset by a decrease in land use for fossil fuel production; likely lower land use than crop-based biofuels, or technologies with higher electricity use (e.g., those based electrolytic hydrogen)

Line of sight	IEA (2021), Global EV Outlook 2021, IEA, Paris https://www.iea.org/reports/global-ev-outlook-2021	Jones, B., R. J. R. Elliott, and V. Nguyen-Tien, 2020: The EV revolution: The road ahead for critical raw materials demand. Appl. Energy, 280, 115072, https://doi.org/10.1016/J.APENERGY.2020.115072., Xu, C., Q. Dai, L. Gaines, M. Hu, A. Tukker, and B. Steubing, 2020: Future material demand for automotive lithium-based batteries. Commun. Mater. 2020 11, 1, 1–10, https://doi.org/10.1038/s43246-020-00095-x. IEA, 2021: The Role of Critical Minerals in Clean Energy Transitions – Analysis. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions (Accessed October 20, 2021). Zhang, J., M. P. Everson, T. J. Wallington, I. Frank R. Field, R. Roth, and R. E. Kirchain, 2016: Assessing Economic Modulation of Future Critical Materials Use: The Case of Automotive-Related Platinum Group Metals. Environ. Sci. Technol., 50, 7687–7695, https://doi.org/10.1021/ACS.EST.5B04654 Milovanoff, A., I. D. Posen, and H. L. MacLean, 2020: Electrification of light-duty vehicle fleet alone will not meet mitigation targets. Nat. Clim. Chang., https://doi.org/10.1038/s41558-020-00921-7.	Arent et al, Implications of high renewable electricity penetration in the U.S. for water use, greenhouse gas emissions, land-use, and materials supply. Applied Energy. 2014, 123: 368-377 https://doi.org/10.1016/j.apenergy.2013.12.022 Orsi, F., 2021: On the sustainability of electric vehicles: What about their impacts on land use? Sustain. Cities Soc., 66, 102680, https://doi.org/10.1016/J.SCS.2020.102680.
Hydrogen FCV for land transport	+	±	±
Role of contexts	The use of fuel cells in the transport sector is growing, and will potentially be important in heavy-duty land transport applications	FCVs are reliant on critical minerals for manufacturing fuel cells, electric motors and supporting batteries. Platinum is the primary potential resource constraint for fuel cells; however, its use may decrease as the technology develops, and platinum is highly recyclable.	
Line of sight	Global EV Outlook 2020 https://www.iea.org/reports/global-ev-outlook-2020	Hao, H., and Coauthors, 2019: Securing Platinum-Group Metals for Transport Low-Carbon Transition. One Earth, https://doi.org/10.1016/j.oneear.2019.08.012. Rasmussen, K. D., H. Wenzel, C. Bangs, E. Petavratzi, and G. Liu, 2019: Platinum Demand and Potential Bottlenecks in the Global Green Transition: A Dynamic Material Flow Analysis. Environmental Science & Technology, https://doi.org/10.1021/ACS.EST.9B01912.	Orsi, F., 2021: On the sustainability of electric vehicles: What about their impacts on land use? Sustainable Cities and Society, 66, 102680, https://doi.org/10.1016/J.SCS.2020.102680.

	Evoronmental-ecological			
	Air pollution	Toxic waste, ecotoxicity eutrophication	Water quantity and quality	Biodiversity
Demand reduction and mode shift	+	0	0	0
Role of contexts	Reduction in demand, increase in fuel efficiency and demand management measures will improve Air Quality			Reduction in demand, fuel efficiency and demand management measures such as Clean Air Zones/ Parking Policy will reduce road supply and protect the biodiversity
Line of sight	Creutzig, F., Roy, J., Lamb, W. F., Azevedo, I. M., De Bruin, W. B., Dalkmann, H., ... & Hertwich, E. G. (2018). Towards demand-side solutions for mitigating climate change. Nature Climate Change, 8(4), 260. Dumortier, J., Carriquiry, M., & Elobeid, A. Where does all the biofuel go? Fuel efficiency gains and its effects on global agricultural production. Energy Policy, 148, 111909. Ambarwati, L., Verhaeghe, R., van Arem, B., & Pel, A. J. (2016). The influence of integrated space–transport development strategies on air pollution in urban areas. Transportation Research Part D: Transport and Environment, 44, 134-146. Clean Air Zone Framework. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/863730/clean-air-zone-framework-feb2020.pdf			
Biofuels for land transport, aviation, and shipping	±	±	-	-
Role of contexts	Biofuels may improve air quality due reduction in the emission of some pollutants, such as SOx and particulate matter, in relation to fossil fuels. Evidence is mixed for other pollutants such as NOx. The biofuels supply chain (e.g., due to increased fertilizer use) may negatively impact air quality.	Increased use of fertilizers and agrochemicals due the biofuel production may increase impacts in ecotoxicity and eutrophication; some biofuels may be less toxic than fossil fuel counterparts	Increasing production of biofuels may increase pressure in water resources due to the need of irrigation. However, some biofuel options may also improve these aspects in respect to conventional agriculture. These impacts will depend on specific local conditions.	Additional land use for biofuels may increase pressure on biodiversity. However, biofuel can also increase biodiversity depending on the previous land use. These impacts will depend on specific local conditions and previous land uses.
Line of sight	Robertson et al., Science 356, 1349 (2017); Humpenöder, Florian, Alexander Popp, Benjamin Leon Bodirsky, Isabelle Weindl, Anne Biewald, Hermann Lotze-Campen, Jan Philipp Dietrich, David Klein, Ulrich Kreidenweis, and Christoph Müller. 2018. “Large-Scale Bioenergy Production: How to Resolve Sustainability Trade-Offs?” Environmental Research Letters 13 (2): 24011. Ai, Zhipin, Naota Hanasaki, Vera Heck, Tomoko Hasegawa, and Shinichiro Fujimori. "Global bioenergy with carbon capture and storage potential is largely constrained by sustainable irrigation." Nature Sustainability (2021): 1-8.			
Ammonia for shipping	±	-	±	LE

Role of contexts	If produced from green hydrogen or coupled with CCS, ammonia could reduce short lived climate forcers and particulate matter precursors including black carbon and SO2. However, the combustion of ammonia could lead to elevated levels of nitrogen oxides and ammonia emissions	Ammonia is highly toxic, and therefore requires special handling procedures to avoid potential catastrophic leaks into the environment. That said, large volumes of ammonia are already safely transported internationally due to a high level of understanding of safe handling procedures. Additionally, the use of ammonia in shipping presents an additional risk to eutrophication and ecotoxicity from the release of ammonia in the water system - either via a fuel leak, or via unburnt ammonia emissions.	May increase or decrease water footprint depending on the upstream energy source	Lack of studies assessing the potential impacts of the technology on biodiversity.
Line of sight	Bicer, Y., and I. Dincer, 2018: Clean fuel options with hydrogen for sea transportation: A life cycle approach. International Journal of Hydrogen Energy, 43, 1179–1193, https://doi.org/https://doi.org/10.1016/j.ijhydene.2017.10.157 Gilbert, P., C. Walsh, M. Traut, U. Kesieme, K. Pazouki, and A. Murphy, 2018: Assessment of full life-cycle air emissions of alternative shipping fuels. Journal of Cleaner Production, 172, 855–866, https://doi.org/10.1016/j.jclepro.2017.10.165; DNV GL, 2019: Maritime Forecast To 2050. 118 pp. https://eto.dnvgl.com/2019. ——, 2020: Ammonia as a marine fuel. 1–28.			
Synthetic fuels for heavy-duty land transport, aviation, and shipping (e.g., DAC-FT)	+	NE	±	LE
Role of contexts	Potential reductions in air pollutants related to reduced presence of sulphur, metals, and other contaminants; improvements likely smaller than for electric vehicles or hydrogen fuel cell vehicles		DAC requires significant amounts of water, which may be a limitation in water stressed areas; typically uses less water than crop-based biofuels	Potential biodiversity issues related to electricity generation; however fossil fuel supply chains also adversely impact biodiversity; net effect is unknown
Line of sight	Beyersdorf, A. J., and Coauthors, 2014: Reductions in aircraft particulate emissions due to the use of Fischer-Tropsch fuels. Atmos. Chem. Phys., https://doi.org/10.5194/acp-14-11-2014; Lobo, P., D. E. Hagen, and P. D. Whitefield, 2011: Comparison of PM emissions from a commercial jet engine burning conventional, biomass, and fischer-tropsch fuels. Environ. Sci. Technol., https://doi.org/10.1021/es201902e; Gill, S. S., A. Tsolakis, K. D. Dearn, and J. Rodríguez-Fernández, 2011: Combustion characteristics and emissions of Fischer-Tropsch diesel fuels in IC engines. Prog. Energy Combust. Sci., https://doi.org/10.1016/j.pecs.2010.09.001		Realmonte, G., Drouet, L., Gambhir, A. et al. An inter-model assessment of the role of direct air capture in deep mitigation pathways. Nat Commun 10, 3277 (2019). https://doi.org/10.1038/s41467-019-10842-5 Byers, E. A., J. W. Hall, J. M. Amezaga, G. M. O'Donnell, and A. Leathard, 2016: Water and climate risks to power generation with carbon capture and storage. Environ. Res. Lett., https://doi.org/10.1088/1748-9326/11/2/024011.	
Electric vehicles for land transport	+	-	±	LE

Role of contexts	Elimination of tailpipe emissions. If powered by nuclear or renewables, large overall improvements in air pollution. Even if powered partially by fossil fuel electricity, tailpipe emissions tend to occur closer to population and thus typically have larger impact on human health than powerplant emissions; negative air quality impacts may occur, but only in fossil fuel heavy grids	Some toxic waste associated with mining and processing of metals for battery and some renewable electricity supply chains (production and disposal)	May increase or decrease water footprint depending on the upstream electricity source	Potential biodiversity issues related to electricity generation; however fossil fuel supply chains also adversely impact biodiversity; net effect is unknown
Line of sight	Requia, W. J., M. Mohamed, C. D. Higgins, A. Arain, and M. Ferguson, 2018: How clean are electric vehicles? Evidence-based review of the effects of electric mobility on air pollutants, greenhouse gas emissions and human health. Atmos. Environ., 185, 64–77, https://doi.org/10.1016/J.ATMOSENV.2018.04.040 Horton, D. E., J. L. Schnell, D. R. Peters, D. C. Wong, X. Lu, H. Gao, H. Zhang, and P. L. Kinney, 2021: Effect of adoption of electric vehicles on public health and air pollution in China: a modelling study. Lancet Planet. Heal., https://doi.org/10.1016/s2542-5196(21)00092-9; Gai, Y., L. Minet, I. D. Posen, A. Smargiassi, L. F. Tétreault, and M. Hatzopoulou, 2020: Health and climate benefits of Electric Vehicle Deployment in the Greater Toronto and Hamilton Area. Environ. Pollut., https://doi.org/10.1016/j.envpol.2020.114983; Choma, E. F., J. S. Evans, J. K. Hammitt, J. A. Gómez-Ibáñez, and J. D. Spengler, 2020: Assessing the health impacts of electric vehicles through air pollution in the United States. Environ. Int., https://doi.org/10.1016/j.envint.2020.106015; Schnell, J. L., V. Naik, L. W. Horowitz, F. Paulot, P. Ginoux, M. Zhao, and D. E. Horton, 2019: Air quality impacts from the electrification of light-duty passenger vehicles in the United States. Atmos. Environ., https://doi.org/10.1016/j.atmosenv.2019.04.003; Air quality impacts from light-duty transportation Christopher W. Tessum, Jason D. Hill, Julian D. Marshall Proceedings of the National Academy of Sciences Dec 2014, 111 (52) 18490-18495; DOI: 10.1073/pnas.1406853111	Lattanzio, R. K., and C. E. Clark, 2020: Environmental Effects of Battery Electric and Internal Combustion Engine Vehicles. Congr. Res. Serv.; Puig-Samper Naranjo, G., D. Bolonio, M. F. Ortega, and M. J. García-Martínez, 2021: Comparative life cycle assessment of conventional, electric and hybrid passenger vehicles in Spain. J. Clean. Prod., https://doi.org/10.1016/j.jclepro.2021.125883; Bicer, Y., and I. Dincer, 2017: Comparative life cycle assessment of hydrogen, methanol and electric vehicles from well to wheel. Int. J. Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2016.07.252; Hawkins, T. R., B. Singh, G. Majeau-Bettez, and A. H. Strømman, 2013: Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. J. Ind. Ecol., https://doi.org/10.1111/j.1530-9290.2012.00532.x.	Onat, N. C., M. Kucukvar, and O. Tatari, 2018: Well-to-wheel water footprints of conventional versus electric vehicles in the United States: A state-based comparative analysis. J. Clean. Prod., https://doi.org/10.1016/j.jclepro.2018.09.010; Kim, H. C., T. J. Wallington, S. A. Mueller, B. Bras, T. Guldberg, and F. Tejada, 2016: Life Cycle Water Use of Ford Focus Gasoline and Ford Focus Electric Vehicles. J. Ind. Ecol., https://doi.org/10.1111/jiec.12329; Wang, L., W. Shen, H. C. Kim, T. J. Wallington, Q. Zhang, and W. Han, 2020: Life cycle water use of gasoline and electric light-duty vehicles in China. Resour. Conserv. Recycl., https://doi.org/10.1016/j.resconrec.2019.104628	

Hydrogen FCV for land transport	+	±	±	LE
Role of contexts	Fuel cells' only tailpipe emission is water vapour. However, blue hydrogen production pathways may generate air pollutants nearby the production sites. Overall, FCV would reduce emissions of criteria air pollutants.	Mining of Platinum Group Metals may generate additional stress on the environment, compared to conventional technologies. Furthermore, the recycling of fuel cell stacks can generate additional impacts.	May increase or decrease water footprint depending on the upstream energy source	Lack of studies assessing the potential impacts of the technology on biodiversity.
Line of sight	Wang, Q., M. Xue, B. Le Lin, Z. Lei, and Z. Zhang, 2020: Well-to-wheel analysis of energy consumption, greenhouse gas and air pollutants emissions of hydrogen fuel cell vehicle in China. Journal of Cleaner Production, https://doi.org/10.1016/j.jclepro.2020.123061.	Velandia Vargas, J. E., and J. E. A. Seabra, 2021: Fuel-cell technologies for private vehicles in Brazil: Environmental mirage or prospective romance? A comparative life cycle assessment of PEMFC and SOFC light-duty vehicles. Science of the Total Environment, 798, 149265, https://doi.org/10.1016/j.scitotenv.2021.149265. Bohnes, F. A., J. S. Gregg, and A. Laurent, 2017: Environmental Impacts of Future Urban Deployment of Electric Vehicles: Assessment Framework and Case Study of Copenhagen for 2016-2030. Environmental Science and Technology, 51, 13995–14005, https://doi.org/10.1021/acs.est.7b01780.		

	Technological		
	Simplicity	Technological scalability	Maturity and technology readiness
Demand reduction and mode shift	+	+	+
Role of contexts	Application of Demand and Fuel efficiency measures can be scaled and developing countries can leapfrog to most advanced technology. India skipped Euro V, and implemented Euro VI from IV, but this shift will require investment in the short-term	Technology to deliver Demand and Fuel efficiency is readily available	Significant economic benefit in short and long term
Line of sight	Vashist, D., Kumar, N., & Bindra, M. (2017). Technical Challenges in Shifting from BS IV to BS-VI Automotive Emissions Norms by 2020 in India: A Review. Archives of Current Research International, 1-8; Clean Air Zone Framework. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/863730/clean-air-zone-framework-feb2020.pdf		
Biofuels for land transport, aviation, and shipping	±	±	+
Role of contexts	Typically based on internal combustion engines, similar to fossil fuels, however, may require engine recalibration	Biofuels are scalable up to and may benefit from economies of scale; potential for scale up of sustainable crop production may be limited	There are many biofuels technologies that are already at commercial scale, while some technologies for advanced biofuels are still under development.

Line of sight	Mawhood, Rebecca, Evangelos Gazis, Sierk de Jong, Ric Hoefnagels, and Raphael Slade. 2016. "Production Pathways for Renewable Jet Fuel: A Review of Commercialization Status and Future Prospects." *Biofuels, Bioproducts and Biorefining* 10 (4): 462–84. Puricelli, Stefano, Giuseppe Cardellini, S. Casadei, D. Faedo, A. E. M. Van den Oever, and M. Grosso. "A review on biofuels for light-duty vehicles in Europe." Renewable and Sustainable Energy Reviews (2020): 110398.		
Ammonia for shipping	-	±	±
Role of contexts	Requires either new engines or retrofits for existing engines. It is likely some ammonia will need to be mixed with a secondary fuel due its relatively low burning velocity and high ignition temperature. This would likely require existing powertrains to be modified to accept dual fuel mixes, including ammonia. Exhaust treatment systems are also required to deal with the release of unburnt ammonia emissions.	Ammonia supply chains are well established; transport and storage more feasible than hydrogen; scalability of electrolytic production routes remain a challenge for producing low GHG ammonia	The production, transport and storage of ammonia is mature based on existing international supply chains. The use of ammonia in ships is still the early stages of research and development. Further research and development will be required for ammonia to be widely used in shipping, including improving the efficiency of combustion, and treatment of exhaust emissions. Ammonia could also potentially be used in fuel cell powertrains in the future, but the development of this technology is even less mature at present.
Line of sight	Frigo, S., Gentili, R., and De Angelis, F., "Further Insight into the Possibility to Fuel a SI Engine with Ammonia plus Hydrogen," SAE Technical Paper 2014-32-0082, 2014, https://doi.org/10.4271/2014-32-0082. Dimitriou, Pavlos & Javaid, Rahat. (2020). A review of ammonia as a compression ignition engine fuel. International Journal of Hydrogen Energy. 45. 10.1016/j.ijhydene.2019.12.209; Man ES, 2019. "Engineering the future two-stroke green-ammonia engine". Available at: https://www.ammoniaenergy.org/wp-content/uploads/2020/01/engineeringthefuturetwostrokegreenammoniaengine1589339239488-1.pdf		
Synthetic fuels for heavy-duty land transport, aviation, and shipping (e.g., DAC-FT)	+	-	-
Role of contexts	Can produce drop-in fuels, which use existing engine technologies	Rate at which DAC or other carbon capture can be scaled-up is likely a limiting factor; large energy inputs (requiring substantial new low carbon energy resources), and sorbent requirements likely to be a challenge	Some processes (e.g., Fischer Tropsch) are well established, but DAC and BECCS are stlil at demonstration stage
Line of sight	Sutter, D., M. van der Spek, and M. Mazzotti, 2019: 110th Anniversary: Evaluation of CO2-Based and CO2-Free Synthetic Fuel Systems Using a Net Zero-CO2-Emission Framework. Ind. Eng. Chem. Res., 58, 19958–19972, https://doi.org/10.1021/acs.iecr.9b00880., The Royal Society, 2019, Sustainable synthetic carbon-based fuels for transport: Policy briefing	The Royal Society, 2019, Sustainable synthetic carbon based fuels for transport: Policy briefing; Realmonte, G., Drouet, L., Gambhir, A. et al. An inter-model assessment of the role of direct air capture in deep mitigation pathways. Nat Commun 10, 3277 (2019). https://doi.org/10.1038/s41467-019-10842-5	Liu, C. M., N. K. Sandhu, S. T. McCoy, and J. A. Bergerson, 2020: A life cycle assessment of greenhouse gas emissions from direct air capture and Fischer-Tropsch fuel production. Sustain. Energy Fuels, 4, 3129–3142, https://doi.org/10.1039/c9se00479c.
Electric vehicles for land transport	±	±	±

Role of contexts	Fewer engine components; lower maintenance requirements than conventional vehicles; potential concerns surrounding battery size/weight, charging time, and battery life	Widespread application already feasible; some limits to adoption in remote communities or long-haul freight; at large scale, may positively or negatively impact electric grid functioning depending on charging behaviour and grid integration strategy	+ Technology is mature for light duty vehicles; - Improvements in battery capacity and density as well as charging speed required for heavy duty applications
Line of sight	Burnham, A., et al, 2021: Comprehensive total cost of ownership quantification for vehicles with different size classes and powertrains., Argonne National Laboratory	IEA (2021), Global EV Outlook 2021, IEA, Paris https://www.iea.org/reports/global-ev-outlook-2021, Milovanoff, A., I. D. Posen, and H. L. MacLean, 2020: Electrification of light-duty vehicle fleet alone will not meet mitigation targets. Nat. Clim. Chang., https://doi.org/10.1038/s41558-020-00921-7., Constance Crozier, Thomas Morstyn, Malcolm McCulloch, The opportunity for smart charging to mitigate the impact of electric vehicles on transmission and distribution systems, Applied Energy, Volume 268, 2020, 114973, ISSN 0306-2619; Kapustin, N. O., and D. A. Grushevenko, 2020: Long-term electric vehicles outlook and their potential impact on electric grid. Energy Policy, https://doi.org/10.1016/j.enpol.2019.111103; Das, H. S., M. M. Rahman, S. Li, and C. W. Tan, 2020: Electric vehicles standards, charging infrastructure, and impact on grid integration: A technological review. Renew. Sustain. Energy Rev., https://doi.org/10.1016/j.rser.2019.109618; Liimatainen, H., O. van Vliet, and D. Aplyn, 2019: The potential of electric trucks – An international commodity-level analysis. Appl. Energy, https://doi.org/10.1016/j.apenergy.2018.12.017; Forrest, K., M. Mac Kinnon, B. Tarroja, and S. Samuelsen, 2020: Estimating the technical feasibility of fuel cell and battery electric vehicles for the medium and heavy duty sectors in California. Appl. Energy, https://doi.org/10.1016/j.apenergy.2020.115439	IEA (2021), Global EV Outlook 2021, IEA, Paris https://www.iea.org/reports/global-ev-outlook-2021; Smith, D., and Coauthors, 2019: Medium-and Heavy-Duty Vehicle Electrification: An Assessment of Technology and Knowledge Gaps. Oak Ridge Natl. Lab. Natl. Renew. Energy Lab.; Forrest, K., M. Mac Kinnon, B. Tarroja, and S. Samuelsen, 2020: Estimating the technical feasibility of fuel cell and battery electric vehicles for the medium and heavy duty sectors in California. Appl. Energy, https://doi.org/10.1016/j.apenergy.2020.115439.
Hydrogen FCV for land transport	±	-	-

Role of contexts	Lower maintenance requirements compared to conventional technologies; potential issues with on-vehicle hydrogen storage, fuel cell degradation and lifetime; fewer weight and refuelling time barriers compared to electric vehicles	Currently the refuelling infrastructure is limited, but it is growing at the pace of the technology deployment. Challenges exist with transport and distribution of hydrogen. Electrolytic hydrogen not currently produced at scale.	The technology is already available to users for light duty vehicle applications and buses, but further improvements in fuel cell technology are needed. Use in heavy duty applications is currently constrained. Maturity and technology readiness level can vary for different parts of the supply chain, and is lower than for EVs
Line of sight	Trencher, G., A. Taeihagh, and M. Yarime, 2020: Overcoming barriers to developing and diffusing fuel-cell vehicles: Governance strategies and experiences in Japan. Energy Policy, 142, 111533 https://doi.org/10.1016/j.enpol.2020.111533.	Pollet, B. G., S. S. Kocha, and I. Staffell, 2019: Current status of automotive fuel cells for sustainable transport. Current Opinion in Electrochemistry, 16, 90–95, https://doi.org/10.1016/j.coelec.2019.04.021.	Wang, J., H. Wang, and Y. Fan, 2018: Techno-Economic Challenges of Fuel Cell Commercialization. Engineering, 4, 352–360, https://doi.org/10.1016/j.eng.2018.05.007. Kampker, A., P. Ayvaz, C. Schön, J. Karstedt, R. Förstmann, and F. Welker, 2020: Challenges towards large-scale fuel cell production: Results of an expert assessment study. International Journal of Hydrogen Energy, 45, 29288–29296, https://doi.org/10.1016/j.ijhydene.2020.07.180.

	4. Economic	
	Costs in 2030 and long term	Employment effects and economic growth
Demand reduction and mode shift	+	LE
Role of contexts	Significant economic benefit in short and long term	
Line of sight	Creutzig, F., Roy, J., Lamb, W. F., Azevedo, I. M., De Bruin, W. B., Dalkmann, H., ... & Hertwich, E. G. (2018). Towards demand-side solutions for mitigating climate change. Nature Climate Change, 8(4), 260.; The UK, The Green Book (2020; https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-governent/the-green-book-2020)	
Biofuels for land transport, aviation, and shipping	±	LE
Role of contexts	Some biofuels are already cost competitive with fossil fuels. In the future, reduction of costs for advanced biofuels may be a challenge	Biofuels are expected to increase job creation in comparison to fossil fuel alternatives. This is still to be further demonstrated.

Line of sight	Daioglou, V., Rose, S.K., Bauer, N., Kitous, A., Muratori, M., Sano, F., Fujimori, S., Gidden, M.J., Kato, E., Keramidas, K. and Klein, D., 2020. Bioenergy technologies in long-run climate change mitigation: results from the EMF-33 study. Climatic Change, 163(3), pp.1603-1620. Brown, A., Waldheim, L., Landälv, I., Saddler, J., Ebadian, M., McMillan, J.D., Bonomi, A. and Klein, B., 2020. Advanced Biofuels—Potential for Cost Reduction. IEA Bioenergy, 88.	
Ammonia for shipping	-	NE
Role of contexts	Green ammonia is likely to be significantly more expensive than conventional fuels for the coming decades.	
Line of sight	Energy Transitions Commission, 2021. Making the hydrogen economy possible. Available at: https://energy-transitions.org/wp-content/uploads/2021/04/ETC-Global-Hydrogen-Report.pdf; Energy Transitions Commission, 2020. The First Wave: A blueprint for commercial-scale zero-emission shipping pilots. Available at: https://www.energy-transitions.org/wp-content/uploads/2020/11/The-first-wave.pdf	
Synthetic fuels for heavy-duty land transport, aviation, and shipping (e.g., DAC-FT)	-	NE
Role of contexts	Large uncertainty on future costs but expected to remain higher than conventional fuels for the coming decades	-
Line of sight	Ueckerdt, F., C. Bauer, A. Dirnaichner, J. Everall, R. Sacchi, and G. Luderer, 2021: Potential and risks of hydrogen-based e-fuels in climate change mitigation. Nat. Clim. Chang., https://doi.org/10.1038/s41558-021-01032-7., Zang, G., P. Sun, E. Yoo, A. Elgowainy, A. Bafana, U. Lee, M. Wang, and S. Supekar, 2021: Synthetic Methanol/Fischer–Tropsch Fuel Production Capacity, Cost, and Carbon Intensity Utilizing CO2 from Industrial and Power Plants in the United States. Environ. Sci. Technol., 55, 7595–7604, https://doi.org/10.1021/acs.est.0c08674., Scheelhaase, J., S. Maertens, and W. Grimme, 2019: Synthetic fuels in aviation - Current barriers and potential political measures. Transportation Research Procedia.	
Electric vehicles for land transport	+	LE
Role of contexts	Life cycle costs for electric vehicles are anticipated to be lower than conventional vehicles by 2030; high confidence for light duty vehicles; lower confidence for heavy duty applications	Some grey studies exist on employment effects of electric vehicles; however, the peer-reviewed literature is not well developed
Line of sight	IEA (2021), Global EV Outlook 2021, IEA, Paris https://www.iea.org/reports/global-ev-outlook-2021, Liimatainen, H., O. van Vliet, and D. Aplyn, 2019: The potential of electric trucks – An international commodity-	

	level analysis. Appl. Energy, https://doi.org/10.1016/j.apenergy.2018.12.017 Kapustin, N. O., and D. A. Grushevenko, 2020: Long-term electric vehicles outlook and their potential impact on electric grid. Energy Policy, https://doi.org/10.1016/j.enpol.2019.111103; Forrest, K., M. Mac Kinnon, B. Tarroja, and S. Samuelsen, 2020: Estimating the technical feasibility of fuel cell and battery electric vehicles for the medium and heavy duty sectors in California. Appl. Energy, https://doi.org/10.1016/j.apenergy.2020.115439	
Hydrogen FCV for land transport	+	LE
Role of contexts	Life cycle costs for hydrogen fuel cell vehicles projected to be competitive with conventional vehicles in future, however high uncertainty remains.	Some studies exist on employment effects of hydrogen economy; however, the literature is not well developed and does not apply directly to FCVs.
Line of sight	Miotti, M., J. Hofer, and C. Bauer, 2017: Integrated environmental and economic assessment of current and future fuel cell vehicles. International Journal of Life Cycle Assessment, 22, 94–110, https://doi.org/10.1007/s11367-015-0986-4. Ruffini, E., and M. Wei, 2018: Future costs of fuel cell electric vehicles in California using a learning rate approach. Energy, 150, 329–341, https://doi.org/10.1016/j.energy.2018.02.071. Olabi, A. G., T. Wilberforce, and M. A. Abdelkareem, 2021: Fuel cell application in the automotive industry and future perspective. Energy, 214, https://doi.org/10.1016/j.energy.2020.118955.	

	Socio-cultural		
	Public acceptance	Effects on health & wellbeing	Distributional effects
Demand reduction and mode shift	±	+	±

Role of contexts	Public support for some measures such as emission charging schemes can be mixed initially, it is likely to again acceptance as benefits are realised and/or focused. Such as recent COVID-19 road network changes in London	Significant economic health and wellbeing benefits	Some measures such as travel restriction, emission charging schemes and others can have mixed distributional effects initially (e.g. accessibility)
Line of sight	Winter, A. K., & Le, H. (2020). Mediating an invisible policy problem: Nottingham's rejection of congestion charging. Local Environment, 1-9.. TfL (2020) London Streetspace changes. content.tfl.gov.uk/doctors-and-health-professionals-support-london-streetspace-changes.pdf. Creutzig, F., Roy, J., Lamb, W. F., Azevedo, I. M., De Bruin, W. B., Dalkmann, H., ... & Hertwich, E. G. (2018). Towards demand-side solutions for mitigating climate change. Nature Climate Change, 8(4), 260.; Clean Air Zone Framework. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/863730/clean-air-zone-framework-feb2020.pdf; Adhikari, M., L. P. Ghimire, Y. Kim, P. Aryal, and S. B. Khadka, 2020: Identification and analysis of barriers against electric vehicle use. Sustain., https://doi.org/10.3390/SU12124850.		
Biofuels for land transport, aviation, and shipping	±	LE	±
Role of contexts	Varied public acceptance of biofuel options is observed in different regions of the world	No known impacts	Food secutiry but agricultural economies
Line of sight	Løkke, S., Aramendia, E. and Malskær, J., 2021. A review of public opinion on liquid biofuels in the EU: Current knowledge and future challenges. *Biomass and Bioenergy*, *150*, p.106094. Taufik, D. and Dagevos, H., 2021. Driving public acceptance (instead of skepticism) of technologies enabling bioenergy production: A corporate social responsibility perspective. Journal of Cleaner Production, p.129273.		
Ammonia for shipping	LE	LE	LE
Role of contexts	Some concerns in industry regarding handling of hazardous fuel; limited evidence overall		
Line of sight	N/A		
Synthetic fuels for heavy-duty land transport, aviation, and shipping (e.g., DAC-FT)	LE	LE	NE
Role of contexts	Currently low public awareness of the technology and little evidence regarding associated perceptions	No known impacts	
Line of sight	N.A.		
Electric vehicles for land transport	±	±	±

Role of contexts	Growing public acceptance, especially in some jurisdictions (e.g., majority of light duty vehicle sales in Norway are electric), but wide differences across regions; range anxiety remains a barrier among some groups	No major impacts; some potential for reduced noise, which can improve wellbeing of city residents but may adversely affect pedestrian safety	Higher vehicle purchase price and access to off-road parking limits access to some disadvantaged groups; potentially insufficient infrastructure for adoption in rural communities (initially); air quality improvements may disproportionately benefit disadvantaged groups, but may also shift some impacts onto communities in close proximity to electricity generators
Line of sight	Coffman, M., P. Bernstein, and S. Wee, 2017: Electric vehicles revisited: a review of factors that affect adoption. Transp. Rev., https://doi.org/10.1080/01441647.2016.1217282, Burkert, A.; Fechtner, H.; Schmuelling, B. Interdisciplinary Analysis of Social Acceptance Regarding Electric Vehicles with a Focus on Charging Infrastructure and Driving Range in Germany. World Electr. Veh. J. 2021, 12, 25; Wang, N., L. Tang, and H. Pan, 2018: Analysis of public acceptance of electric vehicles: An empirical study in Shanghai. Technol. Forecast. Soc. Change, https://doi.org/10.1016/j.techfore.2017.09.011	Campello-Vicente, H., R. Peral-Orts, N. Campillo-Davo, and E. Velasco-Sanchez, 2017: The effect of electric vehicles on urban noise maps. Appl. Acoust., https://doi.org/10.1016/j.apacoust.2016.09.018	Canepa, K., S. Hardman, and G. Tal, 2019: An early look at plug-in electric vehicle adoption in disadvantaged communities in California. Transp. Policy, https://doi.org/10.1016/j.tranpol.2019.03.009., Brown, M. A., A. Soni, M. V Lapsa, K. Southworth, and M. Cox, 2020: High energy burden and low-income energy affordability: conclusions from a literature review. Progress in Energy, 2, 042003, https://doi.org/10.1088/2516-1083/abb954.
Hydrogen FCV for land transport	±	±	±
Role of contexts	Public acceptance is growing in countries where the technology is being promoted and subsidized. However, sparse infrastructure, high costs and perceived safety concerns are currently barriers to a widespread deployment of the technology	No major impacts: some potential for reduced noise, which can improve wellbeing of city residents but may adversely affect pedestrian safety	Higher vehicle purchase price limits access to some disadvantaged groups; potentially insufficient infrastructure for adoption in rural communities (initially); air quality improvements may disproportionately benefit disadvantaged groups
Line of sight	Itaoka, K., A. Saito, and K. Sasaki, 2017: Public perception on hydrogen infrastructure in Japan: Influence of rollout of commercial fuel cell vehicles. International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2016.10.123. Canepa, K., S. Hardman, and G. Tal, 2019: An early look at plug-in electric vehicle adoption in disadvantaged communities in California. Transp. Policy, https://doi.org/10.1016/j.tranpol.2019.03.009., Brown, M. A., A. Soni, M. V Lapsa, K. Southworth, and M. Cox, 2020: High energy burden and low-income energy affordability: conclusions from a literature review. Progress in Energy, 2, 042003, https://doi.org/10.1088/2516-1083/abb954. Trencher, G., 2020: Strategies to accelerate the production and diffusion of fuel cell electric vehicles: Experiences from California. Energy Reports, https://doi.org/10.1016/j.egyr.2020.09.008.		

	Institutional		
	Political acceptance	Institutional capacity & governance, cross-sectoral coordination	Legal and administrative feasibility
Demand reduction and mode shift	±	±	±
Role of contexts	Public support for some measures such as emission charging schemes can be mixed initially, it is likely to again acceptance as benefits are realised and/or focused. Such as recent COVID-19 road network changes in London	Some local authorities have limited capacity to deliver demand management measures as compared to other developed authorities. However, this can be mitigated to optioneering processes to selected the preferred measures in the local context	Legal Air Quality limits is forcing cities and countries to implement travel demand and fuel efficiency measures such in the UK and Europe. However, there be legal and administrative changes in delivery of measures.
Line of sight	Winter, A. K., & Le, H. (2020). Mediating an invisible policy problem: Nottingham's rejection of congestion charging. Local Environment, 1-9. TfL (2020) London Streetspace changes. content.tfl.gov.uk/doctors-and-health-professionals-support-london-streetspace-changes.pdf Creutzig, F., Roy, J., Lamb, W. F., Azevedo, I. M., De Bruin, W. B., Dalkmann, H., ... & Hertwich, E. G. (2018). Towards demand-side solutions for mitigating climate change. Nature Climate Change, 8(4), 260.; Clean Air Zone Framework. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/863730/clean-air-zone-framework-feb2020.pdf		
Biofuels for land transport, aviation, and shipping	±	±	±
Role of contexts	Varied political support for biofuel deployment in different regions of the world	There is varied institutional capacity to coordinate biofuel deployment in the different regions of the world	There is different legal contexts and barriers for biofuel implementation on the different regions of the world
Line of sight	Lynd, L.R., 2017. The grand challenge of cellulosic biofuels. Nature biotechnology, 35(10), pp.912-915.Markel, E., Sims, C. and English, B.C., 2018. Policy uncertainty and the optimal investment decisions of second-generation biofuel producers. Energy Economics, 76, pp.89-100.		
Ammonia for shipping	±	-	-
Role of contexts	Varied political support for deployment in different regions of the world	The major contributor to marine emissions is international shipping which falls under the jurisdiction of the IMO. Coordination with international governments will be required.	Potential challenges related to emission regulations
Line of sight	Hoegh-Guldberg, O., and Coauthors, 2019: The Ocean as a Solution to Climate Change: Five Opportunities for Action. 116; Energy Transitions Commission, 2021. Making the hydrogen economy possible. Available at: https://energy-transitions.org/wp-content/uploads/2021/04/ETC-Global-Hydrogen-Report.pdf;		

	Energy Transitions Commission, 2020. The First Wave: A blueprint for commercial-scale zero-emission shipping pilots. Available at: https://www.energy-transitions.org/wp-content/uploads/2020/11/The-first-wave.pdf		
Synthetic fuels for heavy-duty land transport, aviation, and shipping (e.g., DAC-FT)	LE	-	±
Role of contexts	Plans for adoption of technology remain at early stage; political acceptance not known	Synthetic fuel use in aviation and marine shipping requires international coordination; challenges exist related to carbon accounting frameworks for utilization of CO2; likely fewer barriers for use of fuel in land transport applications	legal barriers exist for synthetic fuel use in aviation; need for development of CO2 capture markets; drop-in fuels are compatible with existing fuel standards in many jurisdictions
Line of sight	Scheelhaase, J., S. Maertens, and W. Grimme, 2019: Synthetic fuels in aviation - Current barriers and potential political measures. Transportation Research Procedia.		
Electric vehicles for land transport	±	±	±
Role of contexts	Varied political support for deployment in different regions of the world	Coordination needed between transport sector (including vehicle manufacturers; charging infrastructure) and power sector (including increased generation and transmission; capacity to handle demand peaks). Institutional capacity is variable;	Compatible with urban low emission zones; grid integration may require market and regulatory changes
Line of sight	Milovanoff, A., I. D. Posen, and H. L. MacLean, 2020: Electrification of light-duty vehicle fleet alone will not meet mitigation targets. Nat. Clim. Chang., https://doi.org/10.1038/s41558-020-00921-7; IEA (2021), Global EV Outlook 2021, IEA, Paris https://www.iea.org/reports/global-ev-outlook-2021		
Hydrogen FCV for land transport	±	±	±
Role of contexts	Varied political support for deployment in different regions of the world	Coordination needed across sector (including vehicle manufacturers, hydrogen producers and refuelling infrastructure); Institutional capacity is variable;	Compatible with urban low emission zones; fuel distribution network may require market and regulatory changes
Line of sight	Itaoka, K., A. Saito, and K. Sasaki, 2017: Public perception on hydrogen infrastructure in Japan: Influence of rollout of commercial fuel cell vehicles. International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2016.10.123.		

Chapter 11: Industry

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Date of Draft: 27/11/2021

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Executive summary

The Paris Agreement, the Sustainable Development Goals (SDGs) and the COVID-19 pandemic provide a new context for the evolution of industry and mitigation of industry greenhouse gas (GHG) emissions *(high confidence)*. This chapter is focused on what is new since AR5. It emphasizes the energy and emissions intensive basic materials industries and key strategies for reaching net zero emissions. {11.1.1}

Net zero CO_2 emissions from the industrial sector are possible but challenging *(high confidence)*. Energy efficiency will continue to be important. Reduced materials demand, material efficiency, and circular economy solutions can reduce the need for primary production. Primary production options include switching to new processes that use low to zero GHG energy carriers and feedstocks (e.g., electricity, hydrogen, biofuels, and carbon capture and utilization (CCU) for carbon feedstock) and carbon capture and storage (CCS) for remaining CO_2 . These options require substantial scaling up of electricity, hydrogen, recycling, CO_2, and other infrastructure, as well as phase-out or conversion of existing industrial plants. While improvements in the GHG intensities of major basic materials have nearly stagnated over the last 30 years, analysis of historical technology shifts and newly available technologies indicate these intensities can be reduced to net zero emissions by mid-century. {11.2, 11.3, 11.4}

Whatever metric is used, industrial emissions have been growing faster since 2000 than emissions in any other sector, driven by increased basic materials extraction and production *(high confidence)*. GHG emissions attributed to the industrial sector originate from fuel combustion, process emissions, product use and waste, which jointly accounted for 14.1 $GtCO_2$-eq or 24% of all direct anthropogenic emissions in 2019, second behind the energy transformation sector. Industry is a leading GHG emitter - 20 $GtCO_2$-eq or 34% of global emissions in 2019 - if indirect emissions from power and heat generation are included. The share of emissions originating from direct fuel combustion is decreasing and was 7 $GtCO_2$-eq, 50% of direct industrial emissions in 2019. {11.2.2}

Global material intensity (in-use stock of manufactured capital, in tonnes per unit of GDP is increasing *(high confidence)*. In-use stock of manufactured capital per capita has been growing faster than GDP per capita since 2000. Total global in-use stock of manufactured capital grew by 3.4% yr^{-1} in 2000–2019. At the same time, per capita material stocks in several developed countries have stopped growing, showing a decoupling from GDP per capita. {11.2.1, 11.3.1}

Plastic is the material for which demand has been growing the strongest since 1970 *(high confidence)*. The current >99% reliance on fossil feedstock, very low recycling, and high emissions from petrochemical processes is a challenge for reaching net zero emissions. At the same time, plastics are important for reducing emissions elsewhere, for example, light-weighting vehicles. There are as yet no shared visions for fossil-free plastics, but several possibilities. {11.4.1.3}

Scenario analyses show that significant cuts in global GHG emissions and even close to net zero emissions from GHG intensive industry (e.g., steel, plastics, ammonia, and cement) can be achieved by 2050 by deploying multiple available and emerging options *(medium confidence)*. Cutting industry emissions significantly requires a reorientation from the historic focus on important but incremental improvements (e.g., energy efficiency) to transformational changes in energy and feedstock sourcing, materials efficiency, and more circular material flows. {11.3, 11.4}

Key climate mitigation options such as materials efficiency, circular material flows and emerging primary processes, are not well represented in climate change scenario modelling and integrated assessment models, albeit with some progress in recent years *(high confidence)*. The character of these interventions (e.g., appearing in many forms across complex value chains, making cost estimates difficult) combined with the limited data on new fossil free primary processes help explain why they are less represented in models than, for example, CCS. As a result, overall mitigation costs and the need for CCS may be overestimated. {11.4.2.1}

Electrification is emerging as a key mitigation option for industry *(high confidence)*. Electricity is a versatile energy carrier, potentially produced from abundant renewable energy sources or other low carbon options; regional resources and preferences will vary. Using electricity directly, or indirectly via hydrogen from electrolysis for high temperature and chemical feedstock requirements, offers many options to reduce emissions. It also can provide substantial grid balancing services, for example through electrolysis and storage of hydrogen for chemical process use or demand response. {11.3.5}

Carbon is a key building block in organic chemicals, fuels and materials and will remain important *(high confidence)*. In order to reach net zero CO_2 emissions for the carbon needed in society (e.g., plastics, wood, aviation fuels, solvents, etc.), it is important to close the use loops for carbon and carbon dioxide through increased circularity with mechanical and chemical recycling, more efficient use of biomass feedstock with addition of low GHG hydrogen to increase product yields (e.g., for biomethane and methanol), and potentially direct air capture of CO_2 as a new carbon source. {11.3, 11.4.1}

Production costs for very low to zero emissions basic materials may be high but the cost for final consumers and the general economy will be low *(medium confidence)*. Costs and emissions reductions potential in industry, and especially heavy industry, are highly contingent on innovation, commercialization, and market uptake policy. Technologies exist to take all industry sectors to very low or zero emissions, but require 5–15 years of intensive innovation, commercialization, and policy to ensure uptake. Mitigation costs are in the rough range of 50–150 USD· tCO_2-eq^{-1}, with wide variation within and outside this band. This affects competitiveness and requires supporting policy. Although production cost increases can be significant, they translate to very small increases in the costs for final products, typically less than a few percent depending on product, assumptions, and system boundaries. {11.4.1.5}

There are several technological options for very low to zero emissions steel, but their uptake will require integrated material efficiency, recycling, and production decarbonisation policies *(high confidence)*. Material efficiency can potentially reduce steel demand by up to 40% based on design for less steel use, long life, reuse, constructability, and low contamination recycling. Secondary production through high quality recycling must be maximized. Production decarbonisation will also be required, starting with the retrofitting of existing facilities for partial fuel switching (e.g., to biomass or hydrogen), CCU and CCS, followed by very low and zero emissions production based on high-capture CCS or direct hydrogen, or electrolytic iron ore reduction followed by an electric arc furnace. {11.3.2, 11.4.1.1}

There are several current and near horizon options to greatly reduce cement and concrete emissions. Producer, user, and regulator education, as well as innovation and commercialization policy are needed *(medium confidence)*. Cement and concrete are currently overused because they are inexpensive, durable, and ubiquitous, and consumption decisions typically do not give weight to their production emissions. Basic material efficiency efforts to use only well-made concrete thoughtfully and only where needed (e.g., using right-sized, prefabricated components) could reduce emissions by 24–50% through lower demand for clinker. Cementitious material substitution with various materials (e.g., ground limestone and calcined clays) can reduce process calcination emissions by up to 50% and occasionally much more. Until a very low GHG emissions alternative binder to Portland cement is commercialized, which does not look promising in the near to medium term, CCS will be essential for eliminating the limestone calcination process emissions for making clinker, which currently represent 60% of GHG emissions in best available technology plants. {11.3.2, 11.3.6, 11.4.1.2}

While several technological options exist for decarbonizing the main industrial feedstock chemicals and their derivatives, the costs vary widely *(high confidence)*. Fossil fuel-based feedstocks are inexpensive and still without carbon pricing, and their biomass- and electricity-based replacements will likely be more expensive. The chemical industry consumes large amounts of hydrogen, ammonia, methanol, carbon monoxide, ethylene, propylene, benzene, toluene, and mixed xylenes & aromatics from fossil feedstock, and from these basic chemicals produces tens of thousands of derivative end-use chemicals. Hydrogen, biogenic or air-capture carbon, and collected plastic waste for the primary feedstocks can greatly reduce total emissions. Biogenic carbon feedstock is likely to be limited due to competing land-uses. {11.4.1.3}

Light industry and manufacturing can be largely decarbonized through switching to low GHG fuels (e.g., biofuels and hydrogen) and electricity (e.g., for electrothermal heating and heat pumps) *(high confidence)*. Most of these technologies are already mature, for example for low temperature heat, but a major challenge is the current low cost of fossil methane and coal relative to low and zero GHG electricity, hydrogen, and biofuels. {11.4.1.4}

The pulp and paper industry has significant biogenic carbon emissions but relatively small fossil carbon emissions. Pulp mills have access to biomass residues and by-products and in paper mills the use of process heat at low to medium temperatures allows for electrification *(high confidence)*. Competition for feedstock will increase if wood substitutes for building materials and petrochemicals feedstock. The pulp and paper industry can also be a source of biogenic carbon dioxide and carbon for organic chemicals feedstock and carbon dioxide removal (CDR) using CCS. {11.4.1.4}

The geographical distribution of renewable resources has implications for industry *(medium confidence)***.** The potential for zero emission electricity and low-cost hydrogen from electrolysis powered by solar and wind, or hydrogen from other very low emission sources, may reshape where currently energy and emissions intensive basic materials production is located, how value chains are organized, trade patterns, and what gets transported in international shipping. Regions with bountiful solar and wind resources, or low fugitive methane co-located with CCS geology, may become exporters of hydrogen or hydrogen carriers such as methanol and ammonia, or home to the production of iron and steel, organic platform chemicals, and other energy intensive basic materials. {11.2; 11.4; Box 11.1}

The level of policy maturity and experience varies widely across the mitigation options *(high confidence)***.** Energy efficiency is a well-established policy field with decades of experience from voluntary and negotiated agreements, regulations, energy auditing and demand side-management (DSM) programs (see AR5). In contrast, materials demand management and efficiency are not well understood and addressed from a policy perspective. Barriers to recycling that policy could address are often specific to the different material loops (e.g., copper contamination for steel and lack of technologies or poor economics for plastics) or waste management systems. For electrification and fuel switching the focus has so far been mainly on innovation and developing technical supply-side solutions rather than creating market demand. {11.5.2, 11.6}

Industry has so far largely been sheltered from the impacts of climate policy and carbon pricing due to concerns for competitiveness and carbon leakage *(high confidence)*. New industrial development policy approaches needed for realising a transition to net zero GHG emissions are emerging. The transition requires a clear direction towards net zero, technology development, market demand for low-carbon materials and products, governance capacity and learning, socially inclusive phase-out plans, as well as international coordination of climate and trade policies. It requires comprehensive and sequential industrial policy strategies leading to immediate action as well as preparedness for future decarbonisation, governance at different levels (from international to local) and integration with other policy domains. {11.6}

11.1 Introduction and new developments

11.1.1 About this chapter

AR5 was published in 2014. The Paris Agreement and the 17 SDGs were adopted in 2015. An increasing number of countries have since announced ambitions to be carbon neutral by 2045-2060. The COVID-19 pandemic shocked the global economy in 2020 and motivated economic stimulus with demands for green recovery and concerns for economic security. All this has created a new context and a growing recognition that all industry, including the energy and emissions intensive industries, need to reach net zero GHG emissions. There is an ongoing mind shift around the opportunities to do so, with electrification and hydrogen emerging among key mitigation options as a result of renewable electricity costs falling rapidly. On the demand side there has been renewed attention to end-use demand, material efficiency and more and better-quality recycling measures. This chapter takes its starting point in this new context and emphasizes the need for deploying innovative processes and practices in order to limit the global warming to 1.5ºC or 2ºC (IPCC 2018a).

The industrial sector includes ores and minerals mining, manufacturing, construction and waste management. It is the largest source of global GHG and CO_2 emissions, which include direct and indirect fuel combustion related emissions, emissions from industrial processes and products use, as well as from waste. This chapter is focused on heavy industry - the high temperature heat and process emissions intensive basic materials industries that account for 65% of industrial GHG and over 70% of industrial CO_2 emissions (waste excluded), where deployment of near-zero emissions technologies can be more challenging due to capital intensity and equipment lifetimes compared with other manufacturing industries. The transition of heavy industries to zero emissions requires supplementing the traditional toolkit of energy and process efficiency, fuel switching, electrification, and decarbonisation of power with material end-use demand management and efficiency, circular economy, fossil-free feedstocks, CCU, and CCS. Energy efficiency was extensively treated in AR5 and remains a key mitigation option. This chapter is focused mainly on new options and developments since AR5, highlighting measures along the whole value chains that are required to approach zero emissions in primary materials production.

11.1.2 Approach to understanding industrial emissions

The Kaya-identity offers a useful tool of decomposing emission sources and their drivers, as well as of weighing the mitigation options. The one presented below (Equation 11.1) builds on the previous assessments (IPCC 2014, 2018b; Hoegh-Guldberg et al. 2018), and reflect a material stock-driven services-oriented vision to better highlight the growing importance of industrial processes (dominated emissions increments in 2010-2019), product use and waste in driving emissions. Services delivery (nutrition, shelter, mobility, education, etc., see chapter 5 for more detail) not only requires energy and materials flows (fuels, food, feed, fertilizers, packaging, etc.), but also material stocks (buildings, roads, vehicles, machinery, etc.), the mass of which has already exceeded 1000 Gtonnes (Krausmann et al. 2018). As material efficiency appears to be an important mitigation option, material intensity or productivity (material extraction or consumption versus GDP (Hertwich et al. 2020; Oberle et al. 2019)) is reflected in the identity with two dimensions: as material stock intensity of GDP (tonnes per dollar) and material intensity of building and operating accumulated in-use stock.[1] For sub-global analysis the ratio of domestically used materials to total material production becomes important to reflect outsourced

FOOTNOTE[1] Accumulated material stock initially was introduced in the analysis of past trends (Krausmann et al. 2018; Wiedenhofer et al. 2019), but recently it was incorporated in different forms in the long-term projections for the whole economy (Krausmann et al. 2020) and for some sectors (buildings and cars in Hertwich et al. (2020)) with a steadily improving regional resolution (Krausmann et al. 2020).

materials production and distinguish between territorial and consumption-based emissions. The identity for industry differs significantly from that for sectors with where combustion emissions dominates (Lamb et al. 2021).

Recent progress in data availability that allows the integration of major emission sources along with socio-economic metabolism, material flows and stock analysis enriches the identity for industry from a perspective of possible policy interventions (Bashmakov 2021):

$$GHG = POP \cdot \frac{GDP}{POP} \cdot \frac{MStock}{GDP} \cdot \left[\frac{MPR + MSE}{MStock} \cdot Dm \cdot \left(\frac{E}{(MPR + MSE)} \cdot \frac{(GHGed + GHGeind)}{E} + \frac{GHGoth}{MPR + MSE}\right)\right]$$

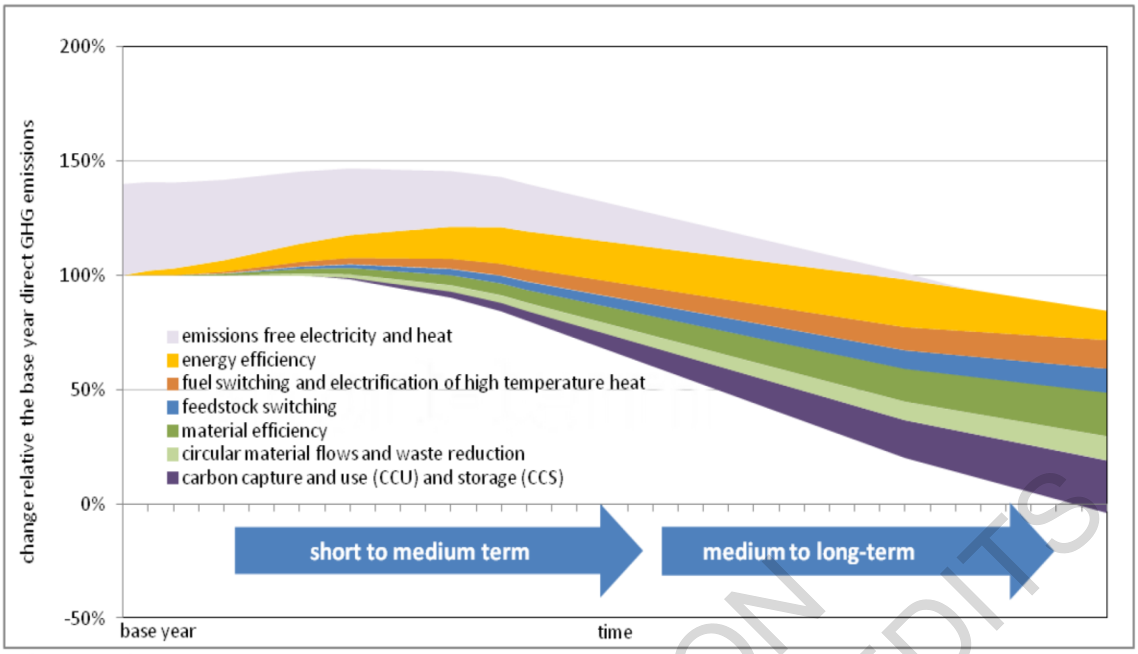
Equation 11.1

Variables	Factors	Policies and drivers	
POP	population	demographic policies	Demand decarbonization
$\frac{GDP}{POP}$	services (expressed via GDP – final consumption and investments needed to maintain and expand stock) per capita	sufficiency and demand management (reduction)	Demand decarbonization
$\frac{MStock}{GDP}$	material stock (*MStock* - accumulated in-use stocks of materials embodied in manufactured fixed capital) intensity of GDP	material stock efficiency improvement	Demand decarbonization
$\frac{MPR + MSE}{MStock}$	material inputs (both virgin (primary materials extraction, *MPR*) and recycled (secondary materials use, *MSE*)) per unit of in-use material stock	material efficiency, substitution and circular economy	Demand decarbonization
Dm	share of allocated emissions – consumption versus production emissions accounting (valid only for sub-global levels)*	trade policies including carbon leakage issues (localization versus globalization)	CBAM
$\frac{E}{(MPR + MSE)}$	sum of energy use for basic material production (*Em*), processing and other operational industrial energy use (*Eoind*) per unit of material inputs	energy efficiency of basic materials production and other industrial processes	Production decarbonization
$\frac{(GHGed + GHGeind)}{E}$	direct (*GHGed*) and indirect (*GHGeind*) combustion-related industrial emissions per unit of energy	electrification, fuel switching, and energy decarbonisation (hydrogen, CCUS-fuels)	Production decarbonization
$\frac{GHGoth}{MPR + MSE}$	emissions from industrial processes and product use, waste, F-gases, indirect nitrogen emissions per unit of produced materials	feedstock decarbonisation (hydrogen), CCUS-industrial processes, waste and F-gases management	Production decarbonization

* *Dm*=1, when territorial emission is considered, and *Dm* equals the ratio of domestically used materials to total material production for the consumption-based emission accounting). CBAM – carbon boarder adjustment mechanism

Factors in (Equation 11.1) are interconnected by either positive or negative feedbacks: scrap-based production or light weighing improves operational energy efficiency, while growing application of carbon capture, use and storage (CCUS) brings it down and increase material demands (Hertwich et al. 2019; IEA 2020a, 2021a). There are different ways to disaggregate Equation 11.1: by industrial subsectors (Bashmakov 2021); by reservoirs of material stock (buildings, infrastructure, vehicles, machinery and appliances, packaging, etc.); by regions and countries (where carbon leakage becomes relevant); by products and production chains (material extraction, production of basic materials, basic materials processing, production of final industrial products); by traditional and low carbon technologies used; and by stages of products' lives including recycling.

An industrial transition to net zero emissions is possible when the three last multipliers in Equation 11.1 (in square parentheses) are approaching zero. Contributions from different drivers (energy efficiency, low carbon electricity and heat, material efficiency, switching to low carbon feedstock and CCUS) to this evolution vary with time. Energy efficiency dominates in the short- and medium-term and potentially long-term (in the range of 10-40% by 2050) (Crijns-Graus et al. 2020; IEA 2020a; IPCC 2018a), but for deep decarbonisation trajectories contributions from the other drivers steadily grow, as the share of non-energy sources in industrial emissions rises and new technologies to address mitigation from these sources mature (Material Economics 2019; CEMBUREAU 2020; BPS 2020; Hertwich et al. 2020, 2019; IEA 2021a, 2020a; Saygin and Gielen 2021) (Figure 11.1).



Mitigation options

	short to medium term	medium to long term
Decarbonizing production	Reduction of indirect emissions via lower carbon electricity and heat supply	Provision of emissions free electricity and high temperature heat
	Energy efficiency improvements to best available technologies	Energy efficiency approaching thermodynamic minimums
	Fuel switching, biomass and electricity use for high temperature process heat	Deep low carbon electrification, green hydrogen use
	Partial substitution of high carbon feedstock	Zero emissions feedstock (green hydrogen, biomass) for basic materials production
	Small scale and sectorally narrow concentrated CO_2 flow CCUS	Broad scale, large-scale concentrated CO_2 flow and possibly post-combustion CCUS
Decarbonizing demand	Material efficiency and substitution	Eco-design, material efficiency, demand reduction
	Increasing recycling rates	Circular material flows and effective industrial waste management

Base year and contributions from the drivers are only illustrative. Drivers' contribution varies across industries. Indirect emissions reduction is considered as outcome of mitigation activities in the energy sector, see chapter 6.

Figure 11.1 Stylized composition and contributions from different drivers to the transition of industry to net zero emissions

11.2 New trends in emissions and industrial development

11.2.1 Major drivers

The use of materials is deeply coupled with economic development and growth. For centuries, humanity has been producing and using hundreds of materials (Ashby 2012), the diversity of which skyrocketed in the recent half-century to achieve the desired performance and functionality of multiple products (density; hardness; compressive strength; melting point, resistance to mechanical and thermal shocks and to corrosion; transparency; heat- or electricity conductivity; chemical neutrality or activity, to name a few). New functions drive the growth of material complexity of products; for example, a modern computer chip embodies over 60 different elements (Graedel et al. 2015).

Key factors driving up industrial GHG emissions since 1900 include population and per capita GDP, [2]while energy efficiency and non-combustion GHG emissions intensity (from industrial processes and waste) has been pushing it down. Material efficiency factors – material stock intensity of GDP and ratio of extraction, processing and recycling of materials per unit of built capital along with combustion-related emissions intensity factors and electrification – were cyclically switching their contributions with relatively limited overall impact. Growing recycling allowed for replacement of some energy intensive virgin materials and thus contributed to mitigation. In 2014–2019, a combination of these drivers allowed for a slowdown in the growth of industrial GHG emissions to below 1% (Figure 11.2 and Table 11.1), while to match a net zero emissions trajectory it should decline by 2% yr^{-1} in 2020-2030 and by 8.9% yr^{-1} in 2030–2050 (IEA 2021a).

There are two major concepts of **material efficiency** (*ME*). The broader one highlights demand reduction via policies promoting more intensive use, assuming sufficient (excl. luxury) living space or car ownership providing appropriate service levels – housing days or miles driven and life-time extension (Hertwich et al. 2019, 2020). This approach focuses on dematerialization of society (Lechtenböhmer and Fischedick 2020), where a "dematerialization multiplier" (Pauliuk et al. 2021) limits both material stock and GDP growth, as progressively fewer materials are required to build and operate the physical in-use stock to deliver sufficient services. According to IRP (2020), reducing floor space demand by 20% via shared and smaller housing compared to the reference scenario would decrease Group of Seven (G7) countries' GHG emissions from the material-cycle of residential construction up to 70% in 2050. The narrower concept ignores demand and sufficiency aspects and focuses on supply chains considering *ME* as less basic materials use to produce a certain final product, for example, a car or meter squared of living space (OECD 2019a; IEA 2020a). No matter if the broader or the narrower concept of *ME* is applied, in 1970-2019 it did not contribute much to the decoupling of industrial emissions from GDP. This is expected to change in the future (Figure 11.2).

FOOTNOTE[2] In 2020 this factor played on the reduction side as the Covid-19 crisis led to a global decline in demand for basic materials, respective energy use and emissions by 3-5 % (IEA 2020a).

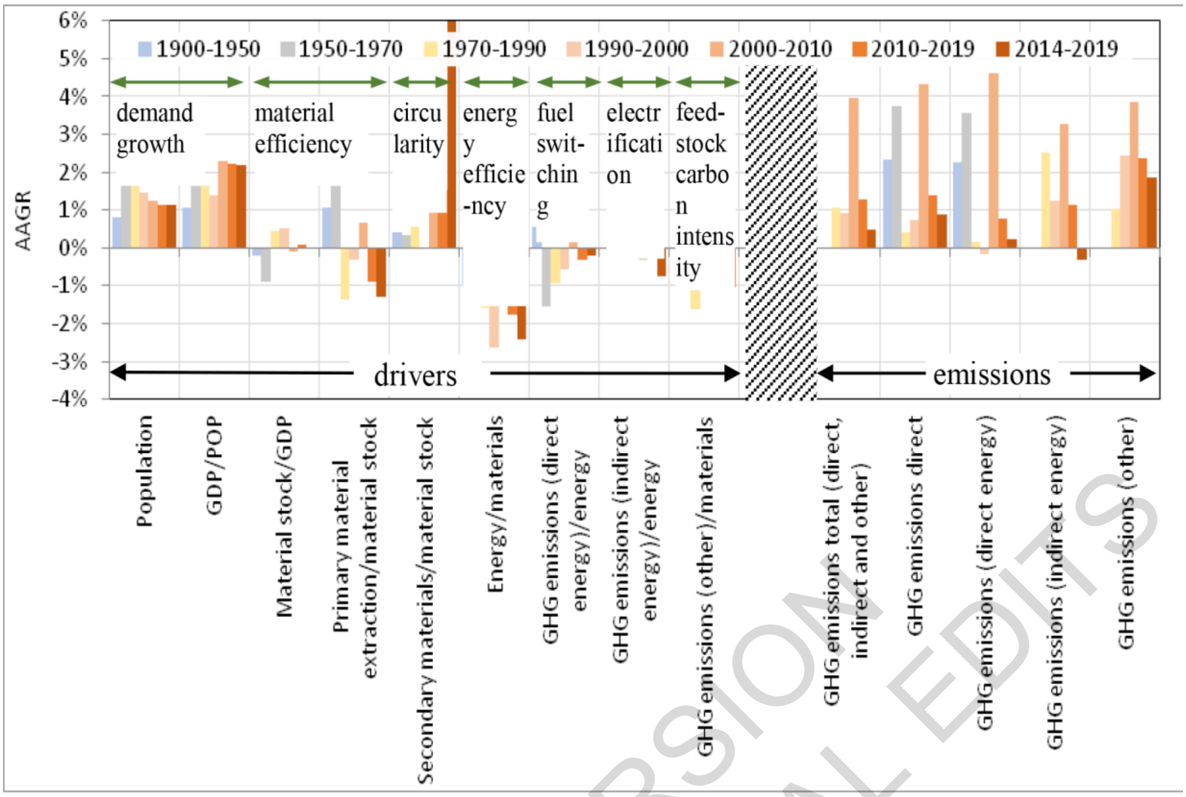


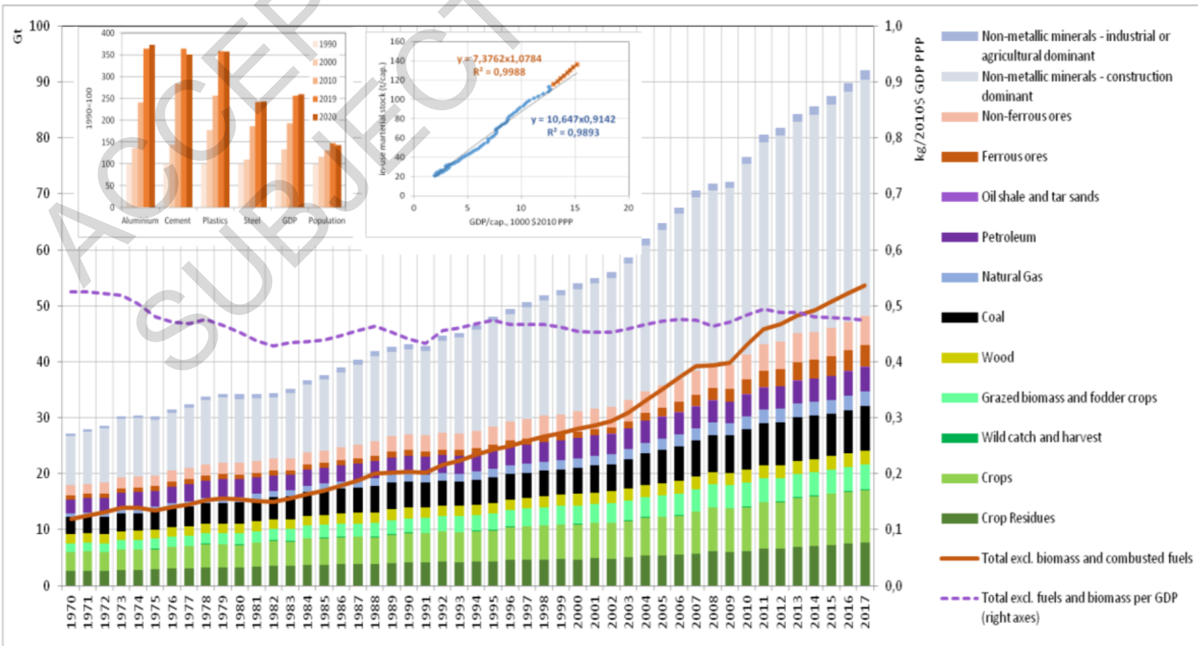
Figure 11.2 Average annual growth rates of industrial sector GHG emissions and drivers. 1900–2019. Before 1970, GHG emission (other) is limited to that from cement production. Waste emission is excluded. Primary material extraction excludes fuels and biomass. Presented factors correspond directly to Equation 11.1

Sources: population before 1950 and GDP before 1960: Maddison Project (2018); population from 1950 to 1970: UN (2015); population and GDP for 1960–2020: World Bank (2021); data on material stock, extraction, and use of secondary materials: Wiedenhofer et al. (2019); data on material extraction: UNEP and IRP (2020); industrial energy use for 1900–1970: IIASA (2018), for 1971–2019: IEA (2021b); data on industrial GHG emissions for 1900–1970: CDIAC (2017); for 1970–2019: Crippa et al. (2021) and Minx et al., (2021)

Material efficiency analysis mostly uses material intensity or productivity indicators, which compare material extraction or consumption with GDP (Oberle et al. 2019; Hertwich et al. 2020). Those indicators are functions of **material stock intensity of GDP** (tonnes per dollar) and material intensity of building and operating accumulated in-use stock. Coupling services or GDP with the built stock allows for a better evaluation of demand for primary basic materials (Cao et al. 2017; Liu et al. 2013; Liu and Müller 2013; Müller et al. 2011; Pauliuk et al. 2013a; Krausmann et al. 2020; Hertwich et al. 2020; Wiedenhofer et al. 2019). Since 1970 material stock growth driven by industrialization and urbanization slightly exceeded that of GDP and there was no decoupling,[3] so in Kaya-like identities material stock may effectively replace GDP. There are different methods to estimate the former (see reviews in Pauliuk et al. (2015, 2019) and Wiedenhofer et al. (2019), the results of which are presented for major basic materials with some geographical resolution (Pauliuk et al. 2013a; Liu and Müller 2013) or globally (Graedel et al. 2011; Krausmann et al. 2018; Geyer et al. 2017; International Aluminium Institute 2021a; Pauliuk et al. 2019; Wiedenhofer et al. 2019).

FOOTNOTE[3] This conclusion is also valid separately for developed countries, rest of the world, and for China, when adjusted GDP for this country is used (Krausmann et al. 2020).

For a subset of materials, such as solid wood, paper, plastics, iron/steel, aluminium, copper, other metals/minerals, concrete, asphalt, bricks, aggregate, and glass, total in-use stock escalated from 36 Gtonnes back in 1900 to 186 Gtonnes in 1970, 572 Gtonnes in 2000, and 960 Gtonnes in 2015, and by 2020 it exceeded 1,100 Gtonnes, or 145 tonnes per capita (Krausmann et al. 2018, 2020; Wiedenhofer et al. 2019). In 1900–2019, the stock grew 31-fold, which is strongly coupled with GDP growth (36-fold). As the UK experience shows, material stock intensity of GDP may ultimately decline after services fully dominate GDP, and this allows for material productivity improvements to achieve absolute reduction in material use, as stock expansion slows down (Streeck et al. 2020). While the composition of basic materials within the stock of manufactured capital was evolving significantly, overall stock use associated with a unit of GDP has been evolving over the last half-century in a quite narrow range of 7.7–8.6 t per 1000 USD (2017 PPP) showing neither signs of decoupling from GDP, nor saturation as of yet. Mineral building materials (concrete, asphalt, bricks, aggregate, and glass) dominate the stock volume by mass (94.6% of the whole stock, with the share of concrete alone standing at 43.5%), followed by metals (3.5%) and solid wood (1.4%). The largest part of in-use stock of our 'cementing societies' Cao et al. (2017) is constituted by concrete: about 417 Gt in 2015 Krausmann et al. (2018) extrapolated to 478 Gt (65 tonnes per capita) in 2018, which contains about 88 Gt of cement[4]. The iron and steel stock is assessed at 25-35 Gtonnes (Gielen et al. 2020; Wang et al. 2021; Wiedenhofer et al. 2019), while the plastics stock reached 2.5-3.2 Gtonnes (Geyer et al. 2017; Wiedenhofer et al. 2019; Saygin and Gielen 2021) and the aluminium stock approached 1.1 Gtonnes (International Aluminium Institute 2021a), or just 0.1% of the total. In sharp contrast to global energy intensity, which has more than halved since 1900 (Bashmakov 2019), in 2019 material stock intensity (in-use stock of manufactured capital per GDP) was only 14% below the 1900 level, but 15% above the 1970 level. In-use stock per capita has been growing faster than GDP per capita since 2000 (Figure 11.3). The growth rate of total in-use stock of manufactured capital was 3.8% in 1971-2000 and 3.5% in 2000-2019, or 32-35 $Gt \cdot yr^{-1}$, to which concrete and aggregates contributed 88%. Recent demand for stockbuilding materials was 51-54 $Gt \cdot yr^{-1}$, to which recycled materials recently contributed only about 10% of material input. About 46-49 $Gtonnes \cdot yr^{-1}$ was virgin inputs, which after accounting for processing waste and short-lived products (over 8 $Gtonnes \cdot yr^{-1}$) scale up to 54-58 $Gtonnes \cdot yr^{-1}$ of primary extraction (Krausmann et al. 2017, 2018; UNEP and IRP 2020). The above indicates that we have only begun to exploit the potential for recycling and circularity more broadly.



FOOTNOTE[4] Cement stock for 2014 was estimated at 75 Gtonnes (Cao et al. 2020).

Figure 11.3 Raw natural materials extraction since 1970. In windows: left - growth of population, GDP and basic materials production (1990=100) in 1990-2020; right - production of major basic materials and in-use stock per capita versus income level (1900–2018, brown dots are for 2000–2018). The regressions provided show that for more recent years elasticity of material stock to GDP was greater than unity, comparing with the lower unity in preceding years.

Source: Developed based on IEA (2020b); Maddison Project (2018); UNEP and IRP (2020); Wiedenhofer et al. (2019); World Steel Association (2021); International Aluminium Institute (2021a); Statista (2021a,b); World Bank (2021); U.S. Geological Survey (2021).

Total **extraction of all basic materials** (including biomass and fuels) in 2017 reached 92 Gtonnes·yr^{-1}, which is 13 times above the 1900 level (Figure 11.3).[5] When recycled resources are added, total material inputs exceed 100 Gtonnes (Circle Economy 2020). In Equation 11.1 *MPR* represents only material inputs to the stock, excluding dissipative use –biomass (food and feed) and combusted fuels. Total extraction of stock building materials (metal ores and non-metallic minerals) in 2017 reached 55 Gtonnes·yr^{-1}.[6] In 1970–2018, it grew 4.3-fold and the ratio of *MPR* to accumulated in-use capital has nearly been constant since 1990 along with ratio to GDP (Figure 11.3).

End-of-life waste from accumulated stocks along with (re)-manufacturing and construction waste is assessed at 16 Gtonnes·yr^{-1} in 2014 and can be extrapolated in 2018 to 19 Gtonnes·yr^{-1} (Krausmann et al. 2018; Wiedenhofer et al. 2019), or 1.8% from stock of manufactured capital. Less than 6 Gtonnes·yr^{-1} was recycled and used to build the stock (about 10% of inputs[7]). While the circularity gap is still large, and limited circularity was engineered into accumulated stocks,[8] **material recycling** mitigated some GHG emissions by replacing energy intensive virgin materials.[9] When the stock saturates, in closed material loops the end-of-life materials waste has to be equal to material input, and primary production therefore has to be equal to end-of-life waste multiplied by unity minus recycling rate. When the latter grows, as the linear metabolism is replaced with the circular one, the share of primary materials production in total material input declines.

Recycling rates for metals are higher than for other materials: the end-of-life scrap input ratio for 13 metals is over 50%, and stays in the range 25–50% for another ten, but even for metals recycling flows fail to match the required inputs (Graedel et al. 2011). Globally, despite overall recycling rates being at 85%, the all scrap ratio for steel production in recent years stays close to 35–38% (IEA 2021b; Gielen et al. 2020) ranging from 22% in China (only 10% in 2015) to 69% in the US and to 83% in Turkey (BIR 2020). For end-of-life scrap this ratio declined from 30% in 1995-2010 to 21–25% after 2010 (Gielen et al. 2020; Wang et al. 2021).

For aluminium, the share of scrap-based production grew from 17% in 1962 to 34% in 2010 and stabilized at this level till 2019, while the share of end-of-life scrap grew from 1.5% in 1962 to nearly 20% in 2019 (International Aluminium Institute 2021a). The global recycling (mostly mechanical) rate

FOOTNOTE[5] IRP (2020) estimate 2017 material extraction at 94 Gtonnes·yr^{-1}.

FOOTNOTE[6] It approaches 60 Gtonnes·yr^{-1} after construction and furniture wood and feedstock fuels are added (Krausmann et al. 2018; UNEP and IRP 2020; Wiedenhofer et al. 2019).

FOOTNOTE[7] Mayer et al. (2019) found that in 2010-2014 secondary to primary materials ratio for the EU-28 was slightly below 9%,

FOOTNOTE[8] According to Circle Economy (2020) 8.6 Gtonnes·yr^{-1} or 8.6% of total inputs for all resources.

FOOTNOTE[9] Environmental impacts of secondary materials are much (up to an order of magnitude) lower compared to primary materials (OECD 2019a; Wang et al. 2021; IEA 2021a) , but to enable and mobilize circularity benefits it requires social system and industrial designing transformation (Oberle et al. 2019).

for plastics is only 9–10%[10] (Geyer et al. 2017; Saygin and Gielen 2021) and that for paper progressed from 34% in 1990 to 44% in 2000 and to over 50% in 2014–2018 (IEA 2020b).

The limited impacts of material efficiency factors on industrial GHG emissions trends reflect the lack of integration of material efficiency in energy and climate policies which partly results from the inadequacy of monitored indicators to inform policy debates and set targets;[11] lack of high-level political focus and industrial lobbying; uncoordinated policy across institutions and sequential nature of decision-making along supply chains; carbon pricing policy lock-in with upstream sectors failing to pass carbon costs on to downstream sectors (due to compensation mechanisms to reduce carbon leakage) and so have no incentives to exploit such options as light-weighting, reusing, re-manufacturing, recycling, diverting scrap, extending product lives, using products more intensely, improving process yields, and substituting materials (Skelton and Allwood 2017; Gonzalez Hernandez et al. 2018b; Hilton et al. 2018). Poor progress with material efficiency is part of the reason why industrial GHG emissions are perceived as 'hard to abate', and many industrial low-carbon trajectories to 2050 leave up to 40% of emissions in place (Material Economics 2019; IEA 2021a). The importance of this factor activation rises as in-use material stock is expected to scale up by a factor of 2.2–2.7 to reach 2215–2720 Gtonnes by 2050 (Krausmann et al. 2020). Material extraction in turn is expected to rise to 140–200 Gtonnes·yr^{-1} by 2060 (Hertwich et al. 2020; OECD 2019a) providing unsustainable pressure on climate and environment and calling for fundamental improvements in material productivity.

In 2014–2019, the average annual growth rate (AAGR) of global **industrial energy use** was 0.4% compared to 3.2% in 2000–2014, following new policies and trends, particularly demonstrated by China[12] (IEA 2020b,d). Whatever metric is applied, industry (coal transformation, mining, quarrying, manufacturing and construction) driven mostly by material production, dominates global energy consumption. About two fifths of energy produced globally goes to industry, directly or indirectly. Direct energy use (including energy used in coal transformation) accounts for nearly 30% of total final energy consumption. When supplemented by non-energy use, the share for the post AR5 period (2015–2019) stands on average close to 40% of final energy consumption, and at 28.5% of primary energy use.[13] With an account of indirect energy use for the generation of power and centralized heat to be consumed in industry, the latter scales up to 37%. Industrial energy use may be split by: material production and extraction (including coal transformation) 51% on average for 2015-2019, non-energy use (mostly chemical feedstock) 22%[14], and other energy use (equipment, machinery, food and tobacco, textile, leather etc.) 27%. Energy use for material production and feedstock[15] makes about three quarters (73%) of industrial energy consumption and is responsible for 77% of its increment in 2015-2019 (based on IEA (2021a)).

For over a century **industrial energy efficiency** improvements have partially offset growth in GHG emissions. Industrial energy use per ton of extracted materials (ores and building materials as a proxy

FOOTNOTE[10] IEA (2021a) assesses the global plastics collection ate at 17% for 2020.

FOOTNOTE[11] Significant progress with data and indicators was reached in recent years with the development of several global coverage material flows datasets (Oberle et al. 2019).

FOOTNOTE[12] China contributed three forth of global industrial energy use increment in 2000-2014. Since 2014 China's share in global industrial energy use slowly declines reaching about a third in 2018 (IEA 2020d).

FOOTNOTE[13] This fits well 28.8% average for 1900-2018 with a slow trend to decline by 0.01% yr^{-1} in response to the growing share of services in global GDP, around which about 60-years-long cycles can be observed.

FOOTNOTE[14] Industry also produce goods traditionally used as feedstock –hydrogen and ammonia – which in the coming future may be widely used as energy carriers.

FOOTNOTE[15] Mapping global flows of fuel feedstock allows for better tailoring downstream mitigation options for chemical products (Levi and Cullen 2018).

for materials going through the whole production chain to final products) fell by 20% in 2000–2019 and by 15% in 2010–2019, accelerated driven by high energy prices to 2.4%$\cdot$yr^{-1} in 2014–2019 matching the values observed back in 1990–2000 (Figure 11.2). Assessed per value added using market exchange rates, industrial energy intensity globally dropped by 12% in 2010-2018, after its 4% decline in 2000–2010, resulting in 2000–2018 decline by 15% (IEA 2020b,a). The 2020 COVID crisis slowed down energy intensity improvements by shifting industrial output towards more energy intensive basic materials (IEA 2020e). Specific energy consumption per tonne of iron and steel, chemicals and cement production in 2019 were about 20% below the 2000 level (IEA 2020b,a). This progress is driven by moving towards best available technologies (BATs) for each product through new and highly efficient production facilities in China, India and elsewhere, and by the contribution from recycled scrap metals, paper and cardboard.

Physical energy intensity for the production of materials typically declines and then stabilizes at the BAT level once the market is saturated, unless a transformative new technology enters the market (Gutowski et al. 2013; Crijns-Graus et al. 2020; IEA 2021a) Thus, the energy saving effect of switching to secondary used material comes to the forefront, as energy consumption per tonne for many basic primary materials approach the BATs. This highlights the need to push towards circular economy, materials efficiency, reduced demand, and fundamental process changes (e.g. towards electricity and hydrogen based steel making). Improved recycling rates allow for a substantial reduction in energy use along the whole production chain – material extraction, production, and assembling – which is in great excess of energy used for collection, separation, treatment, and scrap recycling minus energy used for scrap landfilling. IEA (2019b) estimates, that by increasing the recycling content of fabricated metals average specific energy consumption (SEC) for steel and aluminium may be halved by 2060. Focusing on whole systems ‘integrative design’ expands efficiency resource much beyond the sum of potentials for individual technologies. Material efficiency coupled with energy efficiency can deliver much greater savings than energy efficiency alone. Gonzalez Hernandez et al. (2018b) stress that presently about half of steel or aluminium are scrapped in production or oversized for targeted services. They show that resource efficiency expressed in exergy as a single metric for both material and energy efficiency for global iron and steel sector is only 33%, while secondary steelmaking is about twice more efficient (66%), than ore-based production (29%). While shifting globally in ore-based production from average to the best available level can save 6.4 EJ$\cdot$yr^{-1}, the saving potential of shifting to secondary steelmaking is 8 EJ$\cdot$yr^{-1}, and limited mostly by scrap availability and steel quality requirements.

11.2.2 New trends in emissions

GHG emissions attributable to the industrial sector (see chapter 2) in 2019 originate from industrial fuel combustion (7.1 GtCO_2-eq direct and about 5.9 Gtonnes indirect from electricity and heat generation[16]); industrial processes (4.5 GtCO_2-eq) and products use (0.2 Gtonnes), as well as from waste (2.3 Gtonnes) (Figure 11.4a-b). Overall industrial direct GHG emission amounts to 14.1 GtCO_2-eq, Figure 11.4c and Table 11.1) and scales up to 20 GtCO_2-eq after indirect emissions are added,[17] putting industry (24%, direct emissions) second after the energy sector in total GHG emissions and lifting it to the leading

FOOTNOTE[16] Indirect emissions are assessed based on EDGAR database (Crippa et al. 2021). IEA database reports 6 Gt of CO_2 for 2019 (IEA 2020f).

FOOTNOTE[17] Based on Crippa et al. (2021) and Minx et al. (2021). In 2019, industrial CO_2 only emissions were 10.4 GtCO_2, which due to wider industrial processes and product use (IPPU) coverage exceeds CO_2 emission assessed by IEA (2021a) at 8.9 Gt for 2019 and at 8.4-8.5 Gtonnes for 2020.

position after indirect emissions are allocated (34% in 2019)[18]. The corresponding shares for 1990-2000 were 21% for direct emissions and 30% - for both direct and indirect (Crippa et al. 2021; Lamb et al. 2021; Minx et al. 2021). As the industrial sector is expected to decarbonize slower than other sectors it will keep this leading position for coming decades (IEA 2021a). In 2000–2010, total industrial emissions have been growing faster (3.8% yr^{-1}), than in any other sector (see chapter 2, mostly due to the dynamics shown by basic materials extraction and production. Industry contributed nearly half (45%) of overall incremental global GHG emissions in the 21st century.

Industrial sector GHG emissions accounting is complicated by carbon storage in products (Levi and Cullen 2018). About 35% of chemicals' mass is CO_2, which is emitted at use stage - decomposition of fertilizers, or plastic waste incineration (Saygin and Gielen 2021), and sinks. Re-carbonation mineralization of alkaline industrial materials and wastes (aka the "sponge effect") provide 0.6–1 $GtCO_2 \cdot yr^{-1}$ uptake by cement containing products[19] (Cao et al. 2020; Guo et al. 2021); see section 11.3.6 for further discussion in decarbonisation context.

In 1970–1990, industrial direct combustion-related emissions were growing modestly, and in 1990–2000 even switched to a slowly declining trend, steadily losing their share in overall industrial emissions. Electrification was the major driver behind both indirect and total industrial emissions in those years. This quiet evolution was interrupted in the beginning of the 21st century, when total emissions increased by 60-68% depending on the metric applied (the fastest growth ever seen). In 2000-2019 iron and steel and cement absolute GHGs increased more than any other period in history (Bashmakov 2021). Emissions froze temporarily in 2014–2016, partly in the wake of the financial crisis, but returned to their growth trajectory 2017–2019 (Figure 11.4a).

The largest incremental contributors to industrial emissions 2010–2019 are industrial processes at 40%, then indirect emissions (25%), and only then direct combustion (21%), followed by waste (14%, Figure 11.4). Therefore, to stop emission growth and to switch to zero carbon pathway more mitigation efforts should be focused on industrial processes, products use and waste decarbonisation along with the transition to low carbon electrification (Hertwich et al. 2020).

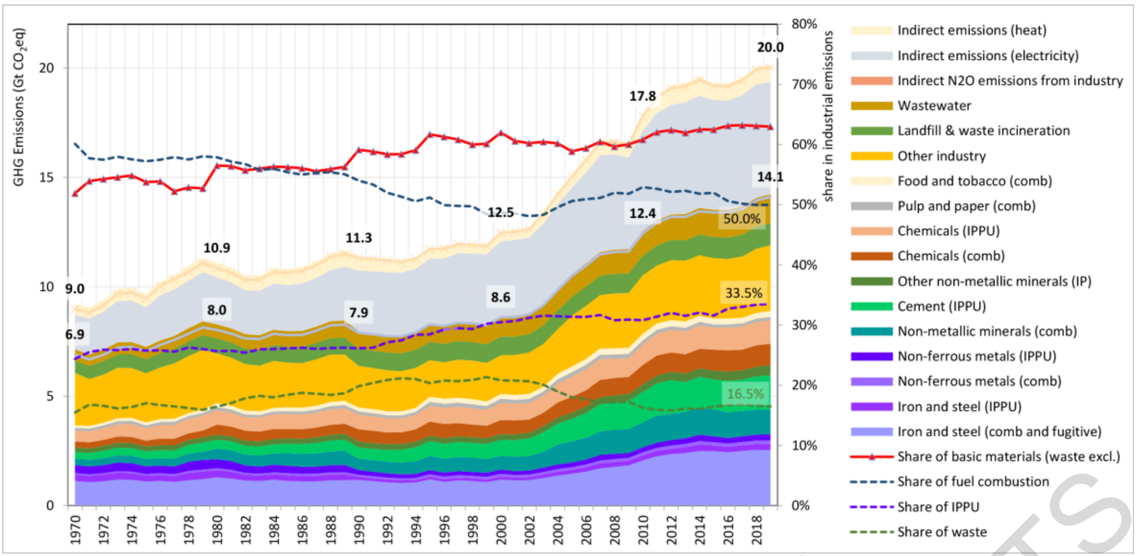
Basic materials production dominates both direct industrial GHG emissions (about 62%, waste excluded)[20] as well as direct industrial CO_2 emissions (70%), led by iron and steel, cement, chemicals, and non-ferrous metals (Figure 11.4e). Basic materials also contribute 60% to indirect emissions. In a zero-carbon power world, with industry lagging behind in the decarbonisation of high-temperature processes and feedstock, it may replace the energy sector as the largest generator of indirect emissions embodied in capital stock[21]. According to Circle Economy (2020) and Hertwich et al. (2020), GHG emissions embodied in buildings and infrastructure, machinery and transport equipment exceed 50% of their present carbon footprint.

FOOTNOTE[18] According to IEA (2020f) industry fuel combustion CO_2 only emissions contributed 24% to total combustion emissions, but combined with indirect emission it accounted for 43% in 2018.

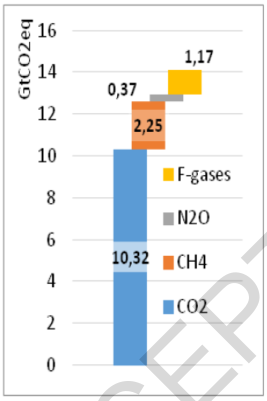
FOOTNOTE[19] There are suggestions to incorporate carbon uptake by cement containing products in IPCC methodology for national GHG inventories (Stripple et al. 2018).

FOOTNOTE[20] Crippa et al. (2021) and IEA (2020a) assess materials related scope 1+2 (direct and indirect emissions) correspondingly at 10.3 for 2019 and at 10.7 for 2018. Hertwich (2021) updated estimates for the global cradle-to-gate material production related GHG emissions for 2018 at 11.8 Gtonnes (5.1 Gtonnes for metals, 3.7 Gtonnes for non-metallic minerals, 1.8 Gtonnes for plastics and rubber, 1 Gtonne for wood) –which is about 69% of direct and indirect industrial emissions (waste excluded). These assessments are consistent as transportation of basic materials contributes around 1 $GtCO_2$-eq. to GHG emissions.

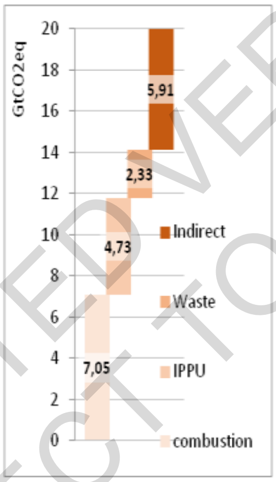
FOOTNOTE[21] According to Hertwich et al. (2020), of 11.5 $GtCO_2$-eq 2015 global materials GHG footprint about 5 Gt were embodied in buildings and infrastructure, and nearly 3 Gtonnes in machinery, vehicles, and electronics.



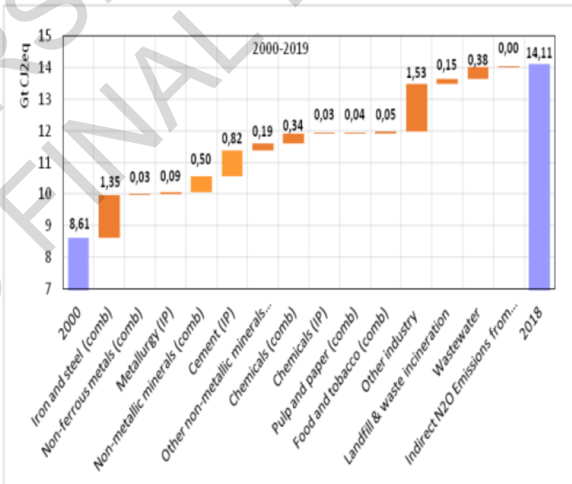
(a) Industrial emissions by source (left scale) and emissions structure (right scale). Comb – indicates direct emissions from fuels combustion. IPPU – indicates emissions from industrial processes and product use. Indirect emissions from electricity and heat generation are shown on the top. Shares on the right are shown for direct emissions



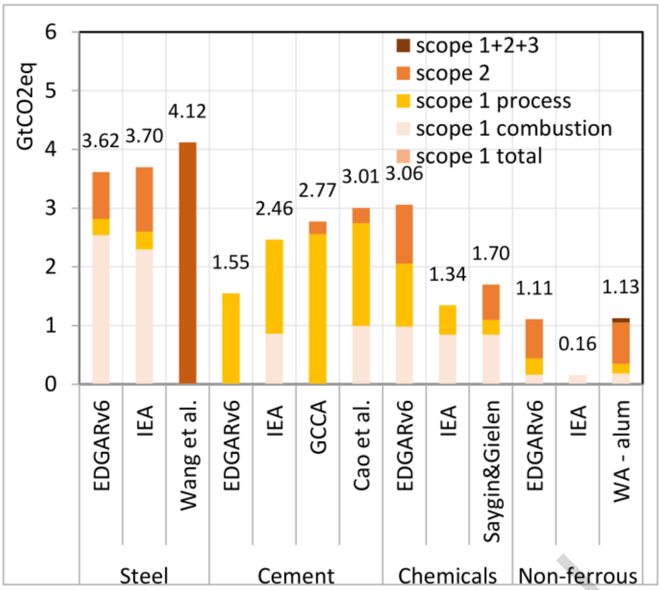
(b) 2019 direct combustion and process emissions split by GHGs



(c) 2019 emissions split by major sources



(d) increments of GHG emissions by sources (direct emissions only)



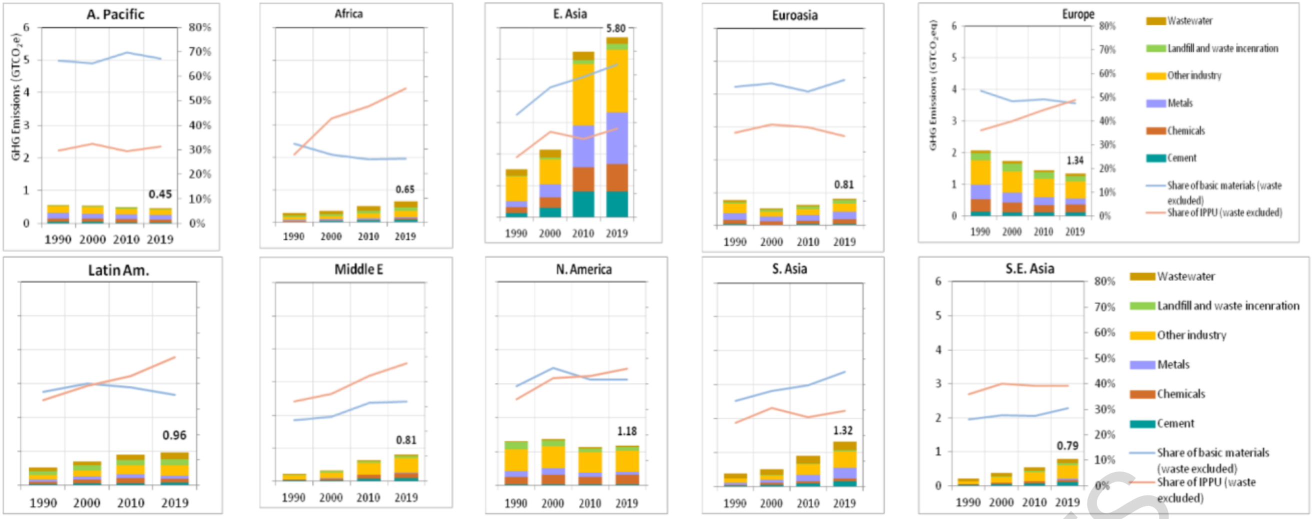
(e) 2019-2020 emissions by major basic materials production

Figure 11.4 Industrial sector direct global GHG emissions

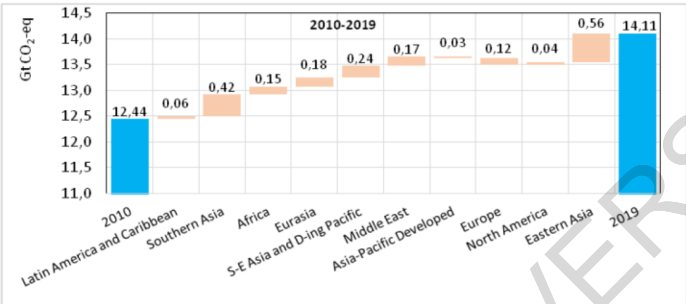
Source: Calculated based on emissions data from Crippa et al., (2021) and Minx et al., (2021). Indirect emissions were assessed using IEA (2021b). For the figure (e): IEA (2020b, 2021a); Cao et al. (2020); Wang et al. (2021); International Aluminium Institute (2021a) and GCCA (2021a).

In 1970–2000, direct GHG emissions per unit of energy showed steady decline interrupted by noticeable growth in 2001–2018 driven by fast expansion of steel and cement production in China (Figure 11.5), where in 2000-2015 on average every month 12 heavy industrial facilities were built (IEA 2021a). Non-energy related GHG emissions per unit of extracted materials decline continuously, as the share of not carbon intensive building materials (aggregates and sand) grows.

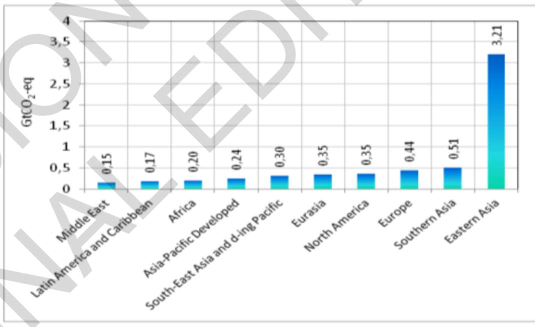
Wang et al. (2021)'s conclusion that iron and steel carbon intensity stagnated in 1995–2015 due to skyrocketing carbon intensive material production in China and India (Figure 11.5) may be extended to 2020 (Bashmakov 2021) and to other basic materials. For aluminium carbon intensity declined in 2010-2019 by only 2% (International Aluminium Institute 2021a). Carbon intensity of cement making since 2010 is down by only 4%. In 1990–2019 it fell by 19.5%, mostly due to energy efficiency improvements (by 18.5%) as the carbon intensity of the fuel mix declined only by 3% (GCCA 2021b). Historical analysis shows the carbon intensity of steel production has declined with "stop and go" patterns in 50-60 years cycles, reflective of the major jumps in best available technology. From 1900–1935 and from 1960–1990 specific scope 1+2+3 emissions fell by 1.5-2.5 tCO_2 per tonne, or as much as needed now to achieve net zero. While historical declines were mostly due to commissioning large capacities with new technologies, with total emissions growing, by 2050 and beyond the decline will likely materialize via new ultra low emission capacity replacements pushing absolute emissions to net zero (Bataille et al. 2021b).



(a) industrial emissions by sources (right axes) and share of materials and emissions from industrial processes and product use in overall industrial emissions



(b) 2010-2019 increments of industrial GHG emissions in 10 world regions (direct emissions only)



(c) 2019 indirect GHG emissions in 10 world regions

Figure 11.5 Industrial sector GHG emissions (direct only) in 10 world regions. 1990-2019

Source: Calculated based on emissions data from Crippa et al. (2021). Indirect emissions were assessed using IEA (2021b).

Table 11.1 Dynamics and structure of industrial GHG emissions

		Average annual growth rates				Share in total industrial sector emissions					2019 emissions $GtCO_2$-eq
		1971-1990	1991-2000	2000-2010	2011-2019	1970	1990	2000	2010	2019	
Direct CO_2 emissions form fuel combustion	Mining (excl. fuels), manufacturing industries and construction	0.13%	-0.18%	4.62%	0.77%	45.8%	37.3%	33.2%	36.6%	34.9%	6981
	Iron and steel	0.20%	0.13%	5.62%	2.28%	12.4%	10.2%	9.4%	11.4%	12.4%	2481
	Chemical and petrochemical	3.66%	1.54%	3.16%	1.19%	3.0%	4.9%	5.2%	4.9%	4.9%	977
	Non-ferrous metals	2.12%	3.20%	1.12%	1.36%	0.7%	0.8%	1.0%	0.8%	0.8%	163
	Non-metallic minerals	2.91%	1.88%	6.24%	-0.04%	3.3%	4.6%	5.0%	6.5%	5.7%	1148
	Paper, pulp and printing	0.78%	2.79%	0.09%	-2.69%	1.4%	1.3%	1.5%	1.1%	0.7%	150
	Food and tobacco	2.55%	1.50%	3.03%	-1.04%	1.3%	1.6%	1.7%	1.6%	1.3%	265
	Other	-1.55%	-2.89%	4.61%	-0.22%	23.8%	13.8%	9.4%	10.3%	9.0%	1797
Indirect emissions - electricity		2,87%	2.06%	3.00%	-0.87%	17.6%	24.6%	27.3%	25.8%	21.2%	4236
Indirect emissions – heat		2,08%	-3.09%	2.53%	9.83%	5.6%	6.7%	4.5%	4.0%	8.3%	1663
Industrial processes CO_2	Total	1.45%	2.16%	5.00%	1.93%	11.0%	11.6%	13.0%	14.9%	15.7%	3144
	Non-metallic minerals	2.22%	2.36%	5.66%	1.67%	5.7%	7.0%	8.0%	9.7%	10.0%	2008
	Chemical and petrochemical	4.51%	2.52%	3.50%	2.01%	1.5%	2.9%	3.4%	3.4%	3.6%	720
	Metallurgy	-3.11%	0.37%	5.16%	3.10%	3.6%	1.5%	1.4%	1.7%	2.0%	391
	Other	1.55%	2.30%	-1.21%	2.89%	0.1%	0.2%	0.2%	0.1%	0.1%	25
Industrial product use GHG		-0,22%	-0.49%	-1.02%	0.41%	2.7%	2.0%	1.7%	1.1%	1.0%	204
Other non-CO_2 GHG		-0,60%	5.20%	4.29%	3.20%	5.5%	3.9%	5.8%	6.2%	7.3%	1470
Waste GHG		1,94%	1.35%	1.22%	1.57%	11.9%	13.8%	14.4%	11.4%	11.6%	2327
Total GHG		1,16%	0.98%	3.61%	1.32%	100.0%	100.0%	100.0%	100.0%	100.0%	20,025

Source: Calculated based on Crippa et al. (2021); IEA (2021b) and Minx et al. (2021).

11.2.3 Industrial development patterns and supply chains (regional)

The dramatic increase in industrial emissions after 2000 is clearly associated with China's[22] and other non-OECD Asian countries' economic growth, which dominated both absolute and incremental emissions (Figure 11.5a-b).

More recent 2010–2019 trends show that regional contributions to additional emissions are distributed more evenly, while a large part still comes from Asian countries, where both rates of economic growth and the share of industrial emissions much exceed the global average. All other regions also contributed to total industrial GHG emissions. Structural shifts towards emissions from industrial processes and products use are common for many regions (Figure 11.5a).

Economic development. Regional differences in emission trends are determined by the differences observed in economic development, trade and supply chain patterns. The major source of industrial emissions is production of energy intensive materials, such as iron and steel, chemical and petrochemicals, non-ferrous metals and non-metallic products. Steel and cement are key inputs to urbanization and infrastructure development (buildings and infrastructure are responsible for about three fourths of the steel stock). Application of a "services-stock-flow-emissions" perspective (Wiedenhofer et al. 2019; Haberl et al. 2021; Bashmakov 2021) shows that relationship patterns between stages of economic development, per capita stocks and flows of materials are not trivial with some clear transition points. Cao et al. (2017) mapped countries by four progressive stages in cement stock per capita S-shape evolution as a function of income and urbanization: initial stage for developing countries with a low level and slow linear growth; take-off stage with accelerated growth; slowdown stage; and finally a shrinking stage (represented by just a few countries with very high incomes exceeding 40k USD 2010 per capita) and urbanization levels above 80%. Bleischwitz et al. (2018) use a similar approach with 5 stages to study material saturation effects for apparent consumption and stocks per capita for steel, cement, aluminium, and copper. This logic may be generalized to other materials from which in-use stock is built. While globally cement in-use stock is about 12 tonnes per capita, in developed countries it is 15-30 tonnes per capita, but order of magnitude lower in developing states with high per capita escalation rates (Cao et al. 2017). When stocks for some materials saturate – per capita stock peaks – the 'scrap age' is coming (Pauliuk et al. 2013a). Steel in-use stock has already saturated in advanced economies at 14±2 tonnes per capita due to largely completed urbanization and infrastructure developments and a switch towards services-dominated economy. This saturation level is 3-4 times that of the present global average, which is below 4 tonnes per capita (Pauliuk et al. 2013a; Wiedenhofer et al. 2019; Graedel et al. 2011). China is entering the maturing stage of steel and cement consumption resulting in a moderate projection of additional demand followed by expected industrial emissions peaking in the next 10-15 years (Bleischwitz et al. 2018; Zhou et al. 2013; Wu et al. 2019; OECD 2019a; Zhou et al. 2020). But many developing countries are still urbanizing, and the growing need for infrastructure services results in additional demand for steel and cement. Materials intensity of the global economy is projected by OECD (2019a) to decline at 1.3% yr^{-1} till 2060, driven by improving resource efficiency and the switch to circular economy, but with a projected tripling of global GDP it means a doubling of projected materials use (OECD 2019a). Under the business-as-usual scenario, India's demand for steel may more than quadruple over the next 30 years (de la Rue du Can et al. 2019; Dhar et al. 2020). In the IEA (2021a) Net Zero Energy scenario saturation effect along with material efficiency counterbalances activity effects and keeps demand growth for basic materials modest while escalate demand for critical materials (copper, lithium, nickel, graphite, cobalt and others).

International trade and supply chain. In Equation 11.1 the share of allocated emissions (*Dm*) equals unity when territorial emission is considered, and to the ratio of domestically used materials to total

FOOTNOTE[22] In 2020 China accounted for nearly 60% of global steel and cement production (IEA 2021a) and in 2015 over than half of the material production associated emissions occurred in China (Hertwich 2021).

material production for consumption-based emission accounting. Tracking consumption-based emissions provides additional insights in the global effectiveness of national climate policies. Carbon emissions embodied in international trade are estimated to account for 20-30% of global carbon emissions (Meng et al. 2018; OECD.Stat 2019) and are the reason for different emissions patterns of OECD versus non-OECD countries (chapter 2).

Based on OECD.Stat (2019) datasets, 2015 CO_2 emissions embodied in internationally traded industrial products (manufacturing and mining excluding fuels) by all countries are assessed at 3 $GtCO_2$, or 30% of direct CO_2 emission in the industrial sector as reported by Crippa et al. (2021). OECD countries collectively have reduced territorial emissions (shares of basic materials in direct emissions in those regions decline, (Figure 11.5b), but demonstrated no progress in reducing outsourced emissions embedded in imported industrial products (Arto and Dietzenbacher 2014; OECD.Stat 2019). Accounting for net carbon emissions embodied in international trade of only industrial products (1283 mln tCO_2 in 2015) escalates direct OECD industrial CO_2 emissions (1333 mln tCO_2 of energy-related and 502 mln tCO_2 of industrial processes) 1.7 fold, 2.3-fold for the US, 1.5-fold for the EU, and more than triples it for the UK, while cutting (*Dm*) by a third for China and Russia (IEA 2020f; OECD.Stat 2019). In most OECD economies, the amount of CO_2 embodied in net import from non-OECD countries is equal to, or even greater than, the size of their Paris 2030 emissions reduction commitments. In the UK, parliament Committee on Energy and Climate Change requested that a consumption-based inventory be complementarily used to assess the effectiveness of domestic climate policy in delivering absolute global emissions reductions (Barrett et al. 2013; UKCCC 2019a). It should be noted that the other side of the coin is that exports from countries with lower production carbon intensities can lead to overall less emissions than if production took place in countries with high carbon intensities, which may become critical in the global evolution toward lower emissions. The evolution of *Dm* to the date was driven mostly by factors other than carbon regulation often equipped with carbon leakage prevention tools. Empirical tests have failed to date to detect meaningful "carbon leakage" and impacts of carbon prices on net import, direct foreign investments, volumes of production, value added, employment, profits, and innovation in industry (Acworth et al. 2020; Branger et al. 2016; Carratù et al. 2020; Ellis et al. 2019; Saussay and Sato. 2018; Zachmann and McWilliams 2020; Naegele and Zaklan 2019; Pyrka et al. 2020; Sartor 2013). In the coming years availability of large low-cost renewable electricity potential and cheap hydrogen may become a new driver for relocation of such carbon intensive industries as steel production (Gielen et al. 2020; Bataille 2020a; Bataille et al. 2021a; Saygin and Gielen 2021).

11.3 Technological developments and options

The following overview of technical developments and mitigation options which relate to the industrial sector is organised in six equally important strategies: (i) demand for materials. (ii) materials efficiency, (iii) circular economy and industrial waste, (iv) energy efficiency, (v) electrification and fuel switching, and (vi) CCUS, feedstock and biogenic carbon. Each strategy is described in detail, followed by a discussion of possible overlaps and interactions between strategies and how conflicts and synergies can be addressed through integration of the approaches.

11.3.1 Demand for materials

Demand for materials is a key driver of energy consumption and CO_2 emissions in the industrial sector. Rapid growth in material demand over the last quarter century has seen demand for key energy-intensive materials increase 2.5– to 3.5–fold (see Figure 11.6), with growth linked to, and often exceeding, population growth and economic development. The International Energy Agency explains, "as economies develop, urbanise, consume more goods and build up their infrastructure, material demand per capita tends to increase considerably. Once industrialised, an economy's material demand may level off and perhaps even begin to decline" (IEA 2019b).

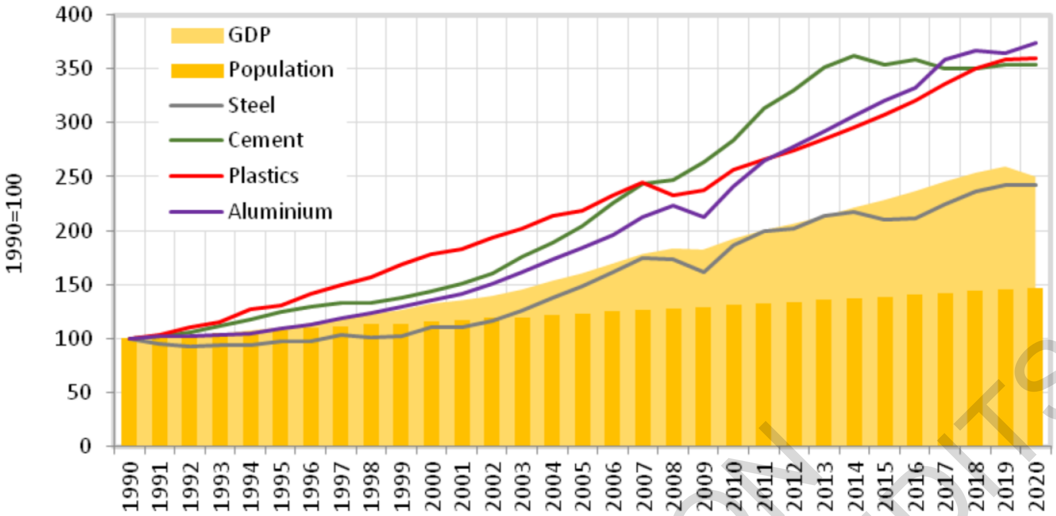


Figure 11.6 Growth in global demand for selected key materials and global population, 1990–2019

Notes: Based on global values, shown indexed to 1990 levels (=100). Steel refers to crude steel production. Aluminium refers to primary aluminium production. Plastic refers to the production of subset of key thermoplastic resins. Cement and concrete follow similar demand patterns.

Sources: 1990-2018: IEA (2020b). 2019-2020: World Steel Association (2021); International Aluminium Institute (2021a); U.S. Geological Survey (2021); GCCA (2021a); World Bank (2021); Statista (2021b).

The Kaya-like identity presented earlier in the chapter (Equation 11.1) suggests that material demand can be decoupled from population and economic development by two means: (i) reducing the accumulated material stock (MStock) used to deliver material services; and, (ii) reducing the material (MPR +MSE) required to maintain material stocks (MStock). Such material demand reduction strategies are linked upstream to material efficiency strategies (the delivery of goods and services with less material demand, and thus energy and emissions) and to demand reduction behaviours, through concepts such as sufficiency, sustainable consumption and social practice theory (Spangenberg and Lorek 2019). Materials demand can also be influenced through urban planning, building codes and related socio-cultural norms that shape the overall demand for square meters per capita of floor space, mobility and transport infrastructures (Chapter 5).

Modelling suggests that per capita material stocks saturate (level off) in developed countries and decouple from GDP. Pauliuk et al. (2013b) demonstrated this saturation effect in an analysis of in-use steel stocks in 200 countries, showing that per capita steel in stocks in countries with a long industrial history (e.g. US, UK, Germany) had saturation levels between 11 and 16 tonnes. More recently, Bleischwitz et al. (2018) confirmed the occurrence of a saturation effect for four materials (steel, cement, aluminium and copper) in four industrialised countries (Germany, Japan, UK, US) together with China. These findings have led to the revision of some material demand forecasts, which previously had been based solely on population and economic trends.

The saturation effect for material stocks is critical for managing material demand in **developed countries**. Materials are required to meet demand for the creation of new stocks and the maintenance of existing stocks (Gutowski et al. 2017). Once saturation is attained the need for new stocks is minimised, and materials are only required for replacing old stocks and maintenance. Saturation allows material efficiency strategies (such as lightweight design, longer lifetimes, and more intense use) to reduce the required per capita level of material stocks, and material circularity strategies (closing material loops through remanufacture, reuse, recycling) to lessen the energy and carbon impacts required to maintain the material stock. However, it should be noted that some materials still show little evidence of saturation (i.e., plastics, see Box 11.2). Furthermore, meeting climate change targets in developed countries will require the construction of new low-carbon infrastructures (i.e., renewable energy generation, new energy distribution and storage systems, electric vehicles and building heating systems) which may increase demand for emissions intensive materials (i.e. steel, concrete, glass).

For **developing countries**, who are still far from saturation levels, strong growth for new products and the creation of new infrastructure capacity may still drive global material demand. However, there is an expectation that economic development can be achieved at lower per capita material stock levels, based on the careful deployment of material efficiency and circularity by design (Grubler et al. 2018).

11.3.2 Material efficiency

ME—the delivery of goods and services with less material—is increasingly seen as an important strategy for reducing GHG emissions in industry (IEA 2017, 2019b). Options to improve ME exist at every stage in the life-cycle of materials and products, as shown in Figure 11.7. This includes: designing products which are lighter, optimising to maintain the end-use service while minimizing material use, designing for circular principles (i.e. longer life, reusability, repairability, and ease of high quality recycling); pushing manufacturing and fabrication process to use materials and energy more efficiently and recover material wastes; increasing the capacity, intensity of use, and lifetimes of product in use; improving the recovery of materials at end-of-life, through improved remanufacturing, reuse and recycling processes. For more specific examples see Allwood et al. (2012); Rissman et al. (2020); Scott et al. (2019); Hertwich et al. (2019) and Lovins (2018).

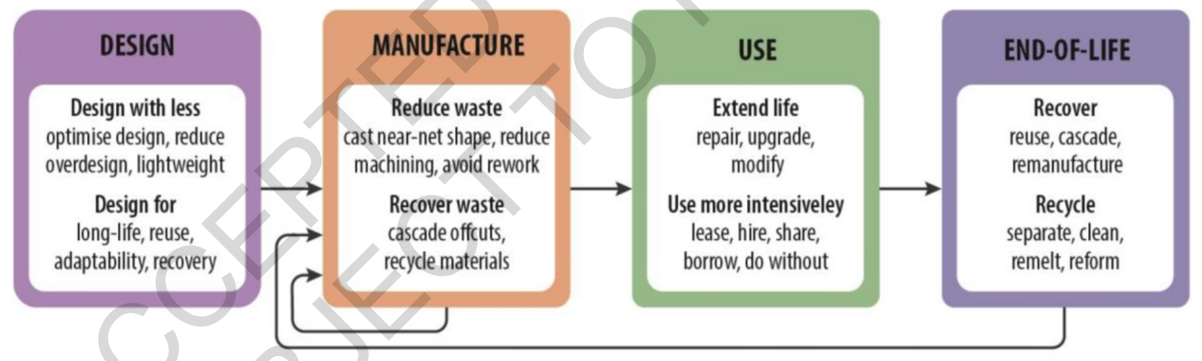


Figure 11.7 Material efficiency strategies across the value chain

Source: derived from strategies in Allwood et al. (2012).

ME provides plentiful options to reduce emissions, yet because interventions are dispersed across supply chains and span many different stakeholders, this makes assessing mitigation potentials and costs more challenging. For this reason, ME interventions have traditionally been under-represented in climate change scenario modelling and integrated assessment models (IAMs) (Grubler et al. 2018; Allwood 2018). However, two advances in the modelling of materials flows have underpinned the recent emergence of ME options being included in climate scenario modelling.

Firstly, over many years, the academic community has built up detailed global material flow maps of the processing steps involved in making energy-intensive materials. Some prominent recent examples include: steel (Gonzalez Hernandez et al. 2018b), pulp and paper (Van Ewijk et al. 2018), petrochemicals (Levi and Cullen 2018). In addition, material flow maps at the regional and sectoral levels have flourished, for example,: steel (Serrenho et al. 2016) and cement (Shanks et al. 2019) in the UK; automotive sheet-metal (Horton et al. 2019); and steel powder applications (Azevedo et al. 2018). The detailed and transparent physical mapping of material supply chains in this manner enables ME interventions to be traced back to where emissions are released, and allows these options to be compared against decarbonisation and traditional energy efficiency measures (Levi and Cullen 2018). For example, a recent analysis by Hertwich et al. (2019) makes the link between ME strategies and reducing greenhouse gas emissions in buildings, vehicles and electronics, while Gonzalez Hernandez et al. (2018a) examines leveraging ME as a climate strategy in EU policy. Research to explore the combined analysis of materials and energy, using exergy analysis (for steel, (Gonzalez Hernandez et al. 2018b)) allows promising comparisons across industrial sectors.

Secondly, many ME interventions result in immediate GHG emissions savings (short-term), for example, light-weighting products, re-using today's product components, and improving manufacturing yields. Yet, for other ME actions emissions savings are delayed temporally (long-term). For example, designing a product for future reuse, or with a longer-life, only reaps emissions savings at the end of the product life, when emissions for a replacement product are avoided. Many durable products have long life-times (cars >10 years, buildings >40 years) which requires dynamic modelling of material stocks, over time, to enable these actions to be included in scenario modelling activities. Consequently, much effort has been invested recently to model material stocks in use, to estimate their lifetimes, and anticipate the future waste and replenishment materials to maintain existing stocks and grow the material stock base. Dynamic material models have been applied to material and product sectors, at the country and global level. These include, for example: vehicles stocks in the UK (Serrenho et al. 2017; Craglia and Cullen 2020) and in China (Liu et al. 2020); buildings stocks in the UK (Cabrera Serrenho et al. 2019), China (Hong et al. 2016; Cao et al. 2018, 2019) and the European Union (Sandberg et al. 2016); electronic equipment in Switzerland (Thiébaud et al. 2017); specific material stocks, such as cement (Cao et al. 2020, 2017), construction materials (Sverdrup et al. 2017; Habert et al. 2020), plastics (Geyer et al. 2017), copper (Daehn et al. 2017), and all metals (Elshkaki et al. 2018); all materials in China (Jiang et al. 2019), Switzerland (Heeren and Hellweg 2019) and the world (Krausmann et al. 2017).

These two advances in the knowledge base have allowed the initial inclusion of some ME strategies in energy and climate change scenario models. The International Energy Agency (IEA) first created a ME scenario (MES) in 2015, with an estimated 17% reduction in industrial energy demand in 2040 (IEA 2015). World energy outlook report includes a dedicated sub-chapter with calculations explicitly on industrial material efficiency (IEA 2019c). They also include ME options in their modelling frameworks and reporting, for example for petrochemicals (IEA 2018a), and in the Material Efficiency in Clean Energy Transitions report (IEA 2019b). In Grubler et al. (2018) 1.5 degree Low Energy Demand (LED) scenario, global material output decreases by 20% from today, by 2050, with one-third due to dematerialisation, and two-thirds due to ME, resulting in significant emissions savings. Material Economics analysis of Industrial Transformation 2050 (Material Economics 2019), found that resource efficiency and circular economy measures (i.e. ME) could almost halve the 530 $MtCO_2$ yr^{-1} emitted by the basic materials sectors in the EU by 2050. Finally, the Emissions gap report, UNEP (2019) includes an assessment of potential material efficiency savings in residential buildings and cars.

Clearly, more work is required to fully integrate ME strategies into mainstream climate change models and future scenarios. Efforts are focused on endogenising ME strategies within climate change modelling, assessing the synergies and trade-offs which exist between energy efficiency and ME interventions, and building up data for the assessment emissions saved and the cost of mitigation from real ME actions. This requires analysts to work in cross-disciplinary teams and to engage with stakeholders from across the full breadth of material supply chains. Efforts should be prioritised to foster engagement between the IAM community and emerging ME models based in the Life Cycle

Assessment, Resource Efficiency, and Industrial Ecology communities (see also Sharmina et al. (2021)).

11.3.3 Circular economy and industrial waste

Circular economy (CE) is another effective approach to mitigate industrial GHG emissions and has been widely promoted worldwide since the fourth IPCC assessment report (AR4). From an industrial point of view, CE focuses on closing the loop for materials and energy flows by incorporating policies and strategies for more efficient energy, materials and water consumption, while emitting minimal waste to the environment (Geng et al. 2013). Moving away from a linear mode of production (sometimes referred to as an "extract-produce-use-discard" model), CE promotes the design of durable goods that can be easily repaired, with components that can be reused, remanufactured, and recycled (Wiebe et al. 2019). In particular, since CE promotes reduction, reuse and recycling, a large amount of energy and GHG intense virgin material processing can be reduced, leading to significant carbon emission reductions. For example, in the case of aluminium, the energy efficiency of primary production is relatively close to best available technology (See **Figure 11.8**) while switching to production using recycled materials requires only about 5% as much energy (11.4.1.4). However, careful evaluation is needed from a life cycle perspective since some recycling activities may be energy and emission intensive, for example, chemical recycling of plastics (11.4.1.3).

As one systemic approach, CE can be seen as conducted at different levels, namely, at the micro-level (within a single company, such as process integration and cleaner production), meso-level (between three or more companies, such as industrial symbiosis or eco-industrial parks) and macro-level (cross-sectoral cooperation, such as urban symbiosis or regional eco-industrial network). Each level requires different tools and policies, such as CE-oriented incentive and tax policies (macro-level), and eco-design regulations (micro-level). This section is focused on industry and a broader discussion of the CE concept is found in Box 12.2 and section 5.3.4.2.

Micro-level: More firms have begun to implement the concept of CE, particularly multi-national companies, since they believe that multiple benefits can be obtained from CE efforts, and it has become common across sectors (D'Amato et al. 2019). Typical CE tools and policies at this level include cleaner production, eco-design, environmental labelling, process synthesis, and green procurement. For instance, leading chemical companies are incorporating CE into their industrial practices, for example, through the design of more recyclable and degradable plastics, a differentiated and market-driven portfolio of resins, films and adhesives that deliver a total package that is more sustainable, cost-efficient and capable of meeting new packaging and plastics preferences. Problematically, at the same time the plastics industry is improving recyclability it has, for example, been expanding into markets without recycling capacity (Mah 2021). Similarly, automakers are pursuing strategies to increase the portion of new vehicles that is fully recyclable when they reach end of life, with increasing ambitions for using recycled material, largely motivated by end-of-life vehicle regulations. This will require networks are available to collect and sort all the materials in vehicles, and policy incentives to do it (Wiebe et al. 2019; Soo et al. 2021).

Meso-level: Industrial parks first appeared in Manchester, UK, at the end of the 19th century and they have been implemented in industrialized countries for maximizing energy and material efficiency, which has also merit for CO_2 emissions reduction, as stated well in AR5. Industrial parks reduce the cost of infrastructure and utilities by concentrating industrial activities in planned areas, and are typical founded around large, long term anchor companies. Complementary industries and services provided by industrial parks can entail diversified effects on the surrounding region and stimulate regional development (Huang et al. 2019a). This is crucial for small and medium enterprises (SMEs) because they often lack access to information and funds for sophisticated technologies.

Typical CE tools and policies at this level include sustainable supply chains and industrial symbiosis. A common platform for sharing information and enhancing communication among industrial stakeholders through the application of information and telecommunication technologies is helpful for facilitating the creation of industrial symbiosis. The main benefit of industrial symbiosis is the overall reduction of both virgin materials and final wastes, as well as reduced/avoided transportation costs from byproduct exchanges among tenant companies, which can specifically help small and medium sized enterprises to improve their growth and competitiveness. From climate perspective, this indicates significant industrial emission mitigation since the extraction, processing of virgin materials and the final disposal of industrial wastes are more energy-intensive. Also, careful site selection of such parks can facilitate the use of renewable energy. Due to these advantages, eco-industrial parks have been actively promoted, especially in East Asian countries, such as China, Japan and South Korea, where national indicators and governance exist (Geng et al. 2019). For instance, the successful implementation of industrial symbiosis at Dalian Economic and Technological Development Zone has achieved significant co-benefits, including GHG emission reduction, economic and social benefits and improved ecosystem functions (Liu et al. 2018). Another case at Ulsan industrial park, South Korea, estimated that 60,522 tonnes CO_2 were avoided annually through industrial symbiosis between two companies (Kim et al. 2018b). The case of China shows a great potential of implementing these measures, estimating 111 million tonne CO_2 equivalent will be reduced in 213 national-level industrial parks in 2030 compared with 2015 (Guo et al. 2018). As such, South Korea's national eco-industrial park project has reduced over 4.7 million tonne CO_2 equivalent through their industrial symbiosis efforts (Park et al. 2019). Meso-level CE solutions have been identified as essential for industrial decarbonisation (see 11.4.3). Moreover, waste prevention as the top of the so-called "waste hierarchy" can be promoted on the meso-level for specific materials or product systems. For instance, the European Environment Agency published a report on plastic waste prevention approaches in all EU 28 member states (Wilts and Bakas 2019). However, challenges exist for industrial symbiosis activities, such as the inter-firm contractual uncertainties, the lack of synergy infrastructure, and the regulations that hamper reuse and recycling. Therefore, necessary legal reforms are needed to address these implementation barriers.

Macro-level: The macro- level uses both micro- and meso-level tools within a broader policy strategy, addressing the specific challenge of CE as a cross-cutting policy (Wilts et al. 2016). More synergy opportunities exist beyond the boundary of one industrial park. This indicates the necessity of scaling up industrial symbiosis to urban symbiosis. Urban symbiosis is defined as the use of by-products (waste) from cities as alternative raw materials for energy sources for industrial operations (Sun et al. 2017). It is based on the synergistic opportunity arising from the geographic proximity through the transfer of physical sources (waste materials) for environmental and economic benefits. Japan is the first country to promote urban symbiosis. For instance, the Kawasaki urban symbiosis efforts can save over 114,000 tons of CO_2 emission annually (Ohnishi et al. 2017). Another simulation study indicates that Shanghai (the largest Chinese city) has a potential of saving up to 16.8 $MtCO_2$ through recycling all the available wastes (Dong et al. 2018). As such, the simulation of urban energy symbiosis networks in Ulsan, South Korea indicates that 243,396 $tCO_2^{-1}\cdot yr^{-1}$ emission and 48 million $USD\cdot yr^{-1}$ fuel cost can be saved (Kim et al. 2018a). Moreover, Wiebe et al. (2019) estimates that the adoption of the CE can lead to a significantly lower global material extraction compared to a baseline. Their global results range from a decrease of about 27% in metal extraction to 8% in fossil fuel extraction and use, 8% in forestry products, and about 7% in non-metallic minerals, indicating significant climate change benefits. A macro-perspective calculation on the circulation of iron in Japan's future society shows that CO_2 emissions from the steel sector can be reduced by 56% as per the following assumptions: the amount recovered from social stock is the same as the amount of inflow, and all scrap was used domestically, and the export of steel products is halved (LCS 2018). A key challenge is to go beyond ensuring proper waste management to setting metrics, targets and incentives to preserve the incorporated value in specific waste streams. Estimations for Germany have shown that despite recycling rates of 64% for all solid waste streams, these activities only lead to a resource use reduction of only 18% (Steger et al. 2019). In general, the identification of the most appropriate CE method for different countries requires understanding and information exchange on background conditions, local policies and myriad other factors influencing material flows from the local up to the global level (Tapia Carlos et al. 2019). Also, an information platform should be created at the national level so that all the stakeholders can share their CE technologies and expertise, information (such as materials/energy/water consumption data), and identify the potential synergy opportunities.

11.3.4 Energy Efficiency

Energy efficiency in industry is an important mitigation option and central in keeping 1.5°C within reach (IPCC SR1.5). It has long been recognized as the first mitigation option in industry (Yeen Chan and Kantamaneni 2016; Nadel and Ungar 2019; IEA 2021a). It allows reduction of the necessary scale of deployment for low-carbon energy supplies and associated mitigation costs (Energy Transitions Commission 2018). The efficiency potentials are greatest in the non-energy intensive industries and often relatively limited in energy intensive ones, such as steel (Pardo and Moya 2013; Arens et al. 2017; Kuramochi 2016). Deep decarbonisation in these subsectors requires fundamental process changes but energy efficiency remains important to reduce costs and the need for low-carbon energy supplies.

Below, we focus mainly on the technical progress and on new options that are reflected in the literature since AR5 and refer the reader there for a broader and deeper treatment of energy efficiency. Digitalisation and the development of industrial high-temperature heat pumps are two notable technology developments that can facilitate energy efficiency improvements.

Industrial energy efficiency can be improved through multiple technologies and practices (Tanaka 2011; Fawkes et al. 2016; Crijns-Graus et al. 2020; IEA 2020a; Lovins 2018). There are two parallel processes in improvement of SEC: progress in energy-efficient BAT, and moving the SEC of industrial plants towards BAT. Both slow down as theoretical thermodynamic minimums are approached (Gutowski et al. 2013). For the last several decades the focus has been on effective spreading of BAT technologies through application of policies for worldwide diffusion of energy-saving technologies (see 11.6). As a result the SEC for many basic primary materials is approaching BAT and there are signs that energy efficiency improvements have been slowing down over recent decades (IEA 2019d, 2020a, 2021a) (**Figure 11.8**).

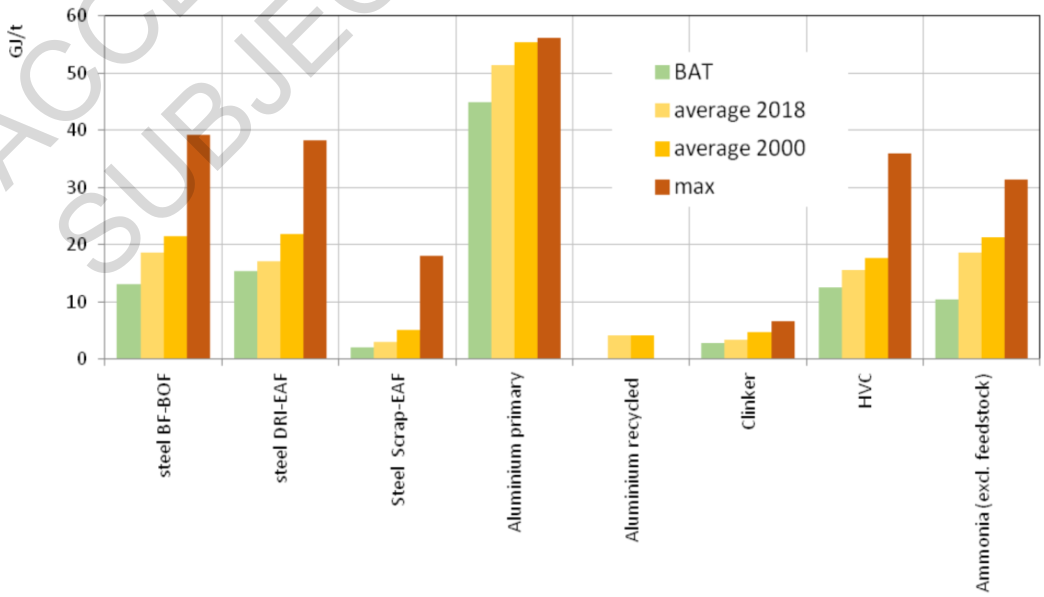


Figure 11.8 Energy efficiency indicators for basic material production. Energy accounting is based on final energy use. Sectoral boundaries for steel are as defined in (IEA 2020c).

Sources: Calculated based on (IEA 2017, 2018b; IEA and WBCSD 2018; IEA 2020b; Hasanbeigi et al. 2012; UNIDO 2010; Saygin et al. 2011; WBCSD 2016; Crijns-Graus et al. 2020; Napp et al. 2014; Moya and Pardo 2013; International Aluminium Institute 2020; IEA 2019b, 2020c)

11.3.4.1 Heat use energy efficiency improvement

While about 10% of global GHG emissions originate from combustion to produce high temperature heat for basic material production processes (Sandalow et al. 2019), limited efforts have been made to decarbonize heat production. There is still a large potential for using various grades of waste heat and the development of high-temperature heat pumps facilitates its use. NEDO (2019) applies a 'Reduce, Reuse, and Recycle' concept for improved energy efficiency, and we use this frame our discussion of heat efficiency.

Reduce refers to reducing heat needs via improved thermal insulation, for example, where porous type insulators have been developed with thermal conductivity half of what is traditionally achieved by heat resistant bricks under conditions of high compressive strength (Fukushima and Yoshizawa 2016). *Reuse* refers to waste heat recovery. A study for the EU identified a waste heat potential of about 300 $TWh \cdot yr^{-1}$, corresponding to about 10 % of total energy use in industry. About 50% of this was below 200°C, about 25% at temperatures 200–500°C, and 25% at temperatures of 500°C and above (Papapetrou et al. 2018). A survey conducted in Japan showed that 9% of the input energy is lost as waste heat, of which heat below 199°C accounts for 68% and that below 149°C was 29% (NEDO 2019). McBrien et al. (2016) identified that in steel sector process heat recovery presently saves 1.8 GJ per tonne of hot rolled steel, while integrated across all production processes heat recovery with conventional heat exchange could save 2.5 GJ per tonne, and it scales up to 3.0 GJ per tonne using an alternative heat exchange that recovers energy from hot steel. High temperature industrial heat pumps represent a new and important development for upgrading waste heat and at the same time the facilitate electrification. One recent example is a high temperature heat pump that can raise temperatures up to 165°C at a coefficient of performance (COP) of 3.5 by recovering heat from unused hot water (35–65°C) (Arpagaus et al. 2018). Commercially available heat pumps can deliver 100–150°C but at least up to 280°C is feasible (Zühlsdorf et al. 2019). Mechanical vapor recompression avoids the loss of latent heat by condensation, then it acts as a highly efficient heat pump with a 5–10 COP (Philibert 2017a).

Waste heat to power (WHP), or *Recycle* in NEDO´s terms, is also an underutilised option. For example, a study for the cement, glass and iron industries in China showed that current technology enables only 7–13% of waste heat to be used for power generation. With improved technologies, potentially 40–57% of waste heat with temperatures above 150°C could be used for power generation via heat recovery. Thermal power fluctuations can be a challenge and negatively affect the operation and economic feasibility of heat recovery power systems such as Steam and/or Organic Rankine Cycle. In such cases, latent heat storage technology and intermediate storage units may be applied (Jiménez-Arreola et al. 2018). The development of thermoelectric conversion materials that produce power from unused heat and energy harvested from higher temperature environment is also progressing, with several possible applications in industrial processes (Ohta et al. 2018; Jood et al. 2018; Lv et al. 2018; Gayner and Kar 2016). A potential early application in industry is to power wireless sensors, a niche that uses microwatts or milliwatts, and avoid power cables (Champier 2017).

11.3.4.2 Smart energy management

Energy management systems to reduce energy costs in an integrated and systematic manner were first developed in the 1970s, mainly in low energy resource countries, for example, by establishing energy managers and institutionalizing management targets (Tanaka 2011). Strategic energy management has since then evolved and been promoted through the establishment of dedicated organizational infrastructures for energy use optimization, such as ISO-50001 which specifies the requirements for establishing, implementing, maintaining, and improving an energy management system (Biel and Glock 2016; Tunnessen and Macri 2017). Digitalisation, sometimes referred to as Industry 4.0, facilitates further improvements in process control and optimisation through technology development involving sensors, communications, analytics, digital twins, machine learning, virtual reality, and other simulation and computing technologies (Rogers 2018), all of which can improve energy efficiency. One example is combustion control systems, where big data analysis of factors affecting boiler efficiency, operation optimization and load forecasting have been shown that it can lead to energy savings of 9% (Wang et al. 2017).

Smart energy systems with real time monitoring allow for optimization of innovative technologies, energy demand response, balancing of energy supply and demand including that on real time pricing, and product quality management, and prediction and reduction of idle time for workers and robots (Legorburu and Smith 2018; Pusnik et al. 2016; Ferrero et al. 2020; ISO 2018; ERIA 2016; Nimbalkar et al. 2020). IEA estimated that smart manufacturing could deliver 15 EJ in energy savings between 2014 and 2030 (IEA 2019d). Smart manufacturing systems that integrate manufacturing intelligence in real time through the entire production operation have not been yet widely spread in the industry. Examples have been demonstrated and integrated in real operation in the electrical appliance assembly industry (Yoshimoto 2016). Combining process controls and automation allows cost optimization and improved productivity (Edgar and Pistikopoulos 2018).

11.3.5 Electrification and fuel switching

The principle of electrification and fuel switching as a GHG mitigation strategy is that industries, to the extent possible, switch their end uses of energy from a high GHG intensity energy carrier to a lower or zero intensity one, including both its direct and indirect production and end-use GHG emissions. In general, and non-exclusively, this implies a transition from coal (~0.09 $tCO_2 \cdot GJ^{-1}$ on combustion), refined petroleum products (~0.07 $tCO_2 \cdot GJ^{-1}$), and natural gas (~0.05 $tCO_2 \cdot GJ^{-1}$) to biofuels, direct solar heating, electricity, hydrogen, ammonia, or net zero synthetic hydrocarbon fuels. Switching to these energy carriers is not necessarily lower emitting, however; how they are made matters.

Fuel switching has already been observed to reduce direct combustion CO_2 emissions in many jurisdictions. There are significant debates about the net effect of upstream fossil fuel production and fugitive emissions, but observers have noted that in the case of US power generation it would take a leakage rate of ~2.7% from natural gas production to undo the direct fuel switching from coal mitigation effect, and the value is likely higher in most cases (Alvarez et al. 2012; Hausfather 2015). Coal mine methane emissions are also estimated to be substantially higher than previously assessed (Kholod et al. 2020). Alvarez et al. (2018) estimated US fugitive emissions (not including the Permian) at 2.3% of supply, 60% more than previously estimated, while recent Canadian papers indicate fugitive emissions are at least 50% more than reported (Chan et al. 2020; MacKay et al. 2021). However, given the potential for energy supply infrastructure lock-in effects (Tong et al. 2019), purely fossil fuel to fossil fuel switching is a limited and potentially dangerous strategy unless it is used very carefully and in a limited way.

Biofuels come in many forms, including ones that are nearly identical to fossil fuels but sourced from biogenic sources. Solid biomass, either from direct from wood chips, lignin or processed pellets are the most commonly used renewable fuel in industry today and are occasionally used in cement kilns and boilers. Biomethane, biomethanol, and bioethanol are all commercially made today using fermentation and anaerobic digestion techniques and are mostly "drop-in" compatible with fossil fuel equivalents. In principle they cycle carbon in and out of the atmosphere, but their life cycle GHG intensities are typically not GHG neutral due to land use changes, soil carbon depletion, fertilizer use, and other dynamics (Hepburn et al. 2019), and are highly case specific. Most commercial biofuel feedstocks come from agricultural (e.g. corn) and food waste sources, and the feedstock is limited; to meet higher levels of biomass use a transition to using higher cellulose feedstocks like straw, switchgrass and wood waste, available in much larger quantities, must be fully commercialized and deployed. Significant efforts have been made to make ethanol from cellulosic biomass, which promises much higher quantities, lower costs, and lower intensities, but commercialization efforts, with a few exceptions, have largely not succeeded (Padella et al. 2019). The IEA estimates, however, that up to 20% of today's fossil methane use, including by industry, could be met with biomethane (IEA 2020g) by 2040, using a mixture of feedstocks and production techniques. Biofuel use may also be critical for producing negative emissions when combined with carbon capture and storage, i.e. BECCS. Most production routes for biofuels, biochemicals and biogas generate large side streams of concentrated CO_2 which is easily captured, and which could become a source of negative emissions (Sanchez et al. 2018) (See section 11-3511.3.6). Finally, it should be noted that biofuel combustion can, if inadequately controlled, have substantial negative local air quality effects, with implications for SDGs 3, 7 and 11.

There is a large identified potential for direct solar heating in industry, especially in regions with strong solar insolation and sectors with lower heat needs (<180°C), for example, food and beverage processing, textiles, and pulp and paper (Schoeneberger et al. 2020). The key challenges to adoption are site and use specificity, capital intensity, and a lack of standardized, mass manufacturing for equipment and supply chain to provide them.

Switching to electricity for end-uses, or "direct electrification", is a highly discussed strategy for net zero industrial decarbonisation (Palm et al. 2016; Lechtenböhmer et al. 2016; Davis et al. 2018; Bataille et al. 2018a; UKCCC 2019b; Åhman et al. 2017; Axelson et al. 2018; Material Economics 2019). Electricity is a flexible energy carrier that can be made from many forms of primary energy, with high potential process improvements in terms of end-use efficiency (Eyre 2021), quality and process controllability, digitizability, and no direct local air pollutants (Deason et al. 2018; McMillan et al. 2016; Jadun et al. 2017; Mai et al. 2018). The net GHG effect of electrification is contingent on how the electricity is made, and because total output increases can be expected for full effect it should be made with a very low GHG intensity primary sources (i.e. <50 grams $CO_2 \cdot kWh^{-1}$: e.g. hydroelectricity, nuclear energy, wind, solar photovoltaics, or fossil fuels with 95+% carbon capture and storage (IPCC 2014)). This has strong implications for the electricity sector and its generation mix when the goal is a net zero emissions electricity system. Despite their falling costs, progressively higher mixes of variable wind and solar on a given grid will require support from grid flexibility sources, including demand response, more transmission, storage on multiple time scales, or firm low to negative emissions generation sources (e.g. nuclear energy, hydrogen fuel cells or turbines, biofuels, fossil or biofuels with CCS, geothermal) to moderate costs (Jenkins et al. 2018; Sepulveda et al. 2018; Williams et al. 2021). Regions that may be slower to reduce the GHG intensity of their electricity production will likely need to consider more aggressive use of other measures, like energy and material efficiency or bioenergy.

The long-term potential for full process electrification is a very sector by sector and process by process phenomenon, with differing energy and capacity needs, load profiles, stock turnover, capacity for demand response, and characteristics of decision makers. Industrial electrification is most viable in the near term in cases with: minimal retrofitting and rebuild in processes; with relatively low local electricity costs; where the degree of process complexity and process integration is more limited and extensive process re-engineering would not be required; where combined heat and power is not used; where induction heating technologies are viable; and where process heating temperatures are lower (Deason et al. 2018).

For these reasons, lighter, manufacturing orientated industries are more readily electrifiable than heavier industry like steel, cement, chemicals and other sectors with high heat and feedstock needs. Steam boilers, curing, drying and small-scale process heating, with typically lower maximum heat temperature needs (<200-250°C) are readily electrifiable with appropriate fossil fuel to electricity price ratios (accounting for capital costs and efficiencies), and direct induction and infrared heating are available for higher temperature needs. These practices are uncommon outside regions with ample hydroelectric power due to the currently relatively low cost of coal, natural gas and heating oil, and especially when there is no carbon combustion cost. Madeddu et al. (2020) argue up to 78% of Europe's industrial energy requirements are electrifiable through existing commercial technologies. In contrast (Mai et al. 2018) saw only a moderate industrial heat supply electrification in their high electrification scenario for the US.

Electrification has also been explored in: raw and recycled steel (Fischedick et al. 2014b; Vogl et al. 2018); ammonia (Philibert 2017a; Bazzanella and Ausfelder 2017); and chemicals (Palm et al. 2016; Bazzanella and Ausfelder 2017). While most chemical production of feedstock chemicals (e.g. H_2, NH_3, CO, CH_3OH, C_2H_4, C_2H_6, C_2H_5OH) is done thermo-catalytically today, it is feasible to use direct electrocatalytic production, by itself or in combination with utilization of previously captured carbon sources if a fossil fuel feedstock is used, or well-known bio-catalytic (e.g. fermentation) and thermo-catalytic processes (De Luna et al. 2019; Kätelhön et al. 2019; Bazzanella and Ausfelder 2017). It may even be commercially possible to electrify cement sintering and calcination through plasma or microwave options (Material Economics 2019).

Increased electrification of industry will result in increased overall demand for electricity. For example, 75 TWh of electricity was used by steel in the EU in 2015 (out of 1000 TWh total used by industry), Material Economics (2019), varying between their new process, circularity and CCUS scenarios, projects increased demand to 355 (+373%), 214 (+185%) and 238 (+217%) TWh. These values are consistent with (Vogl et al. 2018), which projects a tripling of electricity demand in the German or Swedish steel industries if hydrogen direct reduced iron and electric arc furnace steel making (DRI EAFs) replaces BF-BOFs. Material Economics (2019) was conservative with its use of electricity in chemical production, making preferential use of biofeedstocks and some CCUS, and electricity demand still rose from 118 TWh to 510, 395 and 413 TWh in their three scenarios. (Bazzanella and Ausfelder 2017), exploring deeper reductions from the chemical sector using more electrochemistry, projected scenarios with higher electricity demands of 960–4900 TWh (140% of projected available clean electricity at the time) with maximum electricity use. In counterpoint, however, with revised wind capabilities and costs, the (IEA 2019e) Offshore Wind Outlook indicates that ten times current EU electricity use could be produced if necessary. Greater use of electro-catalytic versus thermo-catalytic chemistry, as projected by (De Luna et al. 2019), could greatly reduce these electricity needs, but the technology readiness levels are currently low. Finally, the (UKCCC 2019b), which focussed primarily on CCS for industry in its "Further Ambition" scenario (the UK currently consumes about 300 TWh), in its supplementary "Further electrification" scenario projects an additional 300 TWh for general electrolysis needs and another 200 TWh for synthetic fuel production.

While it has been demonstrated that almost any heating end use can be directly electrified, this would imply very high instantaneous thermal loads for blast furnace-basic oxygen furnace (BF-BOF) steel production, limestone calcination for cement and lime production, and other end-uses where flame front (1000°C–1700°C) temperatures are currently needed. This indicates a possible need for another energy carrier to minimize instantaneous generation and transmission needs. These needs can be met at varying current and potential future costs using: bioliquids or gases hydrogen, ammonia, or net zero synthetic hydrocarbons or alcohols.

Broadly speaking, **hydrogen** can contribute to a cleaner energy system in two ways. 1) Existing applications of hydrogen (e.g., nitrogen fertilizer production, refinery upgrading) can use hydrogen produced using alternative, cleaner production methods. 2) New applications can use low GHG hydrogen as an alternative to current fuels and inputs, or as a complement to the greater use of electricity in these applications. In these cases—for example in transport, heating, industry (e.g. hydrogen direct reduced iron steel production) and electricity—hydrogen can be used in its pure form, or be converted to hydrogen-based fuels, including ammonia, or synthetic net zero hydrocarbons & alcohols like methane or methanol (IEA 2019f). The IEA states that **hydrogen** could be used to help integrate more renewables, including by enhancing storage options and "exporting sunshine & wind" from places with abundant resources; decarbonize steel, chemicals, trucks, ships and planes; and boost energy security by diversifying the fuel mix & providing flexibility to balance grids (IEA 2019f).

Around 70 $Mtonne \cdot yr^{-1}$ of pure hydrogen is produced today, 76% from natural gas and 23% from coal, resulting in emissions of roughly 830 $MtCO_2 \cdot yr^{-1}$ in 2016/17 (IEA 2019f), or 4.7% of global industrial direct and indirect emissions (waste excluded, see Table 11.1) . Fuels refining (~410 $MtCO_2 \cdot yr^{-1}$) and production of ammonia (420 $MtCO_2 \cdot yr^{-1}$) largely dominate its uses. Another 45 Mtonnes hydrogen is being produced along with other gases, on purpose or as by-products, and used as fuel, to make methanol or as a chemical reactant (IEA 2019f). Very low and potentially zero GHG (depending on the energy source) **hydrogen** can be made via: electrolysis separation of water into hydrogen and oxygen (Glenk and Reichelstein 2019), also known as "green H_2"; electrothermal separation of water, as done in some nuclear plants (Bicer and Dincer 2017); partial oxidation of coal or naphtha or steam/auto methane reforming (SMR/ATR) combined with CCS (Leeson et al. 2017), or "blue H_2"; methane pyrolysis, where the hydrogen and carbon are separated thermally and the carbon is left as a solid (Ashik et al. 2015; Abbas and Wan Daud 2010), or via biomass gasification (Ericsson 2017) (which could be negative emissions if the CO_2 from the gasification process is sequestered). All these processes would in turn need to be run using very low or zero GHG energy carriers for the resulting hydrogen to also be low GHG emissions.

Ammonia production, made from hydrogen and nitrogen using the Haber-Bosch process, is the most voluminous chemical produced from fossil fuels, being used as feedstock for nitrogen fertilizers and explosives, as well as a cleanser, refrigerant and for other uses. Most ammonia is made today using methane as the hydrogen feedstock and heat source but has been made using electrolysis-based hydrogen in the past, and there are several announced investments to resume doing so. If ammonia is used as a combustion fuel care must be taken to avoid N_2O as a GHG and NO_x in general as a local air pollutant.

Hydrogen can also be combined with low to zero net GHG carbon (see 11.3.6 and oxygen and made into **methane, methanol** and other potential net zero **synthetic hydrocarbons & alcohol** energy carriers using methanation, steam reforming and Fischer-Tropsch processes, all of which can provide higher degrees of storable and shippable high temperature energy using known industrial processes in novel combinations (Davis et al. 2018; Bataille et al. 2018a). If the hydrogen and oxygen is accessed via electrolysis the terms "power-to-fuel" or "e-fuels" are often used (Ueckerdt et al. 2021). Given their carbon content, if used as fuels, their carbon will eventually be oxidized and emitted as CO_2 to the atmosphere. This makes their net GHG intensity dependent on the carbon source (Hepburn et al. 2019), with recycled fossil fuels, biocarbon and direct air capture carbon all having very different net CO_2 impacts - see the next section on CCS and CCU for elaboration.

START BOX 11.1 HERE

Box 11.1 Hydrogen in industry

The "hydrogen economy" is a long-touted vision for the energy and transport sectors, and one that has gone through hype-cycles since the energy crises in the 1970s (Melton et al. 2016). The widely varying visions of hydrogen futures have mainly been associated with fuel cells in vehicles, small-scale decentralized cogeneration of heat and electricity, and to a certain extent energy storage for electricity (Eames et al. 2006; Syniak and Petrov 2008). However, nearly all hydrogen currently produced is used in industry, mainly for hydrotreating in oil refineries, to produce ammonia, and in other chemical processes, and it is mostly made using fossil fuels.

In the context of net zero emissions new visions are emerging in which hydrogen has a central role to play in decarbonizing industry. Near-term industrial applications for hydrogen includes feeding it into ammonia production for fertilizers, while a noveler application would be as a replacement for coal as the reductant in steelmaking, being piloted by the HYBRIT project in Sweden 2020-2021, and many companies have initiated hydrogen steelmaking projects. As shown in sections 11.3.5 and 11.3.6 there are many other potential applications of hydrogen, some of which are still relatively unexplored. Hydrogen can also be used to produce various lower GHG hydrocarbons and alcohols for fuels and chemical feedstocks using carbon from biogenic sources or direct air capture of CO_2 (Ericsson 2017; Huang et al. 2020).

The geographical distribution of the potential for hydrogen from electrolysis powered by renewables like solar and wind, nuclear electrothermally produced hydrogen, and hydrogen from fossil gas with CCS may reshape where heavy industry is located, how value chains are organized, and what gets transported in international shipping (Gielen et al. 2020; Bataille et al. 2021a; Saygin and Gielen 2021; Bataille 2020a). Regions with bountiful renewables resources, nuclear, or methane co-located with CCS geology may become exporters of hydrogen or hydrogen carriers such as methanol and ammonia, or home to the production of iron and steel, organic platform chemicals, and other energy intensive basic materials. This in turn may generate new trade patterns and needs for bulk transport.

END BOX 11.1 HERE

11.3.6 CCS, CCU, carbon sources, feedstocks, and fuels

Carbon is an important and highly flexible building block for a wide range of fuels, organic chemicals and materials including methanol, ethanol, olefins, plastics, textiles, and wood and paper products. In this chapter we define CCS as requiring return of CO_2 from combustion or process gases or ambient air to the geosphere for geological time periods, i.e. thousands of years (IEA 2009; IPCC 2005; IEA 2019g; Bruhn et al. 2016). CCU is defined as being where carbon (as CO or CO_2) is captured from one process and reused for another, reducing emissions from the initial process, but is then potentially but not necessarily released to the atmosphere in following processes (Tanzer and Ramírez 2019; Detz and van der Zwaan 2019; Bruhn et al. 2016). In both cases the net effect on atmospheric emissions depends on the initial source of the carbon, be it from a fossil fuel, from biomass, or from direct air capture (Cuéllar-Franca and Azapagic 2015; Hepburn et al. 2019) and the duration of storage or use, which can vary from days to millennia.

While CCS and CCU share common capture technologies, what happens to the CO_2 and therefor the strategies that will employ them can be very different. CCS can help maintain near CO_2 neutrality for fossil CO_2 that passes through the process, with highly varying partially negative emissions if the source is biogenic (Hepburn et al. 2019), and fully negative emissions if the source is air capture, all not considering the energy used to drive the above processes. CCS has been covered in other IPCC publications at length, for example, IPCC (2005), and in most mitigation oriented assessments since, for example, the IEA's ETP 2020 and Net Zero scenario reports (IEA 2021a, 2020a). The potentials and costs for CCS in industry vary considerably due to the diversity of industrial processes (Leeson et al. 2017), as well as the volume and purity of different flows of carbon dioxide (Naims 2016); Kearns et al. (2021) provide a recent review. As a general rule it is not possible to capture all the carbon dioxide emissions from an industrial plant. To achieve zero or negative emissions, CCS would need to be combined with some use of sustainably sourced biofuel or -feedstock, or the remaining emissions would need to be offset by CDR elsewhere.

For concentrated CO_2 sources (e.g. cleaning of wellhead formation gas to make it suitable for the pipeline network, hydrogen production using steam methane reforming, ethanol fermentation, or from combustion of fossil fuels with oxygen in a nitrogen free environment, i.e. "oxycombustion") CCS is already amenable to commercial oil and gas reinjection techniques used to eliminate hydrogen sulphide gas and brines at prices of 10–40 USD·tCO_2-eq^{-1} sequestered (Wilson et al. 2003; Leeson et al. 2017). Most currently operating CCS facilities take advantage of concentrated CO_2 flows, for example, from formation gas cleaning on the Snoevit and Sleipner platforms in Norway, from syngas production for the Al Reyadah DRI steel plant in Abu Dhabi, and from SMR hydrogen production on the Quest upgrader in Alberta. Since concentrated process CO_2 emissions are often exempted from existing cap and trade systems, these opportunities for CCS have largely gone unexploited. Many existing projects partially owe their existence to the utilization of the captured CO_2 for enhanced oil recovery, which in many cases counts as both CCS and CCU because of the permanent nature of the CO_2 disposal upon injection if sealed properly (Mac Dowell et al. 2017). There are several industrial CCS strategies and pilot projects working to take advantage of the relative ease of concentrated CO_2 disposal (e.g. LEILAC for limestone calcination process emissions from cement production, HISARNA direct oxycombustion smelting for steel) (Bataille 2020a). An emerging option for storing carbon is methane pyrolysis by which methane is split into hydrogen and solid carbon that may subsequently be stored (Schneider et al. 2020).

There are several post-combustion CCS projects underway globally (IEA 2019g), generally focussed on energy production and processing rather than industry. Their costs are higher but evolving downward – (Giannaris et al. 2020) suggest 47 USD·tCO_2^{-1} for a follow up 90% capture power generation plant based on learnings from the Saskpower Boundary Dam pilot – but crucially these costs are higher than implicit and explicit carbon prices almost everywhere, resulting in limited investment and learning in these technologies. A key challenge with all CCS strategies, however, is building a gathering and transport network for CO_2, especially from dispersed existing sites; hence most pilot are built near EOR/geological storage sites, and the movement towards industrial clustering in the EU and UK (UKCCC 2019b), and as suggested in (IEA 2019f).

In the case of CCU, CO and CO_2 are captured and subsequently converted into valuable products (e.g. building materials, chemicals, synthetic fuels) (Daggash et al. 2018; Styring et al. 2011; Vreys et al. 2019; Artz et al. 2018; Breyer et al. 2019; Brynolf et al. 2018; Bruhn et al. 2016; Kätelhön et al. 2019). CCU has been envisioned as part of the "circular economy" but conflicting expectations on CCU and its association or not with CCS leads to different and contested framings (Palm and Nikoleris 2021). The duration of the CO_2 storage in these products varies from days to millennia according to the application, potentially but not necessarily replacing new fossil, biomass or direct air capture feedstocks, before meeting one of several possible fates: permanent burial, decomposition, recycling or combustion, all with differing GHG implications. While the environmental assessment of CCS projects is relatively straight forward, however, this is not the case for CCU technologies. The net GHG mitigation impact of CCU depends on several factors (e.g. the capture rate, the energy requirements, the lifetime of utilization products, the production route that is substituted, and associated room for improvement along the traditional route) and has to be determined by life cycle CO_2 or GHG analysis (e.g. Nocito and Dibenedetto (2020) and Bruhn et al. (2016)). For example, steel mill gases containing carbon monoxide and carbon dioxide can be used as feedstock together with hydrogen for producing chemicals. In this way, the carbon originally contained in the coke used in the blast furnace is used again, or cascaded, and emissions reduced but not brought to zero. If fossil sourced CO_2 is only reused once and then emitted, the maximum reduction is 50% (Tanzer and Ramírez 2019). The logic of using steel mill CO and CO_2 could equally be applied to gasified biomass, however, with a far lower net GHG footprint, likely negative, which CCU fed by fossil fuels cannot be if end-use combustion is involved.

Partly because of the complexity of the life cycle analysis accounting, the literature on CCU is not always consistent in terms of the net GHG impacts of strategies. For example, Artz et al. (2018), focussed not just on GHG mitigation but multi-attribute improvements to chemical processes from reutilization of CO_2, suggests the largest reduction in the absolute amount of GHGs from CO_2 reutilization could be achieved by coupling of highly concentrated CO_2 sources with carbon-free hydrogen or electrons from low GHG power in so called "Power-to-fuel" scenarios. From the point of view of maximizing GHG mitigation using surplus "curtailed" renewable power, however, Daggash et al. (2018) instead indicates the best use would be for direct air capture and CCS. These results depend on what system is being measured, and what the objective is.

There are several potential crucial transitional roles for synthetic hydrocarbons & alcohols (e.g. methane, methanol, ethanol, ethylene, diesel, jet fuel) constructed using fossil, biomass or direct carbon capture (DAC) and CCU (Fasihi et al. 2017; Sternberg and Bardow 2015; Breyer et al. 2015; Dimitriou et al. 2015; Bataille 2020a; Bataille et al. 2018a). They can allow reductions in the GHG intensity of high value legacy transport, industry and real estate that currently runs on fossil fuels but cannot be easily or readily retrofitted. They can be used by existing long lived energy and feedstock infrastructure, transport and storage, which can compensate for seasonal supply fluctuations and contribute to enhancing energy security (Ampelli et al. 2015). Finally, they can reduce the GHG intensity of end-uses that are very difficult to run on electricity, hydrogen or ammonia (e.g., long haul aviation). However, their equivalent mitigation cost today would be very high (USD 960–1440 $tCO_2\text{-eq}^{-1}$), with the potential to fall to USD 24–324 $tCO_2\text{-eq}^{-1}$) with commercial economies of scale, with very high uncertainty (Hepburn et al. 2019; Ueckerdt et al. 2021; IEA 2020a).

A very large and important uncertainty is the long-term demand for hydrocarbon and alcohol fuels (whether fossil, biomass or DAC based), chemical feedstocks (e.g., methanol and ethylene) and materials, and competition for biomass feedstock with other priorities, including agriculture, biodiversity and other proximate land use needs, as well as need for negative emissions through BECCS. The current global plastics production of around 350 $Mt \cdot yr^{-1}$ is almost entirely based on petroleum feedstock and recycling rates are very low. If this or future demand were to be 100% biomass based it would require tens of exajoules of biomass feedstock (Meys et al. 2021). If demand can be lowered and recycling increased (mechanical as well as chemical) the demand for biomass feedstock can be much lower (Material Economics 2019). Promising routes in the short term would be to utilise CO_2 from anaerobic digestion for biogas and fermentation for ethanol in the production of methane or methanol (Ericsson 2017); methanol can be converted into ethylene and propylene in a methanol-to-olefins process and used in the production of plastics (Box 11.2). New process configurations where hydrogen is integrated into biomass conversion routes to increase yields and utilise all carbon in the feedstock are relatively unexplored (Ericsson 2017; De Luna et al. 2019).

There are widely varying estimates of the capacity of CCU to reduce GHG emissions and meet the net-zero objective. According to Hepburn et al. (2019), the estimated potential for the scale of CO_2 utilisation in fuels varies widely, from 1 to 4.2 $GtCO_2 \cdot yr^{-1}$, reflecting uncertainties in potential market penetration, requiring carbon prices of around USD 40 to 80 tCO_2^{-1}, increasing over time. The high end represents a future in which synthetic fuels have sizeable market shares, due to cost reductions and policy drivers. The low end—which is itself considerable—represents very modest penetration into the methane and fuels markets, but it could also be an overestimate if CO_2-derived products do not become cost competitive with alternative clean energy vectors such as hydrogen or ammonia, or with direct sequestration. Brynolf et al. (2018) indicates that a key cost variable will be the cost of electrolysers for producing hydrogen. Kätelhön et al. (2019) estimate that up to 3.5 $GtC \cdot yr^{-1}$ could be displaced from chemical production by 2030 using CCU, but this would require clean electricity equivalent to 55% of estimated global power production, at the same time other sectors' demand would also be rising. Mac Dowell et al. (2017) suggest that while CCU, and specifically CO_2 based enhanced oil recovery, may be an important economic incentive for early CCS projects (up to 4–8% of required mitigation by 2050), it is unlikely the chemical conversion of CO_2 for CCU will account for more than 1% of overall mitigation.

Finally, there is another class of CCU activities associated with carbonation of alkaline industrial wastes (including iron and steel slags, coal fly ash, mining and mineral processing wastes, incinerator residues, cement and concrete wastes, and pulp and paper mill wastes) using waste or atmospheric CO_2. Given the large volume of alkaline wastes produced by industry, capture estimates are as high at 4 $GtCO_2 \cdot yr^{-1}$ (Pan et al. 2020; Huang et al. 2019c; Kaliyavaradhan and Ling 2017; Cuéllar-Franca and Azapagic 2015; Pasquier et al. 2018; Ebrahimi et al. 2017; Zhang et al. 2020) However, as some alkaline wastes are already used directly as supplementary cementious materials to reduce clinker-to-cement ratios, and their abundant availability in the future is questionable (e.g. steel blast furnace slag and coal fly ash), there will be a strong competition between mitigation uses (see 11.4.2), and the potential for direct removal by carbonation is estimated at about 1 $GtCO_2 \cdot yr^{-1}$ (Renforth 2019).

The above CCU literature has identified that there may be a highly unpredictable competition between fossil, biogenic and direct air capture carbon to provide highly uncertain chemical feedstock, material and fuel needs. Fossil waste carbon will likely initially be plentiful but will add to net atmospheric CO_2 when released. Biogenic carbon is variably, partially net-negative, but the available stock will be finite and compete with biodiversity and agriculture needs for land. Direct air capture carbon will require significant amounts of low GHG electricity or methane with high capture rate CCS (Keith et al. 2018). There are clearly strong interactive effects between low carbon electrification, switching to biomass, hydrogen, ammonia, synthetic hydrocarbons via CCU, and CCS.

11.3.7 Strategy interactions and integration

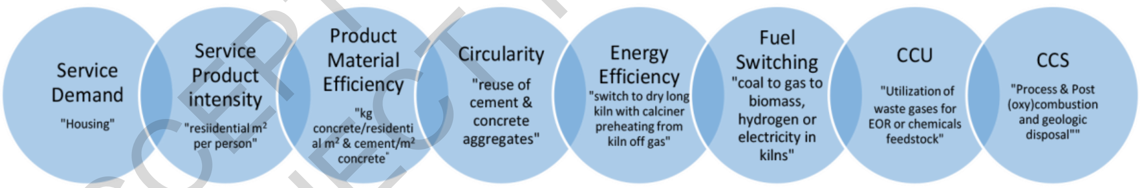


Figure 11.9 Fully interactive, non-sequential strategies for decarbonising industry

In this section we conceptually address interactions between service demand, service product intensity, product material efficiency, energy efficiency, electrication and fuel switching, CCU and CCS, and what conflicts and synergies may exist. Post AR5 a substantial literature has emerged, see Rissman et al. (2020), that addresses integrated and interactive technical deep decarbonization pathways for GHG intense industrial sectors, and how they interact with the rest of the economy (Denis-Ryan et al. 2016; Wesseling et al. 2017; Davis et al. 2018; Axelson et al. 2018; Åhman et al. 2017; Bataille et al. 2018a; Bataille 2020a). It is a common finding across this literature and a related scenario literature (Energy Transitions Commission 2018; Material Economics 2019; IEA 2021a; CAT 2020; UKCCC 2019a,b; IEA 2019b, 2020a) that deep decarbonisation of industry requires integrating all available options. There is no 'silver bullet' and so all behavioural and technological options have to be mobilized, with more emphasis required on the policy mechanisms necessary to engage a challenging transition in the coming decades in highly competitive, currently GHG intense, price sensitive sectors with long lived capital stock (Wesseling et al. 2017; Bataille et al. 2018a; Bataille 2020a), discussed in the final section of this chapter.

While the strategies are not sequential and interact strongly, we discuss them in the order given. Reduced demand through reduced service demand and product intensity per service unit (van Vuuren et al. 2018; Grubler et al. 2018) reduces the need for the next five strategies. Greater material efficiency (see earlier sections) reduces the need for the next four, and so on – see Figure 11.9 above.

Circular economy introduces itself throughout, but mainly at the front end when designing materials and processes to be more materially efficient, efficient in use, and easy to recycle, and at the back end, when a material or product's services life has come to end, and it is time for recycling or sustainable disposal (Korhonen et al. 2018; Murray et al. 2017). The entire chain's potential will be maximized when these strategies are designed in ahead of time instead of considered on assembly, or as a retrofit (Material Economics 2019; Allwood et al. 2012; Gonzalez Hernandez et al. 2018a; IEA 2019b; Bataille 2020a). For example, when designing a building: 1) Is the building shell, interior mass and ducting orientated for passive heating and cooling, and can the shell and roof have building integrated solar PV or added easily, with hard-to-retrofit wiring already incorporated? 2) Are steel and high quality concrete only used where really needed (i.e. for shear, tension and compression strength), can sections be prefabricated off-site, can other materials be substituted, such as wood? 3) Can the interior fittings be built with easy to recycle plastics or other sustainably disposable materials (e.g. wood)? 4) Can this building potentially serve multiple purposes through its anticipated lifetime, are service conduits oversized and easy to access for retrofitting? 5) When it is time to be taken apart, can pieces be reused, and all componnents recycled at high purity levels, for example, can all the copper wiring be easily be found and removed, are the steel beams clearly tagged with their content? The answers to these questions will be very regionally and site specific, and require revision of educational curricula for the entire supply chain, as well as revision of building codes.

Energy efficiency is a critical strategy for net zero transitions and enabling clean electrification (IEA 2021a). Improving the efficiency of energy services provision reduces the need for material intensive energy supply, energy storage, CCU and CCS infrastructure, and limits generation and transmission expansion to meet an ever-higher power demand, with associated generation, transmission, and distribution losses. Using electricity efficiently can help reduces peak demand and the need for peaking plants (currently often powered by fossil fuels), and energy storage systems.

Electrification and final energy efficiency are deeply entangled, because switching to electricity from fossil fuels in most cases improves GJ for GJ end-use energy efficiency: resistance heaters are almost 100% efficient, heat pumps can be 300–400% efficient, induction melting can improve mixing and temperature control, and electric vehicle motors typically translate 90-95% of input electricity to motor drive in contrast to 35–45% for a large, modern internal combustion engine. Overall, the combined effect could be 40 % lower global final energy demand assuming renewable electricity is used (Eyre 2021).

There are potentially complicated physical and market **fuel switching** relationships between low GHG electricity, bioliquids and gases, hydrogen, ammonia, and synthetic hydrocarbons constructed using **CCU**, with remaining CO_2 potentially being disposed of using **CCS**. Whether or not they compete for a wide range of end uses and primary demand needs will be regional and whether or not infrastructure is available to supply them. Regions with less than optimal renewable energy resources, or not sufficient to meet growing needs, could potentially indirectly import them as liquid or compressed hydrogen, ammonia or synthetic hydrocarbon feedstocks made in regions with abundant resources (Armijo and Philibert 2020; Bataille 2020a). Large scale CCU and CCS applications needs additional basic materials to build corresponding infrastructure and energy to operate it thus reducing overall material and energy efficiencies.

There are different roles for different actors in relation to the different mitigation strategies (exemplified in Table 11.2), with institutions and supply chains developed to widely varying levels, for example, while energy efficiency is a relatively mature strategy with an established supply chain, material efficiency is not.

1 **Table 11.2 Examples of the potential roles of different actors in relation to different mitigation strategies indicating the importance of engaging a wide set of actors**
2 **across all mitigation strategies.**

Sectors	Demand control measures (DM)	Materials Efficiency (ME)	Circular Economy	Energy Efficiency	Electrification, hydrogen and fuel switching	CCU	CCS
Architectural, and engineering firms	Build awareness on the material demand implications of e.g., building codes, urban planning, and infrastructure.	Education of designers, architects, engineers, etc. Develop design tools. Map material flows.	Design and build for e.g., repurpose, reuse, and recycle. Improve transparency on volumes and flows.	Maintain high expertise, knowledge sharing, transparency, and benchmarking.	Support innovation. Share best practice. Design for dynamic demand response for grid balancing.	Develop allocation rules, monitoring and transparency. Coordination and collaboration across sectors.	Transparency, monitoring and labelling. Coordination and collaboration for transport and disposal infrastructure.
Industry and service sector	Digital solutions to reduce office space and travel. Service oriented business models for lower product demand.	Design for durability and light weight. Minimize industry scrap.	Design for reuse and recycling. Use recycled feedstock and develop industrial symbiosis.	Maintain energy management systems.	Develop and deploy new technologies in production, engage with lead markets.	Develop new technologies. Engage in new value chains and collaborations for sourcing carbon.	Plan for CCS where possible and phase-out of non-retrofittable plants where necessary.
International bodies	Best practice sharing. Knowledge building on demand options.	Progressivity in international standards (e.g., ISO).	Transparency and regulation around products, waste handling, trade, and recycling.	Maintain efforts for sharing good practice and knowledge.	Coordinate innovation efforts, technology transfer, lead markets, and trade policies.	Coordinate and develop accounting and standards. Ensure transparency.	Align regulation to facilitate export, transport, and storage.
Regional and national government, and cities	Reconsider spatial planning and regulation that has demand implications.	Procurement guidelines and better indicators. Standards and building codes.	Regulation on product design (e.g., Ecodesign directive) Collect material flow data.	Continue energy efficiency policies such as incentives, standards, labels, and disclosure requirements.	R&D and electricity infrastructure. Policy strategies for making investment viable (including carbon pricing instruments).	Align regulation to facilitate implementation and ensure accountability for emissions.	Develop regulation and make investment viable. Resolve long term liabilities.

Civil society and consumer organizations	Information and advocacy related to social norms.	Strengthen lobby efforts and awareness around e.g., planned obsolescence.	Engage in standards, monitoring and transparency.	Monitor progress.	Information on embodied emissions. Assess renewable electricity and grid expansion.	Develop standards and accounting rules.	Ensure transparency and accountability

11.4 Sector mitigation pathways and cross sector implications

This section continues the discussion of the various mitigation options and strategy elements introduced in section 11.3 and makes them explicit for the most relevant industry sectors. For the various sectors 11.4.1 concludes with a tabular overview of key technologies and processes, their technology readiness level (TRL), potential timing of market penetration, mitigation potential and assessment of associated mitigation costs.

An integrated sequencing of mature short-term actions and less mature longer-term actions is crucial to avoid lock-in effects. Temporal implementation and discussion of the general quantitative role of the different options to achieve net zero emissions in the industrial sectors is core to the second part of the section (11.4.2), where industry wide mitigation pathways are analysed. This comprises the collection and discussion of mitigation scenarios available in the literature with a high technological resolution for the industry sector in addition to a set of illustrative global and national GHG mitigation scenarios selected from chapter 3 and 4 representing different GHG mitigation ambitions and different pathways to achieve certain mitigation targets. Comparing technology focussed sector-based scenarios with more top-down oriented scenario approaches allows for a reciprocal assessment of both perspectives and helps to identify robust elements for the transformation of the sector. Comparison of real-world conditions within the sector (e.g., industry structure and logics, investment cycles, market behaviour, power, and institutional capacity) and the transformative pathways described in the scenarios helps researchers, analysts, governments, and all stakeholders understand the need not only for technological change, but for structural (e.g., new value chains, markets, infrastructures, and sectoral couplings) and behavioural (e.g., design practices and business models) change at multiple levels.

When undergoing a transformative process, it is obvious that interactions occur, within the sector but also on a cross-sectoral basis. Relevant interactions are identified and discussed in the third and fourth part of the sub-section. Changes are induced along the whole value chains, i.e., switching to an alternative (climate-friendly, e.g., low GHG hydrogen based) steel making process has substantial impacts on the value chain, associated sub-suppliers, and electricity and coal outputs. In addition, cross-sectoral interactions are discussed. This includes feedback loops with other end-use chapters, for example, higher material demand through market penetration of some GHG mitigation technologies or measures (e.g., insulation materials for buildings, steel for windmills) and lower demand through others (e.g., less steel for fossil fuel extraction, transport and processing), or substantial additional demand of critical materials (e.g., the widely varying demands for copper, lithium, nickel, cobalt and rare earths for producing windmills, solar panels, and batteries). Generally, if consumption (or behaviour) driven additional material demand creates scarcity it becomes important to increase efforts on material efficiency, substitution, recycling/re-use, and sustainable consumption patterns.

11.4.1 Sector specific mitigation potential and costs

Based on the general discussion of strategies across industry in Section 11.3 this sub-section focuses on the sector perspective and provides insights into the sector specific mitigation technologies and potentials. As industry is comprised of many different sub-sectors, the discussion here has its focus on the most important sources of GHG emissions, that is, steel, cement and concrete, as well as chemicals, before other sectors are discussed.

11.4.1.1 Steel

For the period leading up to 2020, in terms of end-use allocation globally, approximately 40% of steel is used for structures, 20% for industrial equipment, 18% for consumer products, 13% for infrastructure, and 10% for vehicles (Bataille 2020b). The global production of crude steel increased by 41 % between 2008 and 2020 (World Steel Association 2021) and its GHG emissions depending on the scope covered is 3.7–4.1 $GtCO_2$-eq. It represented 20% of total global direct industrial emissions in 2019 accounting for coke oven and blast furnace gases use Figure 11.4 and Table 11.1 (Crippa et al. 2021; Lamb et al. 2021; Minx et al. 2021; Olivier and Peters 2018; World Steel Association 2021; IEA 2020a). Steel production can be divided into primary production based on iron ore and secondary production based on steel scrap. The blast furnace to basic oxygen furnace route (BF-BOF) is the main primary steel route globally, while the electric arc furnace (EAF) is the preferred process for the less energy and emissions-intensive melting and alloying of recycled steel scrap. The direct reduced iron (DRI) route is a lesser used route that replaces BFs for reducing iron ore, usually followed by an EAF. In 2019, 73% of global crude steel production was produced in BF-BOFs, while 26% was produced in EAFs, a nominal 5.6% of which is DRI (World Steel Association 2021) .

An estimated 15% energy efficiency improvement is possible within the BF-BOF process (Figure 11.8). Several options exist for deep GHG emissions reductions in steel production processes (Leeson et al. 2017; Axelson et al. 2018; Fan and Friedmann 2021; Fischedick et al. 2014b; Wang et al. 2021; Holappa 2020; Bataille 2020a; Vogl et al. 2018; Rissman et al. 2020). Each could reduce specific CO_2 emissions of primary steel production by 80% or more relative to today's dominant BF-BOF route if input streams are based on carbon-free energy and feedstock sources or if they deploy high capture CCS:

- *Increasing the share of the secondary route* can bring down emissions quickly and potential emissions savings are significant, from a global average 2.3 tCO_2^{-1} per tonne steel in BF-BOFs down to 0.3 (or less) tCO_2^{-1} per tonne steel in EAFs (Pauliuk et al. 2013a; Zhou et al. 2019), the latter depending scrap preheating and electricity GHG intensity. However, realising this potential is dependent on the availability of regional and global scrap supplies and requires careful sorting and scrap management, especially to eliminate copper contamination (Daehn et al. 2017). There is significant uncertainty how much new scrap will be available and usable (IEA 2019b; Xylia et al. 2018; Wang et al. 2021). Most steel is recycled already; the gains are mainly to be made in quality, i.e. separation from contaminants like copper. End of life scrap availability and its contribution to steel production will increase as in use stock saturates in many countries (Xylia et al. 2016).
- BF-BOFs with CCU or CCS. Abdul Quader et al. (2016) and Fan and Friedmann (2021) indicate that it would be difficult to retrofit BF-BOFs beyond 50% capture, which is insufficient for long term emission targets, but may be useful in some cases for avoiding cumulative emissions where other options are not available. However, BF-BOFs need their furnaces relined every 15–25 years (IEA 2021a; Vogl et al. 2021b), at a cost 80–100% of a new build, and this would be an opportunity to build a new facility designed for 90%+ capture (e.g. fewer CO_2 outlets). This would depend upon access to transport to geology appropriate for CCS.
- *Methane based syngas (hydrogen and carbon monoxide) direct reduced iron (DRI) with CCS.* Most DRI facilities currently use a methane-based syngas of H_2 and CO as both reductant and fuel (some use coal). A syngas DRI-EAF steel making facility has been operating in Abu Dhabi since 2016 that captures carbon emitted from the DRI furnace (where it is a co-reductant with hydrogen) and sends it to a nearby oil field for enhanced oil recovery.
- *Hydrogen-based direct reduced iron (H-DRI)* is based on the already commercialized DRI technology but using only hydrogen as the reductant; pure hydrogen has already been used commercially by Circored in Trinidad 1999-2008. The reduction process of iron ore is typically followed by an EAF for smelting. During a transitional period, DRI could start with methane or a mixture of methane and hydrogen as some of the methane (<=30% hydrogen can be substituted with green or blue hydrogen without the need to change the process). If the hydrogen is produced based on carbon-free sources, this steel production process can be nearly CO_2 neutral (Vogl et al. 2018).

- In the *aqueous electrolysis* route (small scale piloted as Siderwin during the EU ULCOS program), the iron ore is bathed in an electrolyte solution and an electric current is used to remove the oxygen, followed by an electric arc furnace for melting and alloying. In the *molten oxide electrolysis* route, an electric current is used to directly reduce and melt the iron ore using electrolysis in one step, followed by alloying. These processes both promise a significant increase in energy efficiency compared with the direct reduced iron and blast furnace routes (Cavaliere 2019). If the electricity used is based on carbon-free sources, this steel production process can be nearly CO_2 neutral. Both processes would require supplemental carbon, but this is typically only up to 0.05% per tonne steel, with a maximum of 2.1%. Aqueous electrolysis is possible with today's electrode technologies, while molten oxide electrolysis would require advances in high temperature electrodes.
- The *HIsarna® process* is a new type of coal-based smelting reduction process, which allows certain agglomeration stages (coking plant, sintering/pelletizing) to be dispensed with. The iron ore, with a certain amount of steel scrap, is directly reduced to pig iron in a single reactor. This process is suitable to be combined with CCS technology because of its relatively easy to capture and pure CO_2 exhaust gas flow. CO_2 emission reductions of 80% are believed to be realisable relative to the conventional blast furnace route (Abdul Quader et al. 2016). The total GHG balance also depends on the further processing in a basic oxygen furnace or in an EAF. The HIsarna process was small scale piloted under the EU ULCOS program.
- *Hydrogen co-firing* in BF-BOFs can potentially reduce emission by 30-40%, referring to experimental work by the Course50 projects and Thyssen Krupp, but coke is required to maintain stack integrity beyond that.

Reflecting the different conditions at existing and potential future plant sites, when choosing one of the above options a combination of different measures and structural changes (including electricity, hydrogen and CCU or CCS infrastructure needs) will likely be necessary in the future to achieve deep reductions in CO_2 emissions of steel production.

In addition, increases in material efficiency (e.g., more targeted steel use per vehicle, building or piece of infrastructure) and increases in the intensity of product use (e.g. sharing cars instead of owning them) can contribute significantly to reduce emissions by reducing the need for steel production. The IEA (2019b) suggested that up to 24% of cement and 40% of steel demand could be plausibly reduced through strong material efficiency efforts by 2060. Potential material efficiency contribution for the EU is estimated to be much higher—48% (Material Economics 2019). Recycling would cut the average CO_2 emissions per tonne of steel produced by 60% (Material Economics 2019), but globally by 2050 secondary steel production is limited to 40–56% in various scenarios (IEA 2019b), with 46% in the IEA (2021a) and up to 56% in 2050 in Xylia et al. (2016). It may scale up to 68% by 2070 (Xylia et al. 2016). CCU and more directly CCS are other options to reduce GHG emissions but depend on the full life cycle net GHGs that can be allocated to the process (see 11.3.6). Bio-based fuels can also substitute for some of the coal input, but due to other demands for biomass this strategy is likely to be limited to specific cases.

Abatement costs for these strategies vary considerably from case to case and for each a plausible cost range is difficult to establish; cf. **Table 11.3** (Leeson et al. 2017; Axelson et al. 2018; Fischedick et al. 2014b; Wang et al. 2021; Vogl et al. 2018; Fan and Friedmann 2021). A key point is that while cost of production increases are significant, the effect on final end-uses is typically very small (Rootzén and Johnsson 2016), with significant policy consequences (See Section 11.6 on public and private lead markets for cleaner materials).

11.4.1.2 Cement and concrete

The cement sector is regarded as a sector where mitigation options are especially narrow (Energy Transitions Commission 2018; Habert et al. 2020). Cement is used as the glue to hold together sand, gravel and stone aggregates to make concrete, the most consumed manufactured substance globally. The production of cement has been increasing faster than the global population since the middle of the last century (Scrivener et al. 2018). Despite significant improvements in energy efficiency over the last couple of decades (e.g. a systematic move from wet to dry kilns with calciner preheaters feeding off the kilns) the direct emissions of cement production (sum of energy and process emissions) are estimated to be 2.1–2.5 $GtCO_2$-eq in 2019 or 14–17% of total global direct industrial GHG emissions (Figure 11.4) (Crippa et al. 2021; Lehne and Preston 2018; Hertwich 2021; Sanjuán et al. 2020; Lamb et al. 2021; Bataille 2020a). Typically, about 40% of these direct emissions originates from process heating (e.g. for calcium carbonate (limestone) decomposition into calcium oxide at 850°C or higher, directly followed by combination with cementious materials at about 1,450°C to make clinker), while 60% are process CO_2 emissions from the calcium carbonate decomposition (Kajaste and Hurme 2016; IEA and WBCSD 2018; Andrew 2019). Some of the CO_2 is reabsorbed into concrete products and can be seen as avoided during the decades long life of the products; estimates of this flux vary between 15 and 30% of the direct emissions (Schneider 2019; Stripple et al. 2018; Andersson et al. 2019; GCCA 2021a; Cao et al. 2020). Some companies are mixing CO_2 into hardening concrete, both to dispose of the CO_2 and more importantly reduce the need for binder (Lim et al. 2019).

One of the simplest and most effective ways to reduce cement and concrete emissions is to make stronger concrete through better mixing and aggregate sizing and dispersal; poorly and well-made concrete can vary in strength by a factor of 4 for a given volume (Fechner and Kray 2012; Habert et al. 2020). This argues for a refocus of the market away from "one size fits all", often bagged, cements to professionally mixed clinker, cementious material and filler mixtures appropriate to the needs of the end use.

Architects, engineers and contractors also tend to overbuild with cement because it is cheap as well as corrosion and water resistant. Buildings and infrastructure can be purposefully designed to minimize cement use to its essential uses (e.g. compression strength and corrosion resistance), and replace its use with other materials (e.g. wood, stone, other fibres) for non-essential uses. This could reduce cement use by 20–30% (D'Alessandro et al. 2016; Imbabi et al. 2012; Brinkerhoff and GLDNV 2015; Lehne and Preston 2018; Shanks et al. 2019; IEA 2019b; Habert et al. 2020).

Because so much of the emissions from concrete come from the limestone calcination to make clinker, anything that reduces use of clinker for a given amount of concrete reduces it GHG intensity. While 95% Portland cement is common in some markets, it is typically not necessary for all end-use applications, and many markets will add blast furnace slag, coal fly ash, or natural pozzolanic materials to replace cement as supplementary cementious materials; 71% was the global average clinker content of cement in 2019 (IEA 2020a). All these materials are limited in volume, but combination of roughly 2–3 parts ground limestone and one part specially selected, calcined clays can also be used to replace clinker (Fechner and Kray 2012; Lehne and Preston 2018; Habert et al. 2020). Local building codes determine what mixes of cementious materials are allowed for given uses, and would need to be modified to allow these alternative mixtures where appropriate.

Ordinary Portland cement process CO_2 emissions cannot be avoided or reduced through the use of non-fossil energy sources. For this reason, CCS technology, which could capture just the process emissions (e.g. the EU LEILAC project, which concentrates the process emissions from the limestone calciner, see following paragraph) or both the energy and process-related CO_2 emissions, is often mentioned as a potentially important element of an ambitious mitigation strategy in the cement sector. Different types of CCS processes can be deployed, including post-combustion technologies such as amine scrubbing and membrane-assisted CO_2-liquefation, oxycombustion in a low to zero nitrogen environment (full or partial) to produce a concentrated CO_2 stream for capture and disposal, or calcium-looping (Dean et al. 2011). The IEA puts cement CCS technologies at the TRL 6-8 level (IEA 2020h). These approaches have different strengths and weaknesses concerning emission abatement potential, primary energy consumption, costs and retrofittability (Voldsund et al. 2019; Gardarsdottir et al. 2019; Hills et al. 2016). Use of biomass energy combined with CCS has the possibility of generating partial negative emissions, with the caveats introduced in 11.3.6 (Hepburn et al. 2019).

The energy-related emissions of cement production can also be reduced by using bioenergy solids, liquids or gases (TRL 9) (IEA and WBCSD 2018), hydrogen or electricity (TRL 4 according to (IEA 2020h)) for generating the high-temperature heat at the calciner – hydrogen and bioenergy co-burning could be complementary due to their respective fast vs slow combustion characteristics. In an approach pursued by the LEILAC research project, the calcination process step is carried out in a steel vessel that is heated indirectly using natural gas (Hills et al. 2017). The LEILAC approach makes it possible to capture the process-related emissions in a comparatively pure CO_2 stream, which reduces the energy required for CO_2 capture and purification. This technology (LEILAC in combination with CCS) could reduce total furnace emissions by up to 85% compared with an unabated, fossil fuelled cement plant, depending on the type of energy sources used for heating (Hills et al. 2017). In principle, the LEILAC approach allows the eventual potential electrification of the calciner by electrically heating the steel enclosure instead of using fossil burners.

In the long run, if some combination of material efficiency, better mixing and aggregate sizing, cementious material substitution and 90%+ capture CCS with supplemental bioenergy are not feasible in some regions or at all to achieve near zero emissions, alternatives to limestone based ordinary Portland cement may be needed. There are several highly regional alternative chemistries in use that provide partial reductions (Fechner and Kray 2012; Lehne and Preston 2018; Habert et al. 2020), for example, carbonatable calcium silicate clinkers, and there have been pilot projects with magnesium oxide based cements, which could be negative emissions. Lower carbon cement chemistries are not nearly as widely available as limestone deposits (Material Economics 2019), and would require new materials testing protocols, codes, pilots and demonstrations.

Any substantial changes in cement and concrete material efficiency or production decarbonisation, however, will require comprehensive education and continuing re-education for cement producers, architects, engineers, contractors and small, non-professional users of cements. It will also require changes to building codes, standards, certification, labeling, procurement, incentives, and a range of polices to help create the market will be needed, as well as those for information disclosure, and certification for quality. Even an end-of-pipe solution like CCS will require infrastructure for transport and disposal. Abatement costs for these strategies vary considerably from case to case and for each a plausible cost range is difficult to establish but are summarized in **Table 11.3** from the following literature and other sources (Moore 2017; Fechner and Kray 2012; Leeson et al. 2017; IEA 2019f; Wilson et al. 2003; Lehne and Preston 2018; Habert et al. 2020).

11.4.1.3 Chemicals

The chemical industry produces a broad range of products that are used in a wide variety of applications. The products range from plastics and rubbers to fertilisers, solvents, and specialty chemicals such as food additives and pharmaceuticals. The industry is the largest industrial energy user and its direct emissions were about 1.1–1.7 $GtCO_2$-eq or about 10% of total global direct industrial emissions in 2019 (Figure 11.4 and Table 11.1) (Crippa et al. 2021; Lamb et al. 2021; Olivier and Peters 2018; IEA 2019f; Minx et al. 2021). With regard to energy requirements and CO_2 emissions, ammonia, methanol, olefins, and chlorine production are of great importance (Boulamanti and Moya Rivera 2017). Ammonia is primarily used for nitrogen fertilisers, methanol for adhesives, resins, and fuels, whereas olefins and chlorine are mainly used for the production of polymers, which are the main components of plastics.

Technologies and process changes that enable the decarbonisation of chemicals production are specific to individual processes. Although energy efficiency in the sector has steadily improved over the past decades (Figure 11.8; (Boulamanti and Moya Rivera 2017; IEA 2018a) a significant share of the emissions is caused by the need for heat and steam in the production of primary chemicals (Box 11.2) (Bazzanella and Ausfelder 2017). This energy is currently supplied almost exclusively through fossil fuels which could be substituted with bioenergy, hydrogen, or low or zero carbon electricity, for example, using electric boilers or high-temperature heat pumps (Thunman et al. 2019; Bazzanella and Ausfelder 2017; Saygin and Gielen 2021). The chemical industry has among the largest potentials for industrial energy demand to be electrified with existing technologies, indicating the possibility for a rapid reduction of energy related emissions (Madeddu et al. 2020).

The production of ammonia causes most CO_2 emissions in the chemical industry, about 30% according to IEA (2018a) and nearly one third according to (Crippa et al. 2021; Lamb et al. 2021; Minx et al. 2021). Ammonia is produced in a catalytic reaction between nitrogen and hydrogen – the latter most often produced through natural gas reforming (Stork et al. 2018; Material Economics 2019) and in some regions through coal gasification, which has several times higher associated CO_2 emissions. Future low-carbon options include hydrogen from electrolysis using on low or zero-carbon energy sources (Philibert 2017a), natural gas reforming with CCS, or methane pyrolysis, a process in which methane is transformed into hydrogen and solid carbon (Material Economics 2019; Bazzanella and Ausfelder 2017) (see also Section 11.3.5 and Box 11.1). Electrifying ammonia production would lead to a decrease in total primary energy demand compared to conventional production, but a significant efficiency improvement potential remains in novel synthesis processes (Wang et al. 2018; Faria 2021). Combining renewable energy sources and flexibility measures in the production process could allow for low-carbon ammonia production on all continents (Fasihi et al. 2021). Steam cracking of naphtha and natural gas liquids for the production of olefins, i.e. ethylene, propylene and butylene, and other high value chemicals is the second most CO_2 emitting process in the chemical industry, accounting for another almost 20% of the emissions from the subsector (IEA 2018a). Future lower-carbon options include electrifying the heat supply in the steam cracker as described above, although this will not remove the associated process emissions from the cracking reaction itself or from the combustion of the by-products. Further in the future, electrocatalysis of carbon monoxide, methanol, ethanol, ethylene and formic acid could allow direct electric recombination of waste chemical products into new intermediate products (De Luna et al. 2019).

A ranking of key emerging technologies with likely deployment dates from the present to 2025 relevant for the chemical industry identified different carbon capture processes together with electrolytic hydrogen production as being of very high importance to reach net zero emissions (IEA 2020a). Methane pyrolysis, electrified steam cracking, and the biomass based routes for ethanol-to-ethylene and lignin-to-BTX were ranked as being of medium importance. While macro-level analyses show that large-scale use of carbon circulation through CCU is possible in the chemical industry as primary strategy, it would be very energy intensive and the climate impact depend significantly on the source of and process for capturing the CO_2 (Kätelhön et al. 2019; Müller et al. 2020; Artz et al. 2018). Significant synergies can be found when combining circular CCU approaches with virgin carbon feedstocks from biomass (Bachmann et al. 2021; Meys et al. 2021).

In a net zero world carbon will still be needed for many chemical products, but the sector must also address the life-cycle emissions of its products which arise in the use phase, for example, CO_2 released from urea fertilisers, or at the end-of-life, for example, incineration of waste plastics which was estimated to emit 100 Mt globally in 2015 (Zheng and Suh 2019). Reducing life-cycle emissions can partly be achieved by closing the material cycles starting with material and product design planning for re-use, re-manufacturing, and recycling of products – ending up with chemical recycling which yields recycled feedstock that substitutes virgin feedstocks for various chemical processes (Smet and Linder 2019; Rahimi and García 2017). However, the chemical recycling processes which are most well studied are pyrolytic processes which are energy intensive and have significant losses of carbon to off-gases and solid residues (Dogu et al. 2021; Davidson et al. 2021). They are thus associated with significant CO_2 emissions, which can even be larger in systems with chemical recycling than energy recovery (Meys et al. 2020). Further, the products from many pyrolytic chemical recycling processes are primarily fuels, which then in their subsequent use will emit all contained carbon as CO_2 (Vollmer et al. 2020). Achieving carbon neutrality would thus require this CO_2 either to be recirculated through energy-consuming synthesis routes or to be captured and stored (Lopez et al. 2018; Material Economics 2019; Geyer et al. 2017; Thunman et al. 2019). As all chemical products are unlikely to fit into chemical recycling systems, CCS can be used to capture and store a large share of their end-of-life emissions when combined with waste combustion plants or heat-demanding facilities like cement kilns (Tang and You 2018; Leeson et al. 2017).

Reducing emissions involves demand-side measures, for example, efficient end-use, materials efficiency and slowing demand growth, as well as recycling where possible to reduce the need for primary production. The following strategies for primary production of organic chemicals which will continue to need a carbon source are key in avoiding the GHG emissions of chemical products throughout their life cycles:

- Recycled feedstocks: *chemical recycling* of plastics unsuitable for mechanical recycling was already mentioned. Through *pyrolysis* of old plastics, both gas and a naphtha-like pyrolysis oil can be generated, a share of which could replace fossil naphtha as a feedstock in the steam cracker (Honus et al. 2018a,b). Alternatively, waste plastics could be *gasified* and combined with low-carbon hydrogen to a syngas, for example, the production and methanol and derivatives (Stork et al. 2018; Lopez et al. 2018). Other chemical recycling options include polymer selective chemolysis, catalytic cracking, and hydrocracking (Ragaert et al. 2017). Carbon losses and process emissions must be minimized and it may thus be necessary to combine chemical recycling with CCS to reach near-zero emissions (Smet and Linder 2019; Thunman et al. 2019; Meys et al. 2021).
- Biomass feedstocks: Substituting fossil carbon at the inception of a product life-cycle for carbon from renewable sources processed in designated biotechnological processes (Hatti-Kaul et al. 2020; Lee et al. 2019) using specific biomass resources (Isikgor and Becer 2015) or residual streams already available (Abdelaziz et al. 2016). Routes with thermochemical and catalytic processes, such as pyrolysis and subsequent catalytic upgrading, are also available (Jing et al. 2019).
- Synthetic feedstocks: carbon captured with direct air capture or from point sources (bioenergy, chemical recycling, or during a transition period from industrial processes emitting fossil CO_2) can be combined with low-GHG hydrogen into a syngas for further valorisation (Kätelhön et al. 2019). Thus, low-carbon methanol can be produced and used in methanol-to-olefins/aromatics (MTO/MTA) processes, substituting the steam cracker (Gogate 2019) or a Fischer-Tropsch processes could produce synthetic hydrocarbons.

Reflecting the diversity of the sector the listed options can only be illustrative. The above listed strategies all rely on low-carbon energy to reach near zero emissions. In considering mitigation strategies for the sector it will be key to focus on those for which there is a clear path towards (close to) zero emissions, with high (carbon) yields over the full product value chain and minimal fossil resource use for both energy and feedstocks (Saygin and Gielen 2021), with CCU and CCS employed for all remnant carbon flows. The necessity of combining mitigation approaches in the chemicals industry with low-carbon energy was recently highlighted in an analysis (see Figure 11.10) which showed how the combined use of different recycling options, carbon capture, and biomass feedstocks was most effective at reducing global life-cycle emissions from plastics (Meys et al. 2021). While most of the chemical processes for doing all the above are well-known and have been used commercially at least partly, they have not been used at large scale and in an integrated way. In the past external conditions (e.g. availability and price of fossil feedstocks) have not set the necessary incentives to implement alternative routes and to avoid emitting combustion and process related CO_2 emissions to atmosphere. Most of these processes will very likely be more costly than using fossil fuels and full scale commercialisation would require significant policy support and the implementation of dedicated lead markets (Wyns et al. 2019; Material Economics 2019; Wesseling et al. 2017; Bataille et al. 2018a). As in other sub-sectors abatement costs for the various strategies vary considerably across regions and products making it difficult to establish a plausible cost range for each (Philibert 2017b; Bazzanella and Ausfelder 2017; Philibert 2017a; Axelson et al. 2018; IEA 2018a; Saygin and Gielen 2021; De Luna et al. 2019).

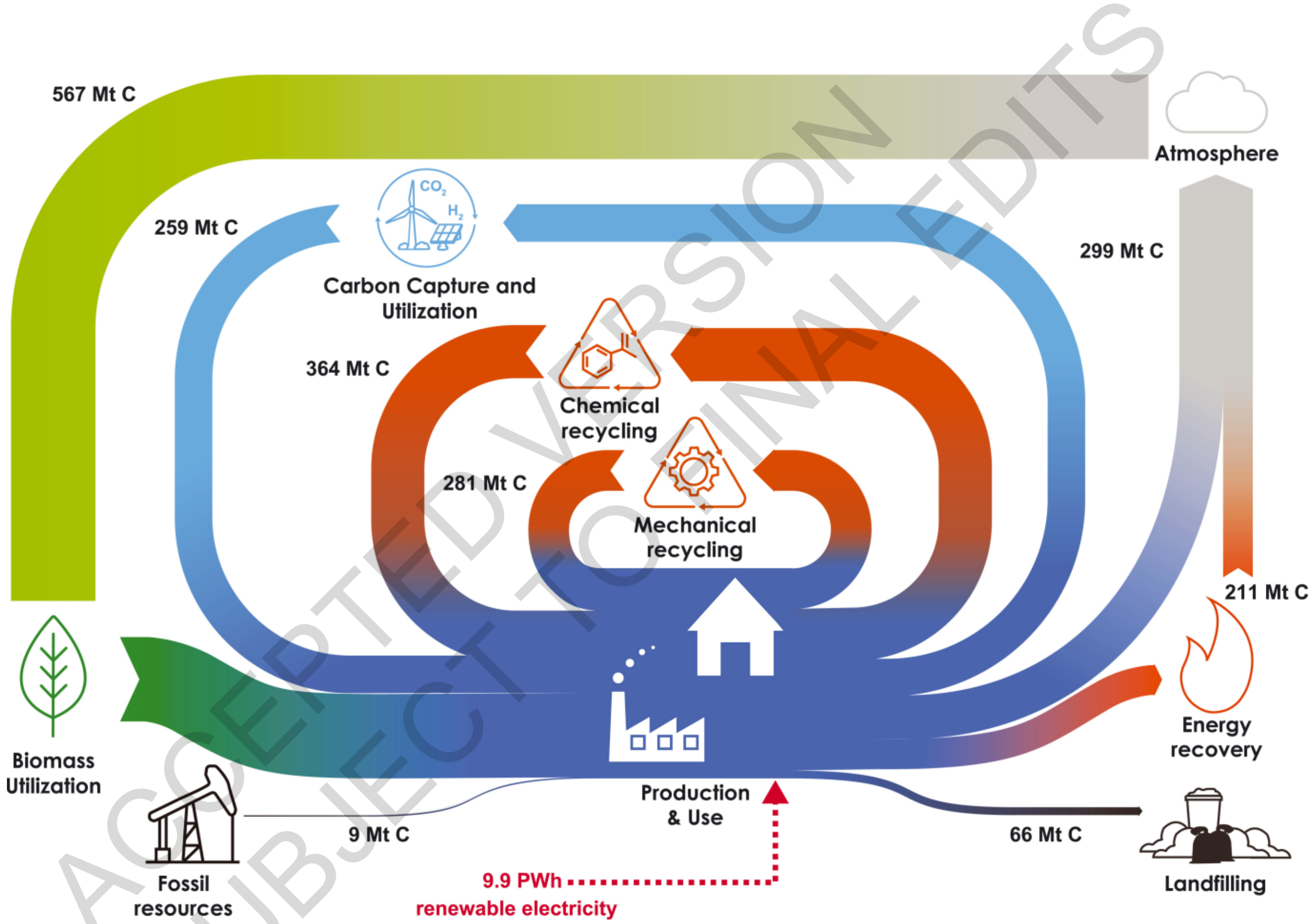


Figure 11.10 Feedstock supply and waste treatment in a scenario with a combination of mitigation measures in a pathway for low-carbon plastics (Meys et al. 2021)

START BOX 11.2 HERE

Box 11.2 Plastics and climate change

The global production of plastics has increased rapidly over the past 70 years, with a compound annual growth rate (CAGR) of 8.4 %, about 2.5 times the growth rate for global GDP (Geyer et al. 2017) and higher than other materials since 1970 (IEA 2019b). Global production of plastics is now more than

400 million tonnes, including synthetic fibres (ibid.) The per capita use of plastics is still up to 20 times higher in developed countries than in developing countries with low signs of saturation and the potential for an increased use is thus still very large (IEA 2018a). Plastics is the largest output category from the petrochemical industry, which as a whole currently uses about 14 % of petroleum and 8 % of natural gas (IEA 2018a). Forecasts for plastic production assuming continued growth at recent rates of about 3.5% point towards a doubled production by 2035, following record-breaking investments in new and increased production capacity based on petroleum and gas in recent years (CIEL 2017; Bauer and Fontenit 2021). IEA forecasts show that even in a world where transport demand for oil falls considerably by 2050 from the current ~100 mbpd, feedstock demand for chemicals will rise from ~12 mbpd to 15–18 mbpd (IEA 2019b). Projections for increasing plastic production as well as petroleum use together with the lack of investments in break-through low-emission technologies do not align with necessary emission reductions.

About half of the petroleum that goes into the chemical industry is used for producing plastics, and a significant share of this is combusted or lost in the energy intensive production processes, primarily the steam cracker. GHG emissions from plastic production depend on the feedstock used (ethane based production is associated with lower emissions than naphtha based), the type of plastic produced (production of simple polyolefins is associated with lower emissions than more complex plastics such as polystyrene), and the contextual energy system (e.g. the GHG intensity of the electricity used) but weighted averages have been estimated to be 1.8 tCO_2-eq·t^{-1} for North American production (Daniel Posen et al. 2017) and 2.3 tCO_2-eq·t^{-1} for European production (Material Economics 2019). In regions more dependent on coal electricity production the numbers are likely to be higher, and several times higher for chemical production using coal as a feedstock - coal-based MTO has 7 times higher emissions than olefins from steam cracking (Xiang et al. 2014). Coal-based plastic and chemicals production has over the past decade been developed and deployed primarily in China (Yang et al. 2019). The production of plastics was thus conservatively estimated to emit 1085 $MtCO_2$-eq·yr^{-1} in 2015 (Zheng and Suh 2019). Downstream compounding and conversion of plastics was estimated to emit another 535 $MtCO_2$-eq·yr^{-1}, while end-of-life treatment added 161 $MtCO_2$-eq·yr^{-1}. While incineration of plastic waste was the cause of only 5% of global plastic life cycle emissions, in regions with waste-to-energy infrastructures this share is significantly larger, for example, 13% of life cycle emissions in Europe (Ive Vanderreydt et al. 2021). The effective recycling rate of plastics remains low relating to a wide range of issues such as insufficient collection systems, sorting capacity, contaminants and quality deficiencies in recycled plastics, design of plastics integrated in complex products such as electronics and vehicles, heterogenous plastics used in packaging, and illegal international trade.

END BOX 11.2 HERE

11.4.1.4 Other industry sectors

The other big sources of direct global industrial combustion and process CO_2 emissions are light manufacturing and industry (9.7% in 2016), non-ferrous metals like aluminium (3.1%), pulp and paper (1.1%), and food and tobacco (1.9%) (Bataille 2020a; Crippa et al. 2021; Lamb et al. 2021).

Light manufacturing and industry

Light manufacturing and industry represent a very diverse sector in terms of energy service needs (e.g., motive power, ventilation, drying, heating, compressed air, etc.) and it comprises both small and large plants in different geographical contexts. Most of the direct fossil fuel use is for heating and drying, and it can be replaced with low GHG electricity, through direct resistance, high temperature heat pumps and mechanical vapour recompression, induction, infrared, or other electrothermal processes (Bamigbetan et al. 2017; Lechtenböhmer et al. 2016). Madeddu et al. (2020) argue up to 78% of

Europe's industrial energy requirements are electrifiable through existing commercial technologies and 99% with addition of new technologies currently under development. Direct solar heating is possible for low temperature needs (<100°C) and concentrating solar for higher temperatures. Commercially available heat pumps can deliver 100-150°C but at least up to 280°C is feasible (Zühlsdorf et al. 2019). Plasma torches using electricity can be used where high temperatures (>1000°C) are required, but hydrogen, biogenic or synthetic combustible hydrocarbons (methane, methanol, ethanol, LPG, etc.) can also be used (Bataille et al. 2018a).

There is also a large potential for energy savings through cascading in industrial clusters similar to the one at Kalundborg, Denmark. Waste heat can be passed at lower and lower temperatures from facility to facility or circulated as low-grade steam or hot water, and boosted as necessary using heat pumps and direct heating. Such geographic clusters would also enable lower cost infrastructure for hydrogen production and storage as well as CO_2 gathering, transport and disposal (IEA 2019f).

Aluminium and other non-ferrous metals

Demand for aluminium comes from a variety of end-uses where a reasonable cost, light-weight metal is desirable. It has historically been used in aircraft, window frames, strollers, and beverage containers. As fuel economy has become more desirable and design improvements have allowed crush bodies made of aluminium instead of steel, aluminium has become progressively more attractive for cars. Primary aluminium demand is total demand (100 Mtonnes·yr^{-1} in 2020) net of manufacturing waste reuse (14% of virgin and recycled input) and end-of-life recycling (about 20% of what reaches market). Primary aluminium consumption rose from under 20 Mtonnes·yr^{-1} in 1995 to over 66 Mtonnes primary ingot production in 2020 (International Aluminium Institute 2021). International Aluminium Institute (2021a) expects total aluminium consumption to reach 150–290 Mtonnes·yr^{-1} by 2050 with primary aluminium contributing 69–170 Mtonnes and secondary recycled 91–120 Mtonnes (as in-use stock triples or quadruples). OECD forecasts increases in demand by 2060 for primary aluminium to 139 Mt·yr^{-1} and for secondary aluminium to 71 Mtonnes (OECD 2019a). Primary (as opposed to recycled) aluminium is generally made in a two-stage process, often geographically separated. In the first stage aluminium oxide is extracted from bauxite ore (often with other trace elements) using the Bayer hydrometallurgical process, which requires up to 200°C heat when sodium hydroxide is used to leach the aluminium oxide, and up to 1000°C for kilning. This is followed by electrolytic separation of the oxygen from the elemental aluminium using the Hall-Héroult process, by far the most energy intense part of making aluminium. This process has large potential emissions from the electricity used (12.5 MWh per tonne aluminium BAT, 14–15 MWh per tonne average). From bauxite mine to aluminium ingot, reported total global average emissions are between 12 and 17.6 tCO_2-eq per tonnes of aluminium, depending on estimates and assumptions made[23] (Saevarsdottir et al. 2020). About 10 % of this, 1.5 tonnes of direct CO_2 per tonne aluminium are currently emitted as the graphite electrodes are depleted and combine with oxygen, and if less than optimal conditions are maintained perfluorocarbons can be emitted with widely varying GHG intensity, up to the equivalent of 2 tCO_2-eq.per tonne aluminium. PFC emissions, however, have been greatly reduced globally and almost eliminated in well-run facilities. Aluminium, if is not contaminated, is highly recyclable and requires 1/20 of the energy required to produce virgin aluminium; increasing aluminium recycling rates from the 20–25% global average is a key emissions reduction strategy (Haraldsson and Johansson 2018).

The use of low and zero GHG electricity (e.g. historically from hydropower) can reduce the indirect emissions associated with making aluminium. A public-private partnership with financial support from the province of Québec and the Canadian federal government has recently announced a fundamental

FOOTNOTE[23] According to International Aluminium Institute (2021b), scope 3 (cradle to gate) emissions from aluminium industry in 2018 reached 1.127 $GtCO_2$-eq or 17.6 tCO_2-eq per tonne of primary aluminium. In Low carbon *B2DS* it expected to be reduced to 2.5 tCO_2-eq per tonne.

modification to the Hall-Héroult process by which the graphite electrode process emissions can be eliminated by substitution of inert electrodes. This technology is slated to be available in 2024 and is potentially retrofittable to existing facilities (Saevarsdottir et al. 2020).

Smelting and otherwise processing of other non-ferrous metals like nickel, zinc, copper, magnesium and titanium with less overall emissions have relatively similar emissions reduction strategies (Bataille and Stiebert 2018): 1) Increase material efficiency. 2) Increase recycling of existing stock. 3) Pursue ore extraction processes (e.g. hydro- and electro-metallurgy) that allow more use of low carbon electricity as opposed to pyrometallurgy, which uses heat to melt and separate the ore after it has been crushed. These processes have been used occasionally in the past but have generally not been used due to the relatively inexpensive nature of fossil fuels.

Pulp and Paper

The pulp and paper industry is a small net-emitter of CO_2, assuming the feedstock is sustainably sourced (see Chapter 7), but it has large emissions of biogenic CO_2 from feedstock (700–800 Mtonne·yr^{-1} (Tanzer et al. 2021). It includes pulp mills, integrated pulp and paper mills and paper mills using virgin pulpwood and other fibre sources, residues and co-products from wood products manufacturing, and recycled paper as feedstock. Pulp mills typically have access to bioenergy in the chemical pulping processes to cover most or all of heat and electricity needs, for example, through chemicals recovery boilers and steam turbines in the kraft process. Mechanical pulping mainly uses electricity for energy; decarbonisation thus depends on grid emission factors. With the exception of the lime kiln in kraft pulp mills, process temperature needs are typically less than or equal to 150ºC to 200ºC, mainly steam for heating and drying. This means that this sector can be relatively easily decarbonised through continued energy efficiency, fuel switching and electrification, including use of high temperature heat pumps (Ericsson and Nilsson 2018). Electrification of pulp mills could, in the longer term, make bio-residues currently used internally for energy available as a carbon source for chemicals (Meys et al. 2021). The PPI also has the capabilities, resources and knowledge, to implement these changes. Inertia is mainly caused by equipment turn-over rates, relative fuel and electricity prices, and the profitability of investments.

A larger and more challenging issue is how the forestry industry can contribute to the decarbonisation of other sectors and how biogenic carbon will be used in a fossil-free society, for example, through developing the forest based bioeconomy (Bauer 2018; Pülzl et al. 2014). In recent years the concept of biorefineries has gained increasing traction. Most examples involve innovations for taking by-products or diverting small streams to produce fuels, chemicals and bio-composites that can replace fossil-based products, but there is little common vision on what really constitutes a biorefinery (Bauer et al. 2017). Some of these options have limited scalability and the cellulose fibre remains the core product even in the relatively large shift from paper production to textiles fibre production.

Pulp mills have been identified as promising candidates for post-combustion capture and CCS (Onarheim et al. 2017), which could allow some degree of net negative emissions. For deep decarbonisation across all sectors, notably switching to biomass feedstock for fuels, organic chemicals and plastics, the availability of biogenic carbon (in biomass or as biogenic CO_2, Chapter 7) becomes an issue. A scenario where biogenic carbon is CCU as feedstock implies large demands for hydrogen, completely new value chains and more closed carbon loops, all areas which are as yet largely unexplored (Ericsson 2017; Meys et al. 2021).

11.4.1.5 Overview of estimates of specific mitigation potential and abatement costs of key technologies and processes for main industry sectors

Climate policy related literature focusing on deep industrial emission reductions has expanded rapidly since AR 5. An increasing body of research proposes deep decarbonisation pathways for energy intensive industries (Figure 11.13). (Bataille et al. 2018a) address the question of whether it is possible to reduce GHG emissions to very low, zero, or negative levels, and identifies preliminary technological and policy elements that may allow the transition, including the use of policy to drive technological innovation and uptake. Material Economics (2019); IEA (2019b), Energy Transitions Commission (2018) and Climate Action Tracker CAT (2020) take steps to identify pathways integrating energy efficiency, material efficiency, circular economy and innovative technologies options to cut GHG emissions across basic materials and value chains. The key conclusion is that net zero CO_2 emissions from the largest sources (steel, plastics, ammonia, and cement) could be achieved by 2050 by deploying already available multiple options packaged in different ways (Material Economics 2019; UKCCC 2019b; Davis et al. 2018). The studies assume that for those technologies that have a kind of breakthrough technology status further technological development and significant cost reduction can be expected.

Table 11.3, modified from Bataille (2020a) and built from (Material Economics 2019; Bazzanella and Ausfelder 2017; Axelson et al. 2018; McMillan et al. 2016; Wesseling et al. 2017; UKCCC 2019b; Energy Transitions Commission 2018; Philibert 2017a; Davis et al. 2018; IEA 2019f, 2020c; Bataille et al. 2018a), presents carbon intensities that could be achieved by implementing mitigation options in major basic material industries, mitigation potential, estimates for mitigation costs, TRL and potential year of market introduction (see also Figure 11.13).

Table 11.3 acknowledges that for many carbon intensive products a large variety of novel processes, inputs and practices capable of providing very deep emission reductions are already available and emerging. However, their application is subject to different economic and structural limitations, therefore in the scenarios assuming deep decarbonisation by 2050–2060 different technological mixes can be observed (section 11.4.2).

Table 11.3 Technological potentials and costs for deep decarbonisation of basic industries. Percentages of maximum reduction are multiplicative, not additive

Sector	Current Intensity (tCO_2-eq t^{-1})	Potential GHG reduction	NASA TRL	Cost per tonne CO_2-eq (2019 USD tCO_2-eq^{-1} for % of emissions) ? = Unknown	Year available assuming policy drivers
Iron and Steel					
Current intensity – all steel (Worldsteel)	1.83				
Current intensity – ~BF-BOF/ Best BF-BOF & NG-DRI (with near zero GHG electricity)	2.3/1.8 & 0.7				
Current intensity – EAF (depends on electricity intensity & pre-heating fuel)	>=0	Up to 99%			
Material efficiency (IEA 2019 "Material Efficiency…")		Up to 40%	9	Subject to supply chain building codes and education	Today
More recycling; depends on available stock, recycling network, quality of scrap, availability of DRI for dilution		Highly regional, growing with time	9	Subject to logistical, transport, sorting, & recycling equipment costs	Today
BF-BOF w/ top gas recirculation & CCU/S[i]		60%	6–7	70–130 USD/t	2025-'30
Syngas (H_2 & CO) DRI EAF with concentrated flow CCU/S		90%+	9	>=40 USD/t	Today
Hisarna with concentrated CO_2 capture[ii]		80–90%	7	40–70 USD/t	2025
Hydrogen DRI EAFiii - Fossil hydrogen with CCS is in operation, electrolysis based hydrogen scheduled for 2026		Up to 99%	7	34–68 EUR/t & 40 EUR/MWh	2025
Aqueous (e.g. SIDERWIN) or Molten Oxide (e.g. Boston Metals) Electrolysis[iv]		Up to 99%	3–5	?	2035-'40
Cement & Concrete					
Current intensity, about 60% is limestone calcination	0.55				
Building design to minimize concrete (IEA 2019b, 2020a)		Up to 24%	9	Low, education, design and logistics related	2025
Alternative lower GHG fuels, e.g. waste (biofuels and hydrogen see above)		40%	9	Cost of alt. fuels	Today

	CCUS for process heating & $CaCO_3$ calcination CO_2 (e.g. LEILAC, possible retrofit)[v]		99% calc., <=90% heat	5–7	<=40 USD/t calc. <=120 USD/t heat	2025
	Clinker substitution (e.g. limestone + calcined clays)[vi]		40–50%	9	Near zero, education, logistics, building code revisions	Today
	Use of multi sized and well dispersed aggregates[vi]		Up to 75%	9	Near zero	Today
	Magnesium or ultramafic cementsvi		Negative?	1–4	?	2040
Aluminium & other non-ferrous						
	Current Al intensity, from hydro to coal based electricity production. 1.5 tonne CO_2 are produced by graphite electrode decay	1.5 t/t + electricity req., i.e. 10/t (NG) to 18 t/t (Coal)				
	Inert electrodes + green electricity[vii]		100%	6–7	Relatively low	2024
	Hydro/Electrolytic smelting (w/CO_2 CCUS if necessary)		Up to 99%	3–9	Ore specific	<2030
Chemicals (see also crosscutting feedstocks above)[viii]						
	Catalysis of ammonia from low/zero GHG hydrogen H_2	1.6 (NG), 2.5 (naptha) 3.8 (coal)	<=99%	9	Cost of H_2	Today
	Electrocatalysis: CH_4, CH_3OH, C_2H_5OH, CO, olefins[ix]		Up to 99%	3	Cost: Elec., H_2, CO_x	2030
	Catalysis of olefins from: (m)ethanol; H_2 & CO_x directly		9%	9,3	Cost: H_2 & CO_x	<2030
	End-use plastics, mainly CCUS and recycling	1.3–4.2, about 2.4	94%	5–6	150–240 USD/t	2030?
Pulp & Paper						
	Full biomass firing, inc. lime kilns		60-75%	9	About 50 USD/t	Today
Other manufacturing						
	Electrification using current tech (boilers, 90°C–140°C heat pumps		99%	9	Cost: Elec. vs. NG	2025
	" using new tech (induction, plasma heating)		99%	3–6		2025
Cross-cutting (CCUS, H_2, net zero $C_oO_xH_y$ fuels/feedstocks)						
	CCUS of post-combustion CO_2 diluted in nitrogenv		Up to 90%	6–7	<=120 USD/t	2025
	CCUS of concentrated CO_2[v]		99%	9	<=40 USD/t	Today
	H_2 prod: Steam or auto-thermal CH_4 reforming w/ CCS[v]		SMR<=90% ATR >90%	6*, 9**	56% @<=40 USD/t chem**, <=120 USD heat*,+20%/kg	<=2025
	H_2 prod: coal with CCUS[v]		<=90%	6	“,+25-50%/kg	<=2025

	H_2 prod: Alkaline or PEM Electrolysis[x]		99%	9	about 50 USD/t or <20-30 USD/MWh	Today
	H_2 prod: Reversible solid oxide fuel electrolysis[x]		99%	6–8	about 40 USD/t or <40 USD/MWh	2025
	H_2 prod: CH_4 pyrolysis or catalytic cracking[xi]		99%	5	?	2030?
	Hydrogen as CH_4 replacement		<=10%	9	See above	Today
	Biogas or liquid replacement hydrocarbons		60–90%	9	Biomass USD/GJ; >=50 USD/t, uncertain	Today
	Anaerobic digestion/fermentation: CH_4, CH_3OH, C_2H_5OH[xii]		Up to -99%	9	Biomass cost	Today
	Methane or methanol from H_2 & CO_x (CCUS for excess). Maximum -50% reduction if C source is FF		50–99%	6–9	Cost: H_2 & CO_x	Today
	850°C woody biomass gasification w/ CCS for excess carbon: CO, CO_2, H_2, H_2O, CH_4, C_2H_4 & C_6H_6[xiii]		Could be negative	7–8	about 50–75 USD/t, uncertain	Today
	Direct air capture for short and long chain $C_oO_xH_y$[xiv]		Up to 99%	3	Cost: E, H_2, CO_x about 94–232 USD/t	<=2030

[i] Data for CCS costs for steel making: Birat (2012); Axelson et al. (2018) and Leeson et al. (2017);
[ii] Data for Hisarna: Axelson et al. (2018);
iii Data for hydrogen DRI electric arc furnaces: Fischedick et al. (2014b) and Vogl et al. (2018);
[iv] Data for molten oxide electrolysis (also known as SIDERWIN): (Axelson et al. 2018; Fischedick et al. 2014b). The TRLs differ by source, the value provided is from Axelson et al. (2018) based on UCLOS SIDERWIN;
[v] Data for making hydrogen from SMR and ATR with CCUS: Moore (2017), Leeson et al. (2017) and IEA (2019f). The cost of CCS disposal of concentrated sources of CO_2 at 15–40 USD·tCO_2-eq^{-1} is well established as commercial for direct or EOR purposes and is based on the long standing practise of disposing of hydrogen sulfide and oil brines underground: Wilson et al. (2003) and Leeson et al. (2017). There is a wide variance, however, in estimated tCO_2-eq^{-1} breakeven prices for industrial post-combustion capture of CO_2 from sources highly diluted in nitrogen (e.g. Leeson et al. (2017) at 60–170 USD·tCO_2-eq^{-1}), but most fall under 120 USD·tCO_2-eq^{-1};
[vi] Data for clinker substitution and use of well mixed and multi sized aggregates: (Fechner and Kray 2012; Lehne and Preston 2018; Habert et al. 2020);
[vii] Rio Tinto, Alcoa and Apple have partnered with the governments of Québec and Canada to formed a coalition to commercialize inert as opposed to sacrificial graphite electrodes by 2024, thereby making the standard Hall Heroult process very low emissions if low carbon electricity is used;
[viii] Data and other information: Bazzanella and Ausfelder (2017); Axelson et al. (2018); IEA (2018a); De Luna et al. (2019) and Philibert (2017b,a);
[ix] See De Luna et al. (2019) for a state of the art review of electrocatalysis, or direct recombination of organic molecules using electricity and catalysts;
[x] Data for hydrogen production from electrolysis: Bazzanella and Ausfelder (2017); Philibert (2017a); Armijo and Philibert (2020); IEA (2019f); Philibert (2017b);
xi Data for methane pyrolysis to make hydrogen: Abbas and Wan Daud (2010). Data for hydrogen production from methane catalytic cracking: Amin et al. (2011) and Ashik et al. (2015);
[xii] Data for anaerobic digestion or fermentation for the production of methane, methanol and ethanol: De Luna et al. (2019);
[xiii] Data for woody biomass gasification: Li et al. (2019) and van der Meijden et al. (2011);
[xiv] Data on direct air capture of CO_2: Keith et al. (2018) and Fasihi et al. (2019).

While deep GHG emissions reduction potential is assessed for various regions, assessment of associated costs is limited to only a few regions; nevertheless those analyses may be illustrative at the global scale. UKCCC (2019b) provides costs assessments for different industrial subsectors (see **Table 11.3**) for the UK. They provide three ranges: core, more ambitious and when energy and material efficiency are limited. The core options range from 2–85 GBP 2019 tCO_2-eq^{-1} (e.g., reduction in GHG emissions by about 50% by 2050 applying energy efficiency (EE), ME, CCS, biomass and electrification). The more ambitious options are estimate at 32–119 GBP 2019 tCO_2-eq^{-1} (e.g., 90% emissions reduction via widespread deployment of hydrogen, electrification or bioenergy for stationary industrial heat/combustion). Finally, costs range from 33–299 GBP tCO_2-eq^{-1} when energy and material efficiency are limited.

In Material Economics (2019) costs are provided for separate technologies and subsectors, and also by pathways, each including new industrial processes, circular economy and CCS components in different proportions allowing for the transition to net zero industrial emission in the EU by 2050. That means that the study provides information about the three main mid- to long-term options which could enable a widely abatement of GHG emissions. Given different electricity price scenarios, average abatement costs associated with the circular economy-dominated pathway are 12–75 EUR 2019 tCO_2-eq^{-1}, for the carbon capture-dominated pathway 79 euro 2019 tCO_2-eq^{-1}, and for the new processes dominated scenario 91 euro 2019 tCO_2-eq^{-1}. Consequently, net zero emission pathways are about 3–25% costlier compared to the baseline (Material Economics 2019). According to Energy Transitions Commission (2018), cement decarbonisation would cost on average 110–130 USD tCO_2^{-1} depending on the cost scenario. Rootzén and Johnsson (2016) state that CO_2 avoidance costs for the cement industry vary from 25 to 110 EUR·tCO_2^{-1}, depending on the capture option considered and on the assumptions made with respect to the different cost items involved. According to Energy Transitions Commission (2018), steel can be decarbonised on average at 60 USD tCO_2^{-1}, with highly varying costs depending on low carbon electricity prices..

For customers of final products, information on the potential impact of supply side decarbonization on final prices may be more useful than that of CO_2 abatement costs. A different approach has been developed to assess the costs of mitigation by estimating the potential impacts of supply-side decarbonization on final products prices. Material Economics (2019) shows that with deep decarbonization, depending on the pathway, steel costs grow by 20–30%; plastics by 20–45%; ammonia by 15–60% and cement (not concrete) by 70–115%. While these are large and problematic costs increases for material producers working with low margins in a competitive market, final end-use product price increases are far less, for example, a car becomes 0.5% more expensive, supported by both Rootzén and Johnsson (2016) and Energy Transitions Commission (2018). For comparison, Rootzén and Johnsson (2017) found that decarbonizing cement making, while doubling the cost of cement, would add <1% to the costs of a residential building; the Energy Transitions Commission (2018) found concrete would be 10-30% more expensive, adding 15,000 USD or 3% to the price of a house includign land value. Finally, IEA (2020a) estimated the impact on end-use prices are rather small, even in a net zero scenario; they find price increases of 0.2% for a car and 0.6% for a house based on higher costs for steel and cement respectively.

Thus, the price impact scales down going across the value chain and might be acceptable for a significant share of customers. However, it has to be reflected that the cumulative price increase could be more significant if several different zero-carbon materials (e.g., steel, plastics, aluminium) in the production process of a certain product have to be combined, indicating the importance of material efficiency being applied along with production decarbonisation.

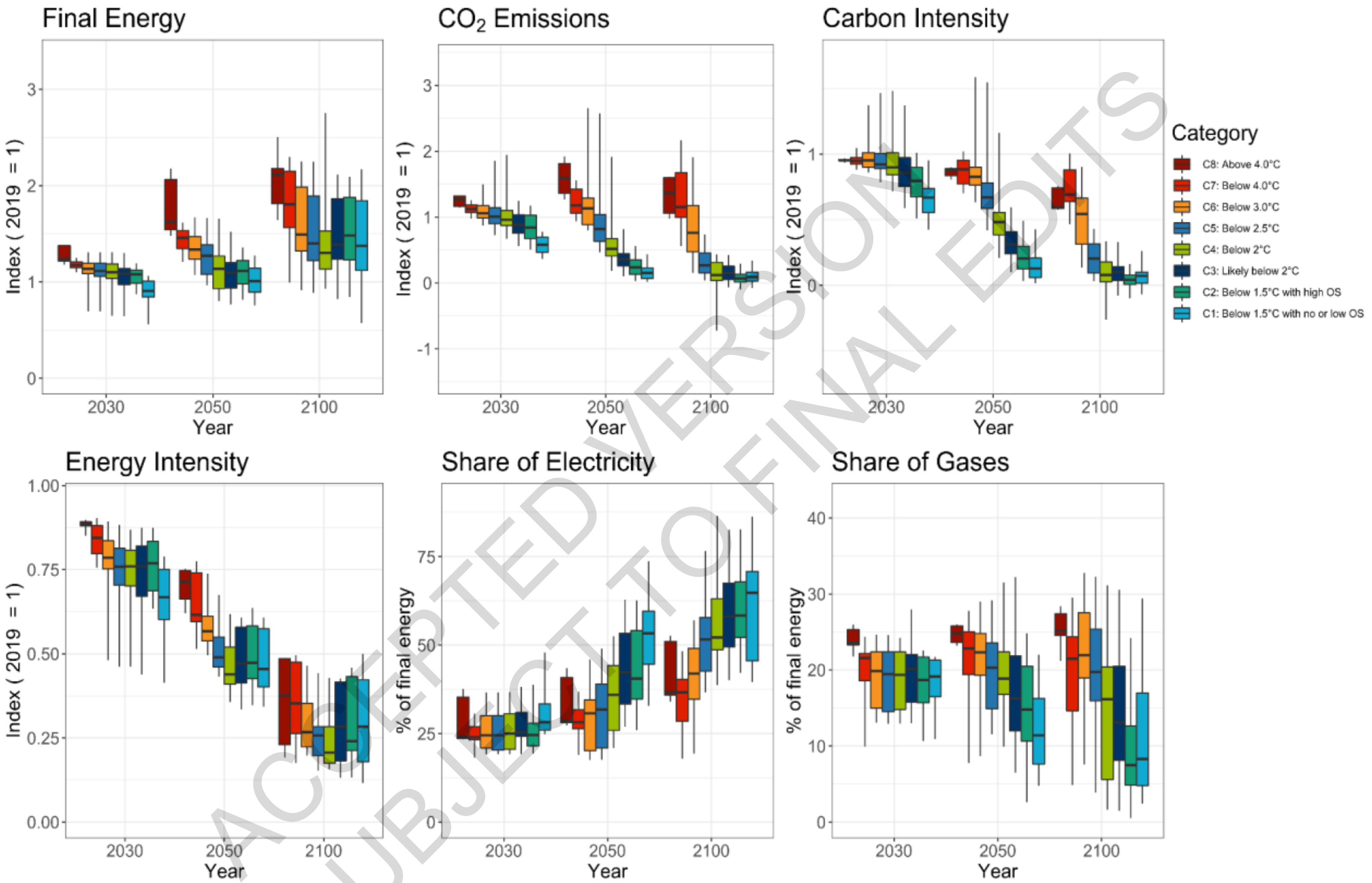
11.4.2 Transformation pathways

To discuss the general role and temporal implementation of the different options for achieving a net-zero GHG emissions industry, mitigation pathways will be analyzed. This starts with showing the results of IAM based scenarios followed by specific studies which provide much higher technological resolution and allow a much deeper look into the interplay of different mitigation strategies. The comparison of more technology-focused sector-based scenarios with top-down oriented scenarios provides the opportunity for a reciprocal assessment across different modelling philosophies and helps to identify robust elements for the transformation of the sector. Only some of the scenarios available in the literature allow for at least rough estimates of the necessary investments and give direction about relevant investment cycles and potential risks of stranded or depreciated assets. In some specific cases cost comparisons can be translated into expected difference costs not only for the overall sector, but also for relevant materials or even consumer products.

11.4.2.1 Central results from (top down) scenarios analysis and illustrative mitigation pathways discussion

Chapter 3 conducted a comprehensive analysis of scenarios based on IAMs. The resulting database comprises more than 1000 model-based scenarios published in the literature. The scenarios span a broad range along temperature categories from rather baseline like scenarios to the description of pathways that are compatible with the 1.5°C target. Comparative discussion of scenarios allows some insights with regard to the relevance of mitigation strategies for the industry sector (Figure 11.11).

1



2
3 **Figure 11.11 Industrial final energy (top left), CO_2 emissions (top right), energy intensity (middle left), carbon intensity (middle right), share of electricity (bottom**
4 **left), and share of gases (bottom right)).**

Energy intensity is final energy per unit of GDP. Carbon intensity is CO_2 emissions per EJ of final energy. The first four indicators are indexed to 2019, where values less than 1 indicate a reduction. Industrial sector CO_2 emissions include fuel combustion emissions only. Boxes indicate the interquartile range, the median is shown with a horizontal black line, while vertical lines show the 5 to 95% interval.

Source: Data is from the AR6 database; only scenarios that pass the vetting criteria are included (see Section 3.2).

The main results from the Chapter 3 analysis from an industry perspective are:

- While all scenarios show a decline in energy and carbon intensity over time final energy demand and associated industry related CO_2 emissions increase in many scenarios. Only ambitious scenarios (category C1) show significant reduction in final energy demand in 2030, more or less constant demand in 2050, but increasing demand in 2100, driven by growing material use throughout the 21st century. While carbon intensity shrinks over time energy related CO_2-emissions decline after 2030 even in less ambitious scenarios, but particularly in those pursuing a temperature increase below 2°C.
- Reduction of CO_2-emissions in the sector are achieved through a combination of technologies which includes nearly all options that have been discussed in this chapter (Section 11.3 and 11.4.1). However, there are big differences with regard to the intensity the scenarios implement the various options. This is particularly true for CCS for industrial applications and material efficiency and material demand management (i.e., service demand, service product intensity). The latter options are still underrepresented in many global IAMs.
- There are only a few scenarios which allow net-negative CO_2-emissions for the industry for the second half of the century while most scenarios assessed (including the majority of 1.5°C scenarios) end up with still significant positive CO_2-emissions. In comparison to the whole system most scenarios expect a slower decrease of industry related emissions.
- There is a great - up to a factor of two - difference in assumptions about the GHG mitigation potential associated with different carbon cost levels between IAMs and sector specific industry models. Consequently, IAMs pick up mitigation options slower or later (or not at all) than models which are more technologically detailed. Due to their top-down perspective IAMs to date have not been able to represent the high complexity of industries in terms of the broad variety of technologies and processes (particularly circularity aspects) and to fully reflect the dynamics of the sector. In addition, as energy and carbon price elasticities are still not completely understood, primarily cost driven models have their limitations. However, there are several ongoing activities to bring in more engineering knowledge and technological details into the IAM models (Kermeli et al. 2021).

In addition to the more aggregated discussion, the IAMs illustrative mitigation pathways (IMPs) allow a deeper look into the transformation pathways related to the scenarios. For the illustrative mitigation pathways (IMPs) approach sets of scenarios have been selected which represent different levels of GHG mitigation ambitions, scenarios which rely on different key strategies or even exclude some mitigation options, represent delayed actions or SDG oriented pathways. For more detailed information about the selection see Chapter 3.3.2. Figure 11.12 compares for a selected number of key variables the results of IMPs and puts them in the context of the whole sample of IAMs scenario results for three temperature categories.

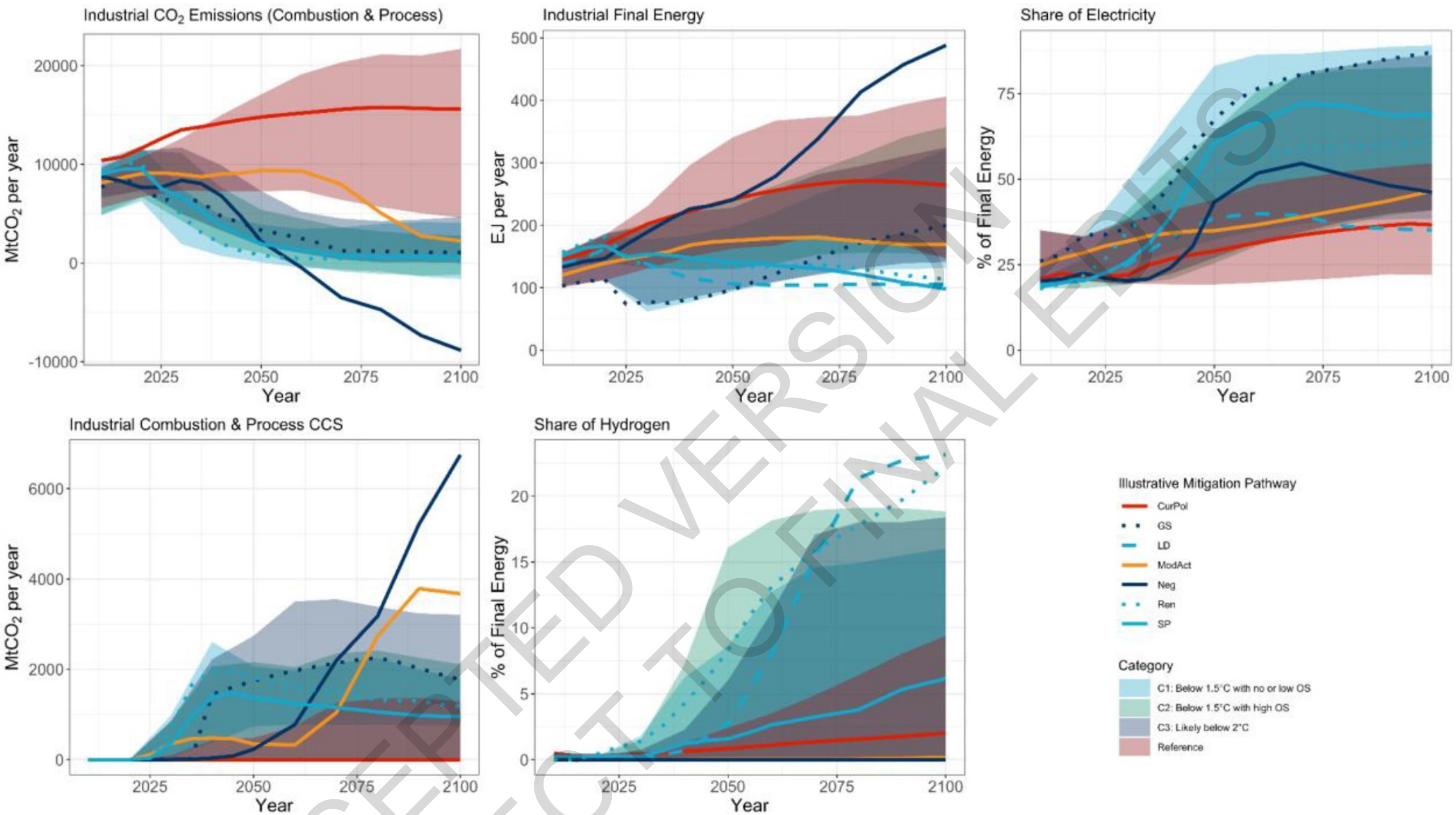


Figure 11.12 Comparison of industry sector related CO_2-emissions (including process emissions), final energy demand, share of electricity and hydrogen in the final energy mix, and industrial CCS for different mitigation scenarios representing illustrative mitigation pathways and the full sample of IAM scenario results for three temperature categories (figure based on scenario data base). Indicators in the Illustrative Mitigation Pathways (lines) and the 5-95% range of Reference, 1.5°C and 2°C scenarios (shaded areas). The selected IMPs reflect the following characteristics: opportunities for reducing demand (IMP-LD; low demand), the role of deep renewable energy penetration and electrification (IMP-Ren; renewables), extensive use of CDR in the industry and the energy sectors to achieve net negative emissions (IMP-Neg), insights how shifting development can lead to deep emission reductions and achieve sustainable development goals (IMP-SP; shifting pathways), and insights how slower short term emissions reductions can be compensated by very fast emission reductions later on (IMP-GS; gradual

strengthening). Furthermore, two scenarios were selected to illustrate the consequences of current policies and pledges; these are CurPol (Current Policies) and ModAct (Moderate Action) and are referred to as Pathways Illustrative of Higher Emissions

Source: Data is from the AR6 database; only scenarios that pass the vetting criteria are included (see Section 3.2).

With growing mitigation ambition final energy demand is significantly lower in comparison of a current policy pathway (CurPol) and a scenario that explores the impact of further moderate actions (ModAct). Based on the underlying assumptions, scenarios IMP-SP and IMP-LD are characterized by the lowest final energy demand, triggered by high energy efficiency improvement rates as well as additional demand side measures while a scenario with extensive use of CDR in the industry and the energy sectors to achieve net negative emissions (IMP-Neg) leads to a significant increase in final energy demand. Scenario IMP-GS represents a pathway where mitigation action is gradually strengthened by 2030 compared to pre-COP 26 NDCs shows the lowest final energy demand. All ambitious IMPs show substantially increasing contributions from electricity, with electricity's end-use share more than doubling for some of them by 2050 and more than tripling by 2100. The share of hydrogen shows a flatter curve for many scenarios, reaching 5% (IMP-Ren) in 2050 and up to 20% in 2100 for some scenarios (Ren, LD). Those scenarios that have a strong focus on renewable energy electrification show high shares of hydrogen in the sector. In comparison to sector specific and national studies which show typically a range between 5 and 15% by 2050, many IAM IMPs expect hydrogen to play a less important role. Results for industrial CCS show a broad variety of contributions, with the GS scenario (where hydrogen is not relevant as mitigation option) representing the upper bound to 2050, with almost 2 $GtCO_2 \cdot yr^{-1}$ captured and stored by 2050. Beyond 2050 the upper bound is associated with scenario IMP-Neg associated with extensive use of CDR in the industry and energy sectors to achieve net negative emissions in the second half of the century - more than 6 $GtCO_2 \cdot yr^{-1}$ is captured and stored in 2100 (this represents roughly 60% of 2018 direct CO_2 emissions of the sector).

11.4.2.2 In-depth discussion and "reality" check of pathways from specific sector scenarios

Since AR5 a number of studies providing a high technological level of detail for the industry sector have been released which describe how the industry sector can significantly reduce its GHG emissions until the middle of the century. Many of these studies try to specifically reflect the particular industry sector characteristics and barriers that hinder industry to follow an optimal transformation pathway. They vary in respect to different characteristics. In respect to their geographical scope, some studies analyse the prospects for industry sector decarbonisation on a global level (Tchung-Ming et al. 2018; IEA 2017a; Grubler et al. 2018; Energy Transitions Commission 2018; IEA 2020a, 2019b, 2020c); regional level, for example, European Commission (2018); Material Economics (2019), or country level - studies for China, from where most industry related emissions come, (e.g. Zhou et al. (2019)).[24] In regard sectoral scope, some studies include the entire industry sector, while others focus on selected GHG emission intensive sectors, such as steel, chemicals and/or concrete. Most of the scenarios focus solely on CO_2 emissions, that is non-CO_2 emissions of the industrial sector are neglected.[25]

Industry sector mitigation studies also differ in regard to whether they develop coherent scenarios or whether they focus on discussing and analysing selected key mitigation strategies, without deriving full

FOOTNOTE[24] In addition, there are many other studies available which have developed country-specific, technologically detailed scenarios for industry decarbonisation e.g. (Gerbert et al. 2018) and a few which have investigated the decarbonisation prospects of individual industrial clusters (Schneider 2019), but these types of studies are not discussed here.

FOOTNOTE[25] Most of the global mitigation scenarios solely focus on CO_2 emissions. Non-CO_2 emissions make up only a small share of the industry sector's current CO_2-eq. emissions and include N_2O emissions (e.g. from nitric and adipic acid production), CH_4 emissions (e.g. from chemical production and iron and steel production) and various F-gases (such as perfluorocarbons from primary aluminium production and semiconductor manufacturing) (Gambhir et al. 2017; USEPA and ICF 2012). Mitigation options for these non-CO_2 emissions are discussed in (Gambhir et al. 2017).

energy and emission scenarios. Coherent scenarios are developed in (IEA 2017; Energy Transitions Commission 2018; Tchung-Ming et al. 2018; Grubler et al. 2018; IEA 2021a; IRENA 2021; IEA 2019b, 2020a,c) on the global level and in Climact (2018); European Commission (2018); Material Economics (2019) on the European level. Recent literature analysing selected key mitigation strategies, for example IEA (2019b) and Material Economics (2019) has focused either exclusively or to a large extent on analysing the potential of materials efficiency and circular economy measures to reduce the need for primary raw materials relative to a business-as-usual development. IEA (2021a, 2020a) also provides deep insides in single mitigation strategies for the industry sector, particularly the role of CCS.

The following discussion mainly concentrates on scenarios from IEA. It has to be acknowledged that they only represent a small segment of the huge scenario family (cf. scenario data base in chapter 3), but this approach enables to show the chronological evolution of scenarios coming from the same institution, using the same modelling approach (which allows a technology-rich analytical backcasting approach), but reflect additional requests that emerge over time (Table 11.5). In the 2DS scenario from the "Energy Technology Perspectives (ETP)" study (IEA 2017), which intends to describe in great technological detail how the global energy system could transform by 2060 so as to be in line with limiting global warming to below 2°C, total CO_2 emission are 74 % lower in 2060 than in 2014, while only 39% lower in the industry sector. The B2DS scenario of the same study intends to show how far known clean energy technologies (including those that lead to negative emissions) could go if pushed to their practical limits, allowing the future temperature increase to be limited to "well below" 2°C and lowering total CO_2 emissions by 100% by 2060 and by 75% relative to 2014 in the industry sector.

Technologies penetration assumed in the CTS scenario by 2060 allows for an industrial emission cut of 45% from 2017 level and a 50% cut against projected 2060 emissions in the Reference Technology Scenario (RTS) from the same study (IEA 2019b) similar to IEA's 2DS scenario. Energy efficiency improvements and deployment of BATs contribute 46% to cumulative emission reduction in 2018–2060, while fuel switch (15%), material efficiency (19%) and deployment of innovative processes (20%) provide the rest. IEA (2020a,c) which continuous the Energy Technology Perspectives series include the new Sustainable Development Scenario (SDS) to describe a trajectory for emissions consistent with reaching global "net zero" CO_2 emissions by around 2070.[26] In 2070 the net zero balance is reached through a compensation of the remaining CO_2-emissions (fossil fuel combustion and industrial processes still lead to around 3 $GtCO_2$) by a combination of BECCS and to a lesser degree Direct Air Capture and storage. In IEA (2020c) the Faster Innovation Case (FIC) shows a possibility to reach net zero emissions level globally already in 2050, assuming that technology development and market penetration can be significantly accelerated. Innovation plays a major role in this scenario as almost half of all the additional emissions reductions in 2050 relative to the reference case would be from technologies that are in an early stage of development and have not yet reached the market today (IEA 2020c). The most ambitious IEA scenario NZE2050 (IEA 2021a) describes a pathway reaching net zero emissions at system level by 2050. With 0.52 $GtCO_2$ industry related CO_2-emissions (including process emissions) it ends up 94% below 2018 level in 2050. Remaining emissions in the industry sector have to be compensated by negative emissions (e.g. via DAC).

FOOTNOTE[26] Following the description of IEA SDS 2020 would limit the global temperature rise to below 1.8°C with a 66% probability if CO_2 emissions remain at net zero after 2070. If CO_2 emissions were to fall below net zero after 2070, then this would increase the possibility of reaching 1.5°C by the end of the century (IEA 2020c).

Table 11.4 Perspectives on industrial sector mitigation potential (comparison of different IEA scenarios)

Reduction of direct CO_2 emissions	Scenario assumptions[i]	IEA (2017, 2020c,i, 2021a)		IEA (2019b)	IEA (2020a,c)	
		2030	2050	2060	2050	2070
Baseline direct emissions from industrial sector						
Reference Technology Scenario (RTS)	Industry sector improvements in energy consumption and CO_2 emissions are incremental, in line with currently implemented and announced policies and targets.	9.8 $GtCO_2$	10.4 $GtCO_2$	9.7 $GtCO_2$		
Emission reduction potential						
2°C Scenario (2DS)	Assumes the decoupling of production in industry from CO_2 emissions growth across the sector that would be compatible with limiting the rise in global mean temperature to 2°C by 2100.	-7% vs 2014[ii] -20% vs RTS[ii]	-39% vs 2014[ii] -50% vs RTS[ii]			
Beyond 2°C Scenario (B2DS)	Pushes the available CO_2 abatement options in industry to their feasible limits in order to aim for the "well below 2°C" target.	-28% vs 2014 -38% vs RTS	-75% vs 2014 -80% vs RTS			
Clean Technology Scenario (CTS)	Strong focus on clean technologies. Energy efficiency and deployment of BATs contribute 46% to cumulative emission reduction in 2018–2060; fuel switch -15%; material efficiency -19%; deployment of innovative processes -20%.			5 Gt CO_2 or -45% vs 2017 level and -50% from 2060 RTS level		
Sustainable Development Scenario 2020 (SDS 2020)	Leads to net zero emissions globally by 2070. Remaining emissions in some sectors (including industry) in 2070 will be compensated by negative emissions in other areas (e.g. through BECCS and DAC)				~ 4.0	~ 0.6
Net-zero emissions across all sectors	-23% (i.e. 2.1 $GtCO_2$) vs. 2018	-94% (i.e. 8.4 $GtCO_2$) vs. 2018	Net-zero emissions across all			

Reduction of direct CO_2 emissions	Scenario assumptions[i]	IEA (2017, 2020c,i, 2021a)		IEA (2019b)	IEA (2020a,c)	
		2030	2050	2060	2050	2070
are reached already by 2050.			sectors are reached already by 2050.			
Faster Innovation Case (FIC)	Achieves net zero emissions status already by 2050 based on accelerated development and market penetration of technologies which have currently not yet reached the market.				0.8 Gt CO_2 (mainly steel and chemical industry)	

[i] Based on bottom-up technology modelling of five energy-intensive industry subsectors (cement, iron and steel, chemicals and petrochemicals, aluminium and pulp and paper).
[ii] Industrial direct CO_2 emissions reached 8.3 $GtCO_2$ in 2014, 24% of global CO_2 emissions.

Source: IEA (2017, 2020c,i, 2021a, 2019b, 2020a).

Two studies complement the discussion of the IEA scenarios and are related to IEA data base.[27] The ETC Supply Side scenario builds on the ETP 2017 study, investigating additional emission reduction potentials in the emissions intensive sectors such as heavy industry and heavy-duty transport so as to be able to reach net zero emission by the middle of the century. The LED scenario (Grubler et al. 2018) also builds on the ETP 2017 study, but focuses on the possible potential of very far-reaching efforts to reduce future material demand.

A comparison of the different mitigation scenarios shows that they depend on how individual mitigation strategies in the industry sector (see Figure 11.13) are assessed, . The use of CCS for example is in many scenarios assessed as very important, while other scenarios indicate that ambitious mitigation level can be achieved without CCS in the industry sector. CCS plays a major role in the B2DS scenario (3.2 $GtCO_2$ in 2050), the ETC Supply Side scenario (5.4 $GtCO_2$ in 2050) and the IEA (2020a), IEA (2021a) scenarios (e.g. 2.8 Gt CO_2 in NZE2050 in 2050, roughly one halve of the captured CO_2 is related to cement production), while it is explicitly excluded in the LED scenario. In the latter scenario, on the other hand, considerable emission reductions are assumed to be achieved by far-reaching reductions in material demand relative to a baseline development. In other words, the analysed scenarios also suggest that to reach very strong emission reductions from the industry sector either CCS needs to be deployed to a great extent or considerable material demand reductions will need to be realised. Such demand reductions only play a minor role in the 2DS scenario and no role in the ETC Supply Side scenario. The SDS described in IEA (2020a) provides a pathway where both CCS and material efficiency contribute significantly. In SDS material efficiency is a relevant factor in several parts of industry, explicitly steel, cement, and chemicals. Combining the different material efficiency options including to a substantial part lifetime extension (particularly of buildings) leads to 29% less steel production by 2070, 26% less cement production, and 25% less chemicals production respectively in comparison to the reference line used in the study (Stated Policy Scenario: STEPS). Sector or sub-sector specific analysis support the growing role of material efficiency. For the global chemical and petrochemical sector (Saygin and Gielen 2021) point out that circular economy (including recycling) has to cover 16% of the necessary reduction that is need for the implementation of a 1.5°C scenario.

In all scenarios, the relevance of biomass and electricity in industrial final energy demand increases, especially in the more ambitious scenarios NZE2050, SDS, ETC Supply Side and LED. While in all scenarios, electrification becomes more and more important hydrogen or hydrogen-derived fuels, on the other hand, do not contribute to industrial final energy demand by the middle of the century in 2DS and B2DS, while LED (1% final energy share in 2050) and particularly ETC supply side (25% final energy share in 2050) consider hydrogen or hydrogen-derived fuels as a significant option. In the updated IEA scenarios hydrogen and hydrogen-based fuels already play a more important role. In the SDS share in industry final energy is around 10% (IEA 2020a) and in the Faster Innovation Case around 12% (IEA 2020c) in 2050. In the latter case this is based on the assumption that by 2050 on average each year 22 hydrogen-based steel plants come into operation (IEA 2020c). In SDS around 60% of the hydrogen is produced onsite via water electrolysis while the remaining 40% is generated in fossil fuel plants (methane reforming) coupled with CCS facilities. In the NZE2050 scenario biomass/biomethane (13%/3%), hydrogen (3%), natural gas with CCUS (4%) and coal with CCUS (4%) are responsible for 27% of the final energy demand of the sector. This is much more than in 2018, starting here from roughly 6% (only biomass). Direct use of electricity still plays a bigger role in the analysis, as share of

FOOTNOTE[27] Several other two global mitigation scenarios (e.g. from Tchung-Ming et al. (2018), Shell Sky Scenario from Shell (2018)) are not included in the following scenario comparison as the study's energy and emission base year data on the industry sector deviates considerably from the other three studies included in the comparison, which all use IEA data. Furthermore, unlike the other studies, Tchung-Ming et al. (2018) do not provide detailed information on the steel, chemicals and concrete sub-sectors. Not included here but worth to be mentioned are many other sector specific studies, for example Napp et al. (2019, 2014), which consider more technologically advanced decarbonisation routes for the sector.

electricity increases in NZE2050 from 22% in 2018 to 28% in 2030 and 46% in 2050 (in 2050 with 15% a part of the electricity is used to produce hydrogen). This is reflecting the effect that since publication of older IEA reports more direct electric applications for the sector become available. In NZE2050 approx. 25% of total heat used in the sector is electrified directly with heat pumps or indirectly with synthetic fuels already by 2030.

For B2DS it is assumed that most of the available abatement options in the industry sector are pushed to their feasible limits. That leads to cumulative direct CO_2 emissions reductions compared to 2DS which come from: energy efficiency improvements and BAT deployment (42%), innovative processes and CCS (37%), switching to lower carbon fuels and feedstocks (13%) and material efficiency strategies in manufacturing processes (8%). Energy efficiency improvements are particular important in the first time period.

IEA World Energy Oulook indicates energy efficiency improvement in the 2020-2030 period as major basis to switch from STEPS (stated policies) to the SDS (net zero emissions by 2070) pathway (IEA 2020i, 2021c). For many energy-intensive industries annual efficiency gains have to be almost doubled (e.g., from 0.6% yr^{-1} to 1.0 % yr^{-1} for cement production) to contribute sufficiently to the overall goal. If net zero CO_2-emissions should be achieved already by 2050 as pursued in the NZE2050 scenario IEA (2020i) and (2021c) further accelerating energy efficiency improvements are necessary (e.g., for cement annual efficiency gains of 1.75%) leading to the effect, that in 2030 many processes are implemented closely to their technological limits. In total, sector final energy demand can be held nearly constant at 2018 level until 2050 and decoupled from product demand growth

The comparative analysis leads to the point that the relevance of individual mitigation strategies in different scenarios depends not only on a scenario's level of ambition. Instead, implicit or explicit assumptions about: a) the costs associated with each strategy, b) future technological progress and availability of individual technologies and c) the future public or political acceptance of individual strategies are likely to be main reasons for the observed differences between the analysed scenarios. For many energy-intensive products technologies capable of deep emission cuts are already available. Their application is subject to different economic and resources constrains (incremental investments needs, products prices escalation, requirements for escalation of new low carbon power generation). To fully exploit potential availability of carbon-free energy sources (e.g., electricity or hydrogen and related derivates) is a fundamental prerequisite and marks the strong interdependencies between the industry and the energy sector.

Assessment of the scenario literature allows to conclude that under specific conditions strong CO_2 emission reductions in the industry sector by 2050–2070 and even net zero emission pathways are possible. However, there is no consensus on the most plausible or most desirable mix of key mitigation strategies to be pursued. In addition it has to be stressed that suitable pathways are very country-specific and depend on the economic structure, resource potentials, technological competences, and political preferences and processes of the country or region in question (Bataille 2020a).

There is a consensus among the scenarios that a significant shift is needed from a transition process in the past mainly based on marginal (incremental) changes (with a strong focus on energy efficiency efforts) to a one based on transformational change. To limit the barriers that are associated with transformational change, besides overcoming the valley of death for technologies or processes with breakthrough character, it is required to carefully identify structural change processes which are connected with substantial changes of the existing system (including the whole process chain). This has to be done at an early stage and has to be linked with considerations about preparatory measures which are able to flank the changes and to foster the establishment of new structures (Section 11.6). The right sequencing of the various mitigation options and building appropriate bridges between the different strategies are important. Rissman et al. (2020) proposes three phases of technologies deployment for the industry sector: (1) energy/material efficiency improvement (mainly incremental) and electrification in combination with demonstration projects for new technologies potentially important in subsequent phases (2020-2035), (2) structural shifts based on technologies which reach maturity in phase (1) such as CCS and alternative materials (2035-2050) (3) widespread deployment for technologies that are nascent today like molten oxide electrolysis based steel making. There are no strong boundaries between the different phases and all phases have to be accompanied by effective policies like R&D programs and market pull incentives.

Taking the steel sector as an illustrative example, sector specific scenarios examining the possibility to reach GHG reduction beyond 80% (CAT 2020; IEA 2021a; Vogl et al. 2021b; Bataille et al. 2021b) indicate that robust measures comprise direct reduction of iron (DRI) with hydrogen in combination with efforts to further close the loops and increase availability of scrap metal (reducing the demand for primary steel). As hydrogen based DRI might not be a fully mature technology before 2030 (depending on further developments of the policy framework and technological progress), risk of path dependencies has to be taken into consideration when reinvestments in existing production capacities will be required in the coming years. For existing plants, implementation of energy efficiency measures (e.g. utilization of waste heat, improvement of high temperature pumps) could build a bridge for further mitigation measures, but have only limited unexhausted potential. As many GHG mitigation measures are associated with high investment costs and missing operating experience, a step by step implementing process might be an appropriate strategy to avoid investment leakage (given the mostly long operation times, investment cycles have to be used so as not to miss opportunities) and to gain experience. In the case of steel, companies can start with the integration of a natural gas based direct reduced iron furnace feeding the reduced iron to an existing blast furnace, blending and later replacing the natural gas by hydrogen in a second stage, and later transitioning to a full hydrogen DRI EAF or molten oxide electrolysis EAF, all without disturbing the local upstream and downstream supply chains.

It is worth mentioning the flexibility of implementing transformational changes not the least depends on the age profile and projected longevity of existing capital stock, especially the willingness to accept the intentional or market-based stranding of high GHG intensity investments. This is a relevant aspect in all producing countries, but particularly in those countries with a rather young industry structure (i.e. comparative low age of existing facilities on average). Tong et al. (2019) suggest that in China using the survival rate as a proxy less than 10% of existing cement or steel production facilities will reach their end of operation time by 2050. Vogl et al. (2021b) argue that the mean blast furnace campaign is considerably shorter than used in Tong et al (2019), at only 17 years between furnace relining, which suggests there is more room for retrofitting with clean steel major process technologies than generally assumed. Bataille et al. (2021b) found if very low carbon intensity processes were mandatory starting in 2025, given the lifetimes of existing facilities, major steel process lifetimes of up to 27 years would still make a full retrofit cycle with low carbon processes possible.

In general, early adoption of new technologies plays a major role. Considering the long operation time (lifetime) of industrial facilities (e.g., steel mills, cement kilns) early adoption of new technologies is needed to avoid lock-in. For the SDS 2020 scenario, IEA (2020h) calculated the potential cumulative reduction of CO_2-emissions from the steel, cement and chemicals sector to be around 57 $GtCO_2$ if production technology is changed at its first mandatory retrofit, typically 25 years, rather than at 40 years (typical retrofitted lifetime) (Figure 11.13). Net zero pathways require that the new facilities are based on zero- or near zero emissions technologies from 2030 onwards (IEA 2021c).

Another important finding is that material efficiency and demand management are still not well represented in the scenario literature. Besides IEA (2020a) two of the few exceptions are Material Economics (2019) for the EU and Zhou et al. (2019) for China. Zhou et al. (2019) describe a consistent mitigation pathway (Reinventing Fire scenario) for China where in 2050 CO_2-emissions are at a level 42% below 2010 emissions. Around 13% of the reduction is related to less material demand, mainly based on extension of building and infrastructure lifetime as well as reduction of material losses in the production process and application of higher quality materials particularly high-quality cement (Zhou et al. 2019). For buildings and cars, Pauliuk et al. (2021) analyzed the potential role of material efficiency and demand management strategies on material demand to be covered by the industry sector.

For the three most important sub-sectors in industry Table 11.5 shows results from Material Economics (2019) for the EU. The combination of circularity, material and energy efficiency, fossil and waste fuels mix, electrification, hydrogen, and biomass use varies from scenario to scenario with no of these options ignored. On the contrary, for CCS the authors set a strong default - in all scenarios CCS is not included as a mitigation option. Scenario studies for Germany Samadi and Barthel (2020) support the Material Economics (2019) findings and show deep mitigation s and even net zero emissions can be reached without application of CCS and with limited contribution of synthetic carbon neutral fuels. In those scenarios there are large contributions from material efficiency, circular economy, material substitution as well as life-style changes.

Table 11.5 Contribution to emission reduction of different mitigation strategies for net zero emission pathways (range represents three different pathways for the industry sector in Europe; each related scenario focus on different key strategies)[28]

	Steel	Plastics	Ammonia	Cement
	Contribution to emission reduction (%) (range represents the three different pathways of the study)			
Circularity	5–27	7–27		10–44
Energy efficiency	5–23	2–9		1–5
Fossil fuels and waste fuels	9–41	0–27		0–51
Decarbonised electricity	36–59	16–22		29–71
Biomass for fuel or feedstock	5–9	18–22		0–9
End-of-life plastic		16–35		
	Required electrification level			
Growth of electricity demand (times compared with 2015)	3–5	3–4		2–5
	Investments and production costs escalation			
Investment needs growth (% versus BAU)	25–65	122–199	6–26	22–49
Cost of production (% versus BAU)	2–20	20–43	15–111	70–115

Source: Material Economics (2019).

The analysis of net zero emission pathways require significantly higher investments compared to business as usual (BAU), 25% to 65% for steel, 6–26% for Ammonia, 22–49% for cement and with 122–199% the highest number for plastics (Material Economics 2019).

While sector specific cost analysis are rare in general, there are scenarios indicating that pathways to net zero CO_2 emissions in the emissions intensive sectors can be realized with limited additional costs. According to Energy Transitions Commission (2018) deep decarbonization from four major industry subsectors (plastics, steel, aluminium and cement) is achievable on a global level with cumulative incremental capital investments (2015–2050) limited to about 0.1% of aggregate GDP over that period. UKCCC (2019a) assesses that total incremental costs (compared to a theoretical scenario with no climate change policy action at all) for cutting industrial emissions by 90% by 2050 is 0.2% of expected 2050 UK GDP (UKCCC 2019a). The additional investment is 0.2% of gross fixed capital formation (Material Economics 2019). The IEA (2020a) indicates the required annual incremental global investment in heavy industry is approximately 40 billion 2019 USD yr^{-1} moving from (STEPS) to the

FOOTNOTE[28] Note: In the described scenarios CCS was not taken into consideration as a mitigation option by the authors.

SDS scenario (2020–2040), rising to 55 billion USD yr^{-1} (2040–2070), effectively 0.05-0.07% of global annual GDP today.

Finally, a new literature is emerging, based on the new sectoral electrification, hydrogen and CCS based technologies listed in previous sections, considering the possibility of rearranging standard supply and process chains using regional and international trade in intermediate materials like primary iron, clinker and chemical feedstocks, to reduce global emissions by moving production of these materials to regions with large and inexpensive renewable energy potential or CCS geology (Gielen et al. 2020; Bataille et al. 2021a; Saygin and Gielen 2021; Bataille 2020a)

In a sequence of sectoral and industry wide figures below (Figure 11.13), it is shown - starting in the present on the left and moving through 2050 to 2070 on the right, how much separate mitigation strategies can contribute and how they are integrated in the literature to reach near zero emissions. For cement, steel and primary chemicals GHG intensities are presented, and for all industry absolute GHG emissions are displayed. Effects of the following mitigation strategies are reflected: energy efficiency, material efficiency, circularity/recycling, feedstock carbon intensity, fuel switching, CCU and CCS. Contributions of technologies split by their readiness for 2050 and 2070 are provided along with ranges of mitigation costs for achieving near zero emissions for each strategy, accompanied by ranges of associated basic materials costs escalations and driven by these final products prices increments.

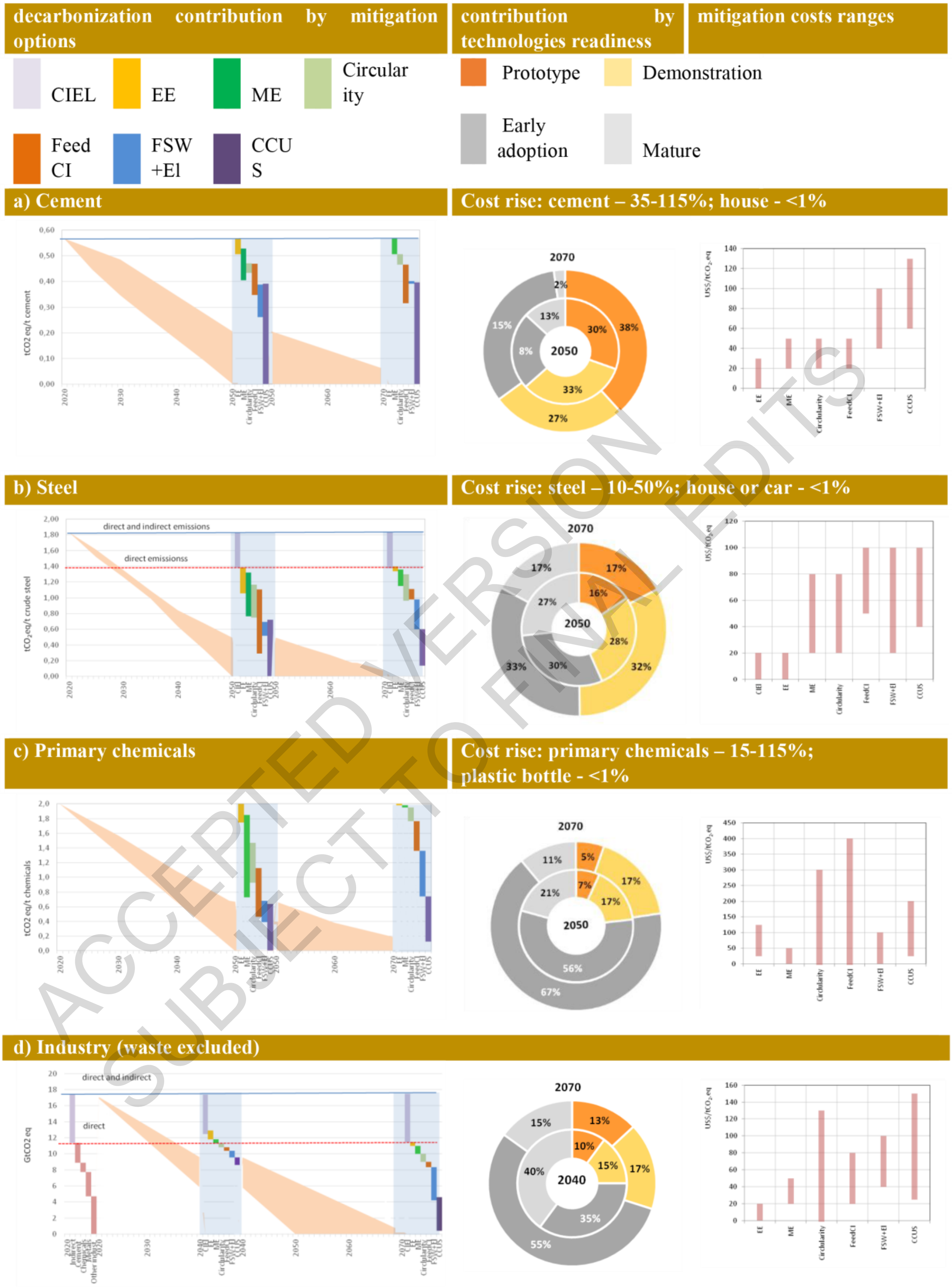


Figure 11.13 Potentials and costs for zero-carbon mitigation options for industry and basic materials *CIEl* –carbon intensity of electricity for indirect emissions; *EE* – energy efficiency; *ME* – material efficiency; *Circularity* - material flows (clinker substituted by coal fly ash, blast furnace slag or other by-products

and waste, steel scrap, plastic recycling, etc.); *FeedCI* – feedstock carbon intensity (hydrogen, biomass, novel cement, natural clinker substitutes); *FSW+El* – fuel switch and processes electrification with low carbon electricity. Ranges for mitigation options are shown based on bottom-up studies for grouped technologies packages, not for single technologies. In circles contribution to mitigation from technologies based on their readiness are shown for 2050 (2040) and 2070. Direct emissions include fuel combustion and process emissions. Indirect emissions include emissions attributed to consumed electricity and purchased heat. For basic chemicals only methanol, ammonia and high-value chemicals are considered. Total for industry doesn't include emissions from waste. Base values for 2020 for direct and indirect emissions were calculated using 2019 GHG emission data (Crippa et al. 2021) and data for materials production from World Steel Association (2020a) and IEA (2021d). Negative mitigation costs for come options like Circularity are not reflected.

Sources: (Fawkes et al. 2016; CEMBUREAU 2020; JULIO Friedmann et al. 2019; CAT 2020; Pauliuk et al. 2013a; Material Economics 2019; EUROFER 2019; Gielen et al. 2020; Sandalow et al. 2019; Saygin and Gielen 2021; WBCSD 2016; World Steel Association 2020b; Scrivener et al. 2018; Bazzanella and Ausfelder 2017; Habert et al. 2020; Lehne and Preston 2018; Bataille 2020a; GCCA 2021a; IEA 2018a, 2019b,g,h, 2020a,c, 2021a).

11.4.3 Cross sectorial interactions and societal pressure on industry

Mitigation involves greater integration and coupling between sectors. This is widely recognised for example in the case of electrification of transport (see 6.6.2 and 10.3.1) but it has been less explored for industrial decarbonisation. Industry is a complex web of sub-sectors and intersectoral interaction and dependence, with associated mitigation opportunities and co-benefits and costs (OECD 2019b; Mendez-Alva et al. 2021). Implementation of the mitigation options assessed in 11.3 will result in new sectoral couplings, value chains, and business models but also in phasing-out of old ones. Notably, electrification in industry, hydrogen and sourcing of non-fossil carbon involves profound changes to how industry interacts with electricity systems and how industrial sub-sectors interact. For example, the chemicals and forestry industries will become much more coupled if various forms of biogenic carbon become an important feedstock for plastics (Figure 11.10). Clinker substitution with blast furnace slag in the cement industry is well established way of reducing CO_2 emissions (Fechner and Kray 2012) but this slag will no longer be available if blast furnaces are phased-out. Furthermore, additional material demand resulting from mitigation in other sectors, as well as adaptation, and the importance of material efficiency improvements are issues that has attracted increasing attention since AR5 (Hertwich et al. 2020; IEA 2019b; Bleischwitz 2020). How future material will be affected under different climate scenarios is underexplored and typically not accounted for in modelling (Bataille et al. 2021a).

Using industrial waste heat for space heating, via district heating, is an established practice that still has a large potential with large quantities of low-grade heat being wasted (Fang et al. 2015). For Denmark it is estimated that 5.1% of district heating demand could be met with waste heat (Bühler et al. 2017) and for four towns studied in Austria 3-35% of total heat demand could be met (Karner et al. 2016). A European study shows that temporal heat demand flexibility could allow for up to 100% utilization of excess heat from industry (Karner et al. 2018). A study of a Swedish chemicals complex estimated that 30-50% of excess heat generated on-site could be recovered with payback periods below 3 years (Eriksson et al. 2018).

A European study found that most of the industrial symbiosis or clustering synergies today are in the chemicals sector with shared streams of energy, water, and carbon dioxide (Mendez-Alva et al. 2021). For future mitigation the UKCCC (2019b) finds that industrial clustering may be essential for achieving the necessary efficiencies of scale and to build the infrastructure needed for industrial electrification; carbon capture, transport and disposal; hydrogen production and storage, heat cascading between industries and to other potential heat users (e.g. residential and commercial buildings).

With increasing shares of renewable electricity production there is a growing interest in industrial demand response, storage and hybrid solutions with on-site PV and CHP (Schriever and Halstrup 2018; Scheubel et al. 2017; Shoreh et al. 2016). With future industrial electrification, and in particular with hydrogen used as reduction agent in ironmaking or as feedstock in the chemicals industry, the level of interaction between industry and power systems becomes very high. Large amounts of coking coal, or oil and gas as petrochemical energy and feedstock, are then replaced by electricity. For example, Meys et al. (2021) estimates a staggering future electricity demand of 10,000 TWh in a scenario for a net zero emissions plastics production of 1100 Mt in 2050 (see 11.3.5 for other estimates of electricity demand). Much of this electricity is used to produce hydrogen to allow for CCU and this provides a very large potential flexible demand if electrolysers are combined with hydrogen storage. Vogl et al. (2018) describe how hydrogen DRI and EAF steel plants can be highly flexible in their electricity demand by storing hydrogen or hot-briquetted iron and increasing the share of scrap in EAF. The IEA (2019f) Future of Hydrogen report suggests that hydrogen production and storage networks could be in locations with already existing hydrogen production and storage, for example, chemical industries, and that these could be ideal for system load balancing and demand response, and in case of district heating systems - for heat cascading.

The climate awareness that investors, shareholders, and customers demand from companies has been increasing steadily. It is reflected in growing number of environmental management, carbon footprint accounting, benchmarking and reporting schemes (e.g., the Carbon Disclosure Project, Task Force on Climate-Related Financial Disclosures, Environmental Product Declarations and others, e.g., Qian et al. (2018)) requiring companies to disclose both direct and indirect GHG emissions, and creating explicit (for regulatory schemes) as well as implicit GHG liabilities. This requires harmonised and widely accepted methods for environmental and carbon footprint accounting (Bashmakov et al. 2021b). From an investor perspective there are both physical risks (e.g., potential damages from climate change to business) and transition risks (e.g., premature devaluation of assets driven by new policies and technologies deployment and changes in public and private consumer preferences (NGFS 2019a)). Accompanied by reputational risks this leads to increased attention to Sustainable and Responsible Investment (SRI) principles and increased demands from investors, consumers and governments on climate and sustainability reporting and disclosure (NGFS 2019b). For example, Japan's Keidanren promotes a scheme by different each industries to reduce GHG through the global value chain, including material procurement, product use stages, and disposal, regardless of geographical origin, with provided quantitative visualization (Keidanren (Japan Business Federation) 2018). EU adopted a non-financial disclosure Directive in 2014 (Kinderman 2020) and a Taxonomy for Sustainable Finance in 2019 (see also 15.6.1).

11.4.4 Links to climate change, mitigation, adaptation

Sectors that are particularly vulnerable to climate change include agriculture, forestry, fisheries and aquaculture, and their downstream processing industries (Bezner et al. 2021). Many of the energy intensive industries are located based on access to fresh water (e.g., pulp and paper) or sea transport (e.g., petrochemicals). Risks of major concern for industry include disrupted supply chains and energy supplies due to extreme weather events, as well as risks associated with droughts, floods with dirty water, sea level rise and storm surges (Dodman et al. 2021). Adaptation measures may in turn affect the demand for basic materials (e.g., steel and cement), for example, increased demand to build sea walls and protect infrastructure, but we have not found any estimates of the potential demand. Increased heat stress is unsafe for outdoor labourers and can reduce worker productivity, for example, in outdoor construction, resource extraction and waste handling (Ranasinghe et al. 2021).

11.5 Industrial infrastructure, policy, and SDG contexts

11.5.1 Existing industry infrastructures

Countries are at different stages of different economic development paths. Some are already industrialised, while developing and emerging economies are on earlier take-off stages or accelerated growth stages and have yet to build the basic infrastructure needed to allow for basic mobility, housing, sanitation, and other services (see 11.2.3). The available in-use stock of material per capita and in each country therefore differs significantly, and transition pathways will require a different mix of strategies, depending on each country's material demand to build, maintain, and operate stock of long-lived assets. Industrialised economies have much greater opportunities for reusing and recycling materials, while emerging economies have greater opportunities to avoid carbon lock-in. The IEA projected that more than 90% of the additional 2050 production of key materials will originate in non-OECD countries (IEA 2017). As incomes rise in emerging economies, the industry sector will grow in tandem to meet the increased demand for the manufactured goods and raw materials essential for infrastructure development. The energy and feedstocks needed to support this growth is likely to constitute a large portion of the increase in the emerging economies' GHG emissions in the future unless new low carbon pathways are identified and promoted.

Emissions are typically categorised by the territory, sub-sector or group of technologies from which they emanate. An alternative sub-division is that between existing sources that will continue to generate emissions in the future, and those that are yet to be built (Erickson et al. 2015). The rate of emissions from existing assets will eventually tend to zero, but in a timeframe that is relevant to existing climate and energy goals, the cumulative contribution to emissions from existing infrastructure and equipment is likely to be substantial. Aside from the magnitude of the contribution, the distinction between emissions from existing and forthcoming assets is instructive because of the difference in approach to mitigation that may be necessary or desirable in each instance to avoid getting locked into decades of highly carbon-intensive operations (Lecocq and Shalizi 2014).

Details of the methodologies to assess 'carbon lock-in' or 'committed emissions' differ across studies but the core components of the approaches adopted are common to each: an account of the existing level of emissions for the scope being assessed is established; this level is projected forward with a stylised decay function that is informed by assessments of the current age and typical lifetimes of the underlying assets. From this, a cumulative emissions estimate is calculated. The future emissions intensity of the operated assets is usually assumed to remain constant, implying that nothing is done to retrofit with mitigating technologies (e.g., carbon capture) or alter the way in which the plant is operated (e.g. switching to an alternative fuel or feedstock). While the quantities of emissions derived are often referred to as 'committed' or 'locked-in', their occurrence is of course dependent on a suite of economic, technology and policy developments that are highly uncertain.

Data on the current age profile and typical lifetimes of emissions-intensive industrial equipment are difficult to procure and verify and most of the studies conducted in this area contain little detail on the global industrial sector. Two recent studies are exceptions, both of which cover the global energy system, but contain detailed and novel analysis on the industrial sector (Tong et al. 2019; IEA 2020a). Tong et al. (2019) use unpublished unit-level data from China's Ministry of Ecology and Environment to obtain a more robust estimate of the age profile of existing capacity in the cement and iron and steel sectors in the country. The IEA (2020a) uses proprietary global capacity datasets for the iron and steel, cement and chemicals sectors, and historic energy consumption data for the remaining industry sectors as a proxy for the rate of historic capacity build-up.

Both studies come to similar estimates on the average age of cement plants and blast furnaces in China of around 10-12 years old, which are the figures for which they have overlapping coverage. Both studies also use the same assumption of the typical lifetime of assets in these sectors of 40 years, whereas the IEA (2020a) study uses 30 years for chemical sector assets and 25 years for other industrial sectors. The studies come to differing estimates of cumulative emissions by 2050 from the industry sector; 196 $GtCO_2$ in the IEA (2020a) study, and 162 $GtCO_2$ in the Tong et al. (2019) study. This difference is attributable to a differing scope of emissions, with the IEA (2020a) study including industrial process emissions (which for the cement sector in particular are substantial) in addition to the energy-related emissions quantities accounted for in the Tong et al. (2019) study. After correcting for this difference in scope, the emissions estimates compare favourably.

The IEA (2020a) study provides supplementary analysis for the industry sector, examining the impact of considering investment cycles alongside the typical lifetimes assumed in its core analysis of emissions from existing industrial assets. For three heavy industry sectors – iron and steel, cement and chemicals – the decay function applied to emissions from existing assets is re-simulated using a 25-year investment cycle assumption (Figure 11.14). This is 15 years shorter than the typical lifetimes assumed for assets in the iron and steel and cement sectors, and 5 years shorter than that considered for the chemical sector. The shorter timeframe for the investment cycle is a simplified way of representing the intermediate investments that are made to extend the life of a plant, such as the re-lining of a blast furnace, which can occur multiple times during the lifetime of an installation. These investments can often be similar in magnitude to that of replacing the installation, and they represent key points for intervention to reduce emissions. The findings of this supplementary analysis are that around 40%, or 60 $GtCO_2$, could be avoided by 2050 if near-zero emissions options are available to replace this capacity, or units are retired, retro-fitted or refurbished in a way that significantly mitigates emissions (e.g. retro-fitting carbon capture, or fuel or process switching to utilise bioenergy or low-carbon hydrogen).

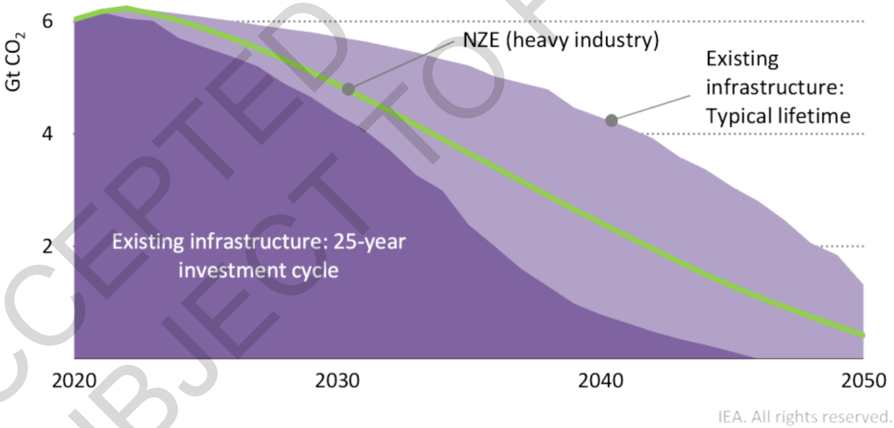


Figure 11.14 CO_2 emissions from existing heavy industrial assets in the NZE

Source: IEA (2021a).

As this review was being finalized several papers were released that somewhat contradict the Tong et al (2010) results (Vogl et al. 2021b; Bataille et al. 2021b). Broadly speaking, these papers argue that while high emitting facilities may last for long time, be difficult to shut down early, and are inherent to local boarder supply chains, individual major processes that are currently highly GHG intense, such as blast furnaces and basic oxygen smelters, could be retired and replaced during major retrofits on much shorter time cycles of 15–25 years.

The cost of retrofitting or retiring a plant before the end of its lifetime depends on plant specific conditions as well as a range of economic, technology and policy developments. For industrial decarbonisation it may be a greater challenge to accelerate the development and deployment of zero emission technologies and systems than to handle the economic costs of retiring existing assets before end of life. The 'lock-in' also goes beyond the lifetime of key process units, such as blast furnaces and crackers, since they are typically part of large integrated plants or clusters with industrial symbiosis, as well as infrastructures with feedstock storage, ports, and pipelines. Individual industrial plants are often just a small part of a complex network of many facilities in an industrial supply chain. In that sense, current assessments of 'carbon lock-in' rely on simplifications due to the high the complexity of industry.

Conditions are also sub-sector and context specific in terms of mitigation options, industry structures, markets, value chains and geographical location. For example, the hydrogen steelmaking joint venture in Sweden involves three different companies headquartered in Sweden (in mining, electricity and steelmaking, respectively), two of which are state owned, with a shared vision and access to iron ore, fossil-free electricity and high-end steel markets (Kushnir et al. 2020). In contrast, chemical clusters may consist of several organisations that are subsidiaries to large multinational corporations with headquarters across the world, that also compete in different markets. Even in the presence of a local vision for sustainability this makes it difficult to engage in formalised collaboration or get support from headquarters (Bauer and Fuenfschilling 2019).

Furthermore, it is relevant to consider also institutional and behavioural lock-in (Seto et al. 2016). On one side, existing high-emitting practices may be favoured through formal and informal institutions (e.g., regulations and social norms or expectations, respectively), for example around building construction and food packaging. On the other side, mitigation options may face corresponding institutional barriers. Examples include how cars are conventionally scrapped (i.e., crushed, leading to copper contamination of steel) rather than being dismantled, or slow permitting procedures for new infrastructure and industrial installations for reducing emissions.

11.5.2 Current industrial and broader policy context

The basic motivation for industrial policy historically has been economic development and wealth creation. Industrial policy can be progressive and promote new developments or be protective to help infant or declining industries. It may also involve the phase-out of industries, including efforts to retrain workers and create new jobs. Industrial policy is not one policy intervention but rather the combined effects of many policy instruments that are coordinated towards an industrial goal. Industrial policies can be classified as being either vertical or horizontal depending on whether singular sectors or technologies are targeted (e.g., through R&D, tariffs and subsidies) or the whole economy (e.g., education, infrastructure, and general tax policies). The horizontal policies are not always thought of as industrial policy although taking a broad view, including policy coordination and institution building, is important for industrial policy to be effective (see e.g., Andreoni and Chang (2019)).

In the past ten years there has been increasing interest and attention to industrial policy. One driver is the desire to retain industry or re-industrialise in regions within Europe and North America where industry has a long record of declining shares of GDP. The need for economic growth and poverty eradication is a key driver in developing countries. An important aspect is the need to meet the "dual challenge of creating wealth for a growing population while staying within planetary boundaries" (Altenburg and Assman 2017). The need for industrial policy that supports environmental goals and green growth has been analysed by Rodrik (2014); Aiginger (2014); Warwick (2013) and Busch et al. 2018). Similar ideas are taken up in OECD reports on green growth (OECD 2011) and system innovation (OECD 2015). However, these approaches to green industrial policy and innovation tend to focus on opportunities for manufacturing industries to develop through new markets for cleaner technologies. They rarely include explicit attention to the necessity of zero emissions and the profound changes in production, use and recycling of basic materials that this entails. This may also involve the phase-out or repurposing of industries that currently rely on fossil fuels and feedstock.

The policy implications of zero emissions for heavy industries are relatively unexplored although some analyses in this direction are available (e.g., (Wesseling et al. 2017; Philibert 2017a; Wyns et al. 2019; Fan and Friedmann 2021; Åhman et al. 2017; Bataille 2020a; Bataille et al. 2018a)). For industry, there has been a long time focus on energy efficiency policies through voluntary and negotiated agreements, energy management and audit schemes, and various programs targeting industry (Fischedick et al. 2014a). Since AR5, interest in circular economy policies has increased and they have become more prevalent across regions and countries, including EU, China, U.S., Japan and Brazil (e.g. (McDowall et al. 2017; Ranta et al. 2018; Geng et al. 2019)). For electrification and CCUS, efforts are nascent and mainly focused on technology development and demonstrations. Policies for demand reduction and materials efficiency are still relatively unexplored (e.g., Pollitt et al. (2020) and IEA (2019b)). Since zero emissions in industry is a new governance challenge it will be important to build awareness and institutional capacity in industrialised as well as developing countries.

In the context of climate change policy, it is fair to say that industry has so far been sheltered from the increasing costs that decarbonisation may entail. This is particularly true for the energy and emissions intensive industries where cost increases and lost competitiveness may lead to carbon leakage, i.e., that industry relocates to regions with less stringent climate policies. Heavy industries typically pay no or very low energy taxes and where carbon pricing exists (e.g., in the European Trading Scheme) they are sheltered through free allocation of emission permits and potentially compensated for resulting electricity price increases. For example, Okereke and McDaniels (2012) shows how the European steel industry was successful in avoiding cost increases and how information asymmetry in the policy process was important for that purpose.

11.5.3 Co-benefits of Mitigation Strategies and SDGs

The deployment of climate change mitigation strategies is primarily influenced by its costs and potential, but also by other broader sustainable development factors such as the SDGs. Mitigation actions therefore are to be considered through the prism of impacts on achieving other economic, social and environmental goals. Those impacts are classified as co-benefits when they are positive or as risk when they are negative. Co-benefits can serve as additional drivers, whiles risks can inhibit the deployment of available mitigation options. Actions taken to mitigate climate change have direct and indirect interactions with SDGs, both positive (synergies) or negative (trade-off) (Fuso Nerini et al. 2019).

Given the wide range of stakeholders involved in climate actions and their (often contradictory) interests and priorities, the nature of co-benefits and risk can affect decision-making processes and behaviour of stakeholders (Labella et al. 2020). Co-benefits form an important driver supporting the adoption of mitigation strategies, yet are commonly overlooked in policymaking. Karlsson et al. (2020), based on a review of 239 peer-reviewed articles concluded that diverse co-benefit categories, including air, soil and water quality, diet, physical activity, biodiversity, economic performance, and energy security, are prevalent in the literature.

11.5.3.1 SDGs co-Benefits through Material Efficiency and Demand Reduction

Material efficiency, an important mitigation option (SDG 13 - Climate action) for heavy industries, is yet to be fully acknowledged and leveraged (Gonzalez Hernandez et al. 2018a; Sudmant et al. 2018;

Dawkins et al. 2019). Material efficiency directly address SDG 12 (Responsible production and consumption) but also provide opportunities to reduce the pressures and impacts on environmental systems (SDG 6 – Clean water and sanitation) (Olivetti and Cullen 2018). Exploiting material efficiency usually requires new business models and provides potential co-benefits of increased employment and economic opportunities (SDG 8 - Decent work and economic growth).

Material efficiency also provides co-benefits through infrastructural development (SDG 9 – Industry, innovation and infrastructure) (Mathews et al. 2018) to support the wide range of potential material efficiency strategies including light-weighting, re-using, re-manufacturing, recycling, diverting scrap, extending product lives, using products more intensely, improving process yields, and substituting materials (Allwood et al. 2011). Worrell et al. (2016) also emphasises how material efficiency improvements, in addition to limiting the impacts of climate change help deliver sustainable production and consumption co-benefits through environmental stewardship. Binder and Blankenberg (2017) and Dhandra (2019) show that sustainable consumption is positively related to life satisfaction and subjective well-being (SDG 3) and Guillen-Royo (2019) adds positive association with happiness and life satisfaction.

The reduction in excessive consumption and demand for products and services generates a reduction in post-consumption waste and so enhances clear water and sanitation (SDG 6) (Govindan 2018; Minelgaitė and Liobikienė 2019) and reduces waste along product supply chains and lifecycle (SDG 12) (Unstats 2020). Genovese et al. (2017) At the risk side there are possible reduction of employment, incomes, sales taxes from the material extraction and processing activities, considered as excessive for sustainable consumption (Thomas 2003).

11.5.3.2 SDGs co-Benefits from Circular Economy and Industrial Waste

While the circular economy concept first emerged in the context of waste avoidance, resource depletion, closed-loop recycling, etc., it has now evolved as a tool for a broader systemic national policy due to its potential wider benefits (Geng et al. 2013). It represents new circular business models that encourage design for re-use and to improve material recovery and recycling, and so represents a departure from the traditional linear production and consumption systems (with landfilling at the end), with a wide range of potential co-benefits to a wide range of SDGs (Genovese et al. 2017; Schroeder et al. 2019; Unstats 2020; Guo et al. 2016).

Genovese et al. (2017) articulates the advantages from an environmental and responsible consumption and production point of view (SDG 12). Many studies have outlined new business models based on the circular economy that fosters sustainable economic growth and the generation of new jobs (SDG 8) (Antikainen and Valkokari 2016), as well as global competitiveness and innovation in business and the industrial sector (Pieroni et al. 2019), such as its potential synergies with industry 4.0 (Garcia-Muiña et al. 2018).

Following a review of the literature, Schroeder et al. (2019) identified linkages between circular economy practices and SDGs based on a relationship scoring system and highlighted that such SDGs as SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 8 (Decent Work and Economic Growth), SDG 12 (Responsible Consumption and Production), and SDG 15 (Life on Land) all strongly benefit from circular economy practices. With the potential to impact on all stages of the value chain (micro, meso- and macro-level of the economy), circular economy has also been identified as key industrial strategy to managing waste across sectors.

Chatziaras et al. (2016) highlights the co-benefit to SDG 7 (Affordable and Clean Energy) resulting from waste derived fuel for the cement industry. Through the management of industrial waste using circular economy practices, studies such as (Geng et al. 2012; Bonato and Orsini 2017) have pointed out co-benefits to SDGs beyond clear environmental and economic benefits, highlighting how it also benefits SDG 3 and 11 through improved social relations between industrial sectors and local societies, and improved public environmental awareness and public health level.

11.5.3.3 SDG co-Benefits from Energy Efficiency

Beyond the very direct links between energy and climate change, reliable, clean, and affordable energy (SDG 7) presents a cross-cutting issue, central to all SDGs and fundamental to development, and energy efficiency enables its provision by reducing the direct supply and necessary infrastructure required. Energy efficiency improvements can be delivered through multiple technical options and tested policies, delivering energy and resource savings simultaneously with other socio-economic and environmental co-benefits. At the macro-level, this includes enhancement of energy security (SDG 16 – Peach, Justice and Strong Institutions) delivered through clean low carbon energy systems (Fankhauser and Jotzo 2018). Much of the literature, including Sari and Akkaya (2016); Garrett-Peltier (2017) and Allan et al. (2017) points out that energy efficiency improvements deliver superior employment opportunities (SDG 8 - Decent Work and Economic Growth), while a limited number of studies have reported that it can negatively impact employment in fuel supply sectors (Costantini et al. 2018).

Many studies report that energy efficiency improvements are essential for supporting overall economic growth, contributing to positive changes in multi-factor productivity (SDG 8 - Decent Work and Economic Growth & Industry, Innovation, and Infrastructure) (Bashmakov 2019; Bataille and Melton 2017; Stern 2019; Lambert et al. 2014; Rajbhandari and Zhang 2018) through industrial innovation (SDG 9) (Kang and Lee 2016), with some dissent e.g., (Mahmood and Ahmad 2018). Improved energy efficiency against a background of growing energy prices helps industrial plants stay competitive (Bashmakov and Myshak 2018). Energy efficiency allows continued economic growth under strong environmental regulation. Given that energy efficiency measures reduce the combustion of fossil fuels it leads to reduced air pollution at industrial sites (Williams et al. 2012) and better indoor comfort at working places.

Since less energy supply infrastructure is needed in cities and less energy is needed to produce materials such as cement & concrete, and metals, energy efficiency indirectly supports Sustainable Cities and Communities (SDG 11) (Di Foggia 2018). In addition, energy efficiency in industry reflects achievements in meeting SDG12 (Responsible Consumption and Production.

11.5.3.4 SDGs co-Benefits from Electrification and Fuel Switching

A key, generally underappreciated SDG benefit of electrification is improved urban and indoor air quality (at working places as well) and associated health benefits (SDG 3) from clean electrification (SDG 7) of industrial facilities (IEA 2016). With energy being such an important cross-cutting issue to sustainable development, some SDGs, such as SDG 1, 3, 4, 5 (Harmelink et al. 2018) are co-beneficiaries to using electrification and fuel switching as a climate action mitigation option.

11.5.3.5 SDGs co-Benefits from CCU and CCS

CCU and CCS have been identified as playing key roles in the transition of industry to net zero. Advancements in the development and deployment of both CCS and CCU foster climate action (SDG 13). Other co-benefits for CCS include control of non-CO_2 pollutants (SDG 3), direct foreign investment and know-how (SDG 9), enhanced oil recovery from existing resources, and diversified employment prospects and skills (SDG 8) (Bonner 2017). For CCU, the main co-benefit related contributions are expected within the context of energy transition processes, and in societal advancements that are linked to technological progress (Olfe-Kräutlein 2020). Therefore, the expectations are that the deployment of CCU technologies would have least potential for meeting the SDG targets relating to society/people, compared with the anticipated contributions to the pillars of ecology and economy.

These mitigation options carry a large number of risks as well. The high cost of the capture and storage process not only limit the technology penetration, but also makes energy and products more expensive (risk to SDG 7), potential leaks from under see or underground CO_2 storages carries risks for achieving SDG 6, 14 and 15. While there are economic costs involved with the deployment of CCS and CCU (Bataille et al. 2018a), there are also significant economic and developmental costs associated with taking no action, because of the potential negative impact of climate change. CCS and CCU have been argued as providing public good (Bergstrom and Ty 2017) and co-benefits to key SDGs (Schipper et al. 2011). On the other hand, Fan et al. (2018) among others have noted the potential lock-in of existing energy structures due to CCS. Refer to Table 17.1 for CCS and CCU co-benefits with respect to other sector chapters.

11.6 Policy approaches and strategies

Industrial decarbonisation is technically possible on the mid-century horizon, but requires scale up of technology development and deployment, multi-institutional coordination, and sectoral and national industrial policies with detailed sub-sectoral and regional mitigation pathways and transparent monitoring and evaluation processes (Åhman et al. 2017; Wesseling et al. 2017; Nilsson et al. 2021; Rissman et al. 2020; Bataille et al. 2018a). Transitions of industrial systems entail innovations, plant and technology phase-outs, changes across and within existing value-chains, new sectoral couplings, and large investments in enabling electricity, hydrogen, and other infrastructures. Low carbon transitions are likely to be contested, non-linear and require a multi-level perspective policy approach that addresses a large spectrum of social, political, cultural and technical changes as well as accompanying phase-out policies, and involve a wide range of actors, including civil society groups, local authorities, labour unions, industry associations etc. (Geels et al. 2017; Rogge and Johnstone 2017; Yamada and Tanaka 2019; Koasidis et al. 2020). See also cross chapter Box 12.

Deployment of the mitigation options presented in this chapter (see 11.3 and 11.4) needs support from a mix of policy instruments including: GHG pricing coupled with border adjustments or other economic signals for trade exposed industries; robust government support for research, development, and deployment; energy, material and emissions standards; recycling policies; sectoral technology roadmaps; market pull policies; and support for new infrastructure (See Figure 11.15) (Creutzig 2019; Flanagan et al. 2011; Tvinnereim and Mehling 2018; Rogge et al. 2017; Rissman et al. 2020; Bataille 2020a; Bataille et al. 2018a). The combination of the above will depend on specific sectoral market barriers, technology maturity, and local political and social acceptance (Rogge and Reichardt 2016; Hoppmann et al. 2013). Industrial decarbonization policies need to be innovative and definitive about net zero CO_2 emissions to trigger the level of investment needed for the profound changes in production, use and recycling of basic materials needed (Nilsson et al. 2017). Inclusive and transparent governance that assesses industry decarbonization progress, monitors innovation and accountability, and provides regular recommendations for policy adjustments is also important for progressing (Mathy et al. 2016; Bataille 2020a).

The level of policy experience and institutional capacity needed varies widely across the mitigation options. In many countries, energy efficiency is a well-established policy field with decades of experience from voluntary and negotiated agreements, regulations, standards, energy audits, and demand side management (DSM) programs (see AR5), but there are also many countries where the application of energy-efficiency policy is absent or nascent (See AR5) (García-Quevedo and Jové-Llopis 2021; Tanaka 2011; Saunders et al. 2021; Fischedick et al. 2014a). The application of DSM and load flexibility will also need to grow with electrification and renewable energy integration.

Materials efficiency and circular economy are not well understood from a policy perspective and were for a long time neglected in low-GHG industry roadmaps although they may represent significant potential (Allwood et al. 2011; Polverini 2021; Calisto Friant et al. 2021; IEA 2019b; Gonzalez Hernandez et al. 2018b; IEA 2020a). Material efficiency is also neglected in products design, architectural and civil engineering education, infrastructure and building codes, and urban planning (see Ch 5.6) (Orr et al. 2019; Braun et al. 2018). For example, the overuse of steel and concrete in construction is well documented but policies or strategies (e.g., design guidelines, or regulation) for improving the situation are lacking (Shanks et al. 2019; Dunant et al. 2018). Various circular economy solutions are gaining interest from policy makers with examples such as regulations and economic incentives for repair and reuse, initiatives to reduce planned obsolescence, and setting targets for recycling. Barriers that policies need to address are often specific to the different material loops (e.g., copper contamination for steel and lack of technologies or poor economics for plastics).

There is also a growing interest from policymakers in electrification and fuel switching but the focus has been mainly on innovation and on developing technical production-side solutions rather than on creating markets for enabling demand for low carbon products, although the concept of green public procurement is gaining traction. The situation is similar for CCU and CCS. Low carbon technologies adoption represent an additional cost to producers, and this must be handled through fiscal incentives like tax benefits, GHG pricing, green subsidies, regulation and permit procedures. For example, the 45Q tax credit provides some incentives to reduce investor risk for CCS and attract private investment in the US (Ochu and Friedmann 2021).

Since industrial decarbonisation is only recently emerging as a policy field there is little international collaboration on facilitation (Oberthür et al. 2021). Given that most key materials markets are global and competitive, unless there is much greater global governance to contribute to the decarbonisation of GHG intensive industry through intergovernmental and transnational institutions it is questionable that the world will achieve industry decarbonisation by 2050.

As GHG pricing, through GHG taxes or cap and trade schemes, has remained a central avenue for climate policy, this section begins with a review of how the industrial sector has been concerned with these instruments. The rest of the section is then structured into five key topics, following insights on key failures that policy must address to enable and support large-scale transformations as well as the need for complementary mixes of policies to achieve this goal (Grillitsch et al. 2019; Weber and Rohracher 2012; Rogge and Reichardt 2016). The section describes how the need to focus on long-term transitions rather than incremental changes can be managed through the planning and strategizing of transition pathways; discusses the role of research, development, and innovation policy; highlights the need for enabling low-carbon demand and market creation; reflects on the necessity of establishing and maintaining a level of knowledge and capacity in the policy domain about the industrial transition challenge; and points to the critical importance of coherence across geographical and policy contexts. The section concludes with a reflection on how different groups of actors needs to take up different parts of the responsibility for mitigating climate change in the industrial sector.

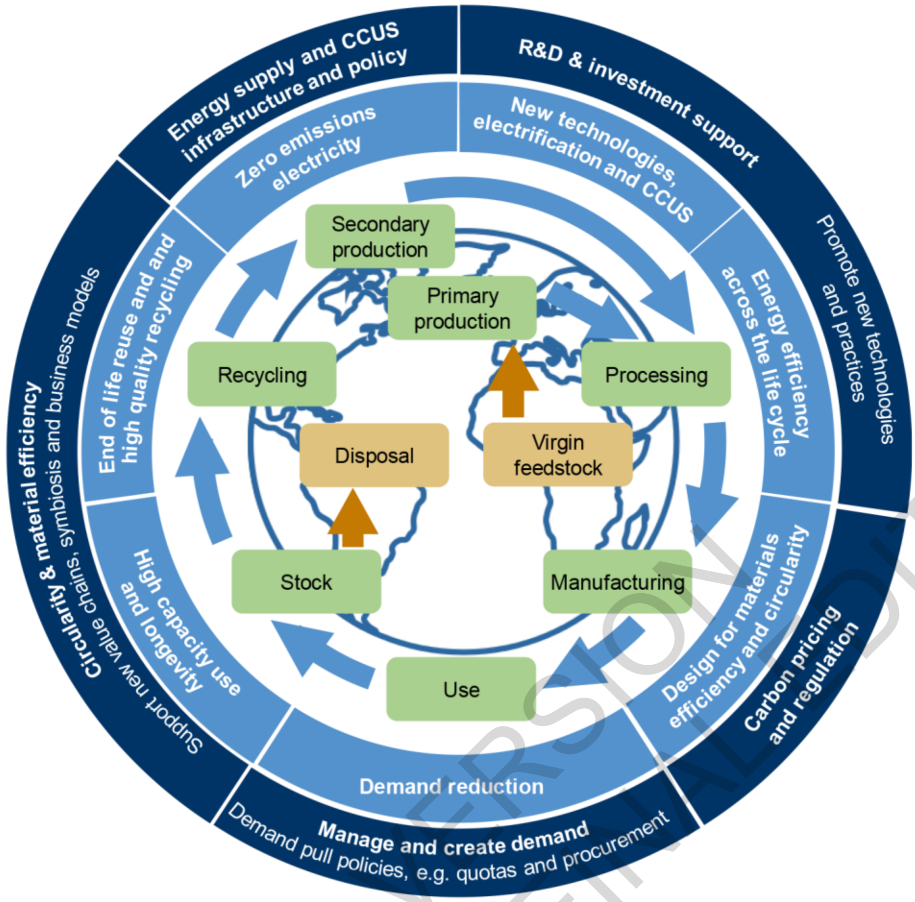


Figure 11.15 Schematic Figure showing the life cycle of materials (green), mitigation options (light blue) and policy approaches (dark blue).

11.6.1 GHG Prices and GHG Markets

Internalizing the cost of GHG emissions in consumer choices and producer investment decisions has been a major strategy promoted by economists and considered by policy makers to mitigate emissions cost-effectively and to incentivize low GHG innovations in a purportedly technology neutral way (Stiglitz et al. 2017; Boyce 2018a). In the absence of a coordinated effort, individual countries, regions and cities have implemented carbon pricing schemes. As of August 23rd, 2021, 64 carbon schemes have been implemented or are scheduled by law for implementation, covering 22.5% of global GHG emissions (World Bank 2020), 35 of which are carbon taxes, primarily implemented on a national level and 29 of which are emissions trading schemes, spread across national and subnational jurisdictions.

Assessments of pricing mechanisms show generally that they lead to reduced emissions, even in sectors that receive free allocation such as industry (Bayer and Aklin 2020; Narassimhan et al. 2018; Martin et al. 2016; Haites et al. 2018; Metcalf 2019). However, questions remain as to whether these schemes can bring emissions down fast enough to reach the Paris Agreement goals (World Bank Group 2019; Tvinnereim and Mehling 2018; Boyce 2018b). Most carbon prices are well below the levels needed to motivate investments in high-cost options that are needed to reach net zero emissions (see Section 11.4.1.5). Among the 64 carbon price schemes implemented worldwide today, only nine have carbon prices above 40 USD (World Bank 2020). These are all based in Europe and include EU Emissions Trading System (ETS) (above 40 USD since March 2021), Switzerland ETS, and seven countries with carbon taxes. Furthermore, emissions-intensive and trade-exposed (EITE) industries are typically allowed exemptions and receive provisions that shelter them from any significant cost increase in virtually all pricing schemes (Haites 2018). These provisions have been allocated due to concerns about loss of competitiveness and carbon leakage which result from relocation and increased imports from jurisdictions with no, or weak, GHG emission regulations (Branger and Quirion 2014a; Jakob 2021a; Branger and Quirion 2014b). Embodied emissions in international trade accounts for one quarter of global CO_2 emissions in 2015 (Moran et al. 2018) and has increased significantly over the past few decades, representing a significant challenge to competitiveness related to climate policy. CBAM, or CBA) are trade-based mechanisms designed to 'equalise' the carbon costs for domestic and foreign producers. They are increasingly being considered by policy makers to address carbon leakage and create a level playing field for products produced in jurisdiction with no, or lower, carbon price (Mehling et al. 2019; Markkanen et al. 2021). On 14 July 2021, the European Commission adopted a proposal for a CBAM that requires importers of aluminium, cement, iron and steel, electricity and fertiliser to buy certificates at the ETS price for the emissions embedded in the imported products (European Commission 2021; Mörsdorf 2021). CBAMs should be crafted very carefully, to meet technical and legal challenges (Rocchi et al. 2018; Sakai and Barrett 2016; Jakob et al. 2014; Cosbey et al. 2019; Pyrka et al. 2020; Joltreau and Sommerfeld 2019). Technical challenges arise because estimating the price adjustment requires reliable data on the GHG content of products imported as well as a clear understanding of the climate policies implications from the countries of imports. Application of pricing tools in industry requires standardization (benchmarking) of carbon intensity assessments at products, installations, enterprises, countries, regions, and the global level. The limited number of existing benchmarking systems are not yet harmonizeded and thus not able fulfill this function effectively. This limits the scope of products that can potentially be covered by CBAM type policies (Bashmakov et al. 2021a).

Legal challenges arise because CBAM can be perceived as a protectionist measure violating the principle of non-discrimination under the regulations of World Trade Organization (WTO). However the absence of GHG prices can also been perceived as a subsidy for fossil fuel based production (Al Khourdajie and Finus 2020; Stiglitz 2006; Kuusi et al. 2020). Another argument supporting CBAM implementation is the possibility to induce low GHG investment in nonregulated regions (Cosbey et al. 2019).

Thus far, California is the only jurisdiction that has implemented CBA tariffs applied on electricity imports from neighbouring states and provides insights on how a CBA can work in practice by using "default" GHG emissions intensity benchmarks (Fowlie et al. 2021). CBAM is an approach likely to be applied first to a few selected energy-intensive industries that are at risk of carbon leakage as the EU is considering. The implementation of CBA needs to balance applicability versus fairness of treatment. An option recently proposed is individual adjustment mechanism to give companies exporting to the EU the option to demonstrate their actual carbon intensity (Mehling and Ritz 2020). Any CBAMs will have to comply with multilaterally agreed rules under the WTO Agreements to be implemented.

The adoption of CBAM by different countries may evolve into the formation of climate club where countries would align on specific elements of climate regulation (e.g. primary iron or clinker intensity) to facilitate implementation and incentivize countries to join (Nordhaus 2015; Hagen and Schneider 2021; Tagliapietra and Wolff 2021a,b). However, not all the countries have the same abilities to report, adapt and transition to low carbon production. The implications of CBAMs on trade relationships should be considered to avoid country divide and separation from a common goal of global decarbonization (Eicke et al. 2021; Banerjee 2021; Bashmakov 2021; Kuusi et al. 2020; Michaelowa et al. 2019).

The globalization of markets and the fragmentation of supply chains complicates the assignment of responsibility for greenhouse gas emissions mitigations related to trade (Jakob et al. 2021). Production-based carbon price schemes minimize the incentives for downstream carbon abatement due to the imperfect pass through of carbon costs and therefore overlook demand-side solutions such as material efficiency (Skelton and Allwood 2017; Baker 2018). An alternative approach is to set the carbon pricing downstream on the consumption of carbon intensive materials, whether they are imported or produced locally (Munnings et al. 2019; Neuhoff et al. 2015, 2019). However, implementation of consumption based GHG pricing is also challenged by the need of product GHG traceability and enforcement transaction costs (Munnings et al. 2019; Jakob et al. 2014). Hybrid approaches are also considered (Neuhoff et al. 2015; Jakob et al. 2021; Bataille et al. 2018a). The efficacy of GHG prices to achieve major industry decarbonization has been challenged by additional real world implementation problems, such as highly regionally fragmented GHG markets (Tvinnereim and Mehling 2018; Boyce 2018b) and the difficult social acceptance of price increases (Raymond 2019; Bailey et al. 2012). The higher GHG prices likely needed to incentivize industry to adopt low GHG solutions pose social equity issues and resistance (Huang et al. 2019b; Wang et al. 2019; Grainger and Kolstad 2010; Bataille et al. 2018b; Hourcade et al. 2018). GHG pricing is also associated with promoting mainly incremental low-cost options and not investments in radical technical change or the transformation of sociotechnical systems (Rosenbloom et al. 2020; Stiglitz 2019; Vogt-Schilb et al. 2018; Grubb 2014). Transparent and strategic management of cap-and-trade proceeds toward inclusive decarbonization transition that support high abatement cost options can contribute toward easing these shortcomings (Raymond 2019; Carl and Fedor 2016). In California, Senate Bill 535 (De León, Statutes of 2012) require that at least a quarter of the proceeds go to projects that provide a benefit to disadvantaged communities (California Climate Investments 2020).

Clear and firm emission reduction caps towards 2050 are essential for sending strong signals to businesses. However, many researchers recognize that complementary policies must be developed to set current production and consumption patterns toward a path consistent with achieving the Paris agreement goals as cap and trade or carbon taxes are not enough (Schmalensee and Stavins 2017; Kirchner et al. 2019; Vogt-Schilb and Hallegatte 2017; Bataille et al. 2018b). In this broader policy context, proceeds from pricing schemes can be used to support the deployment of options with near term abatement costs that are too high to be incentivised by the prevailing carbon price, but which show substantial cost reduction potential with scale and learning, and to ensure a just transition (Wang and Lo 2021).

11.6.2 Transition pathways planning and strategies

Decarbonising the industry sector requires transitioning how material and products are produced and used today to development pathways that include the strategies outlined in Sections 11.3 and 11.4 and Figure 11.15. Such broad approaches require the development of transition planning that assesses the impacts of the different strategies and consider local conditions and social challenges that may result from conflicts with established practices and interests, with planning and strategies directly linked to these challenges.

Governments have traditionally used voluntary agreements or mandatory energy or emission reduction targets to achieve emission reduction for specific emission intensive sectors (e.g., UK Climate Change Agreements; India Performance, Achieve and Trade scheme). Sector visions, roadmaps and pathways combined with a larger context of socio-economic goals, with clear objectives and policy direction are needed for every industrial sectors to achieve decarbonisation and at the time of writing they are emerging for some sectors. Grillitsch et al. (2019b) working from the socio-technical transitions literature, focuses on the need for maintaining "directionality" for innovation (e.g. towards net zero transformation), the capacity for iterative technological and policy "experimentation" and learning, "demand articulation" (e.g. engagement of material efficiency and high value circularity), and "policy coordination" as four main framing challenges. Wesseling et al. (2017b) bridges from the socio-technical transitions literature to a world more recognisable by executives and engineers, composed of structural components that include actors (e.g., firms, trade associations, government, research organisations, consumers, etc.), institutions (e.g., legal structures, norms, values and formal policies or regulations), technologies (e.g. facilities, infrastructure) and system interactions.

Several studies (Åhman et al. 2017; Material Economics 2019; Wyns et al. 2019; Bataille et al. 2018a) offer detailed transition plans using roughly the same five overarching strategies: 1) policies to encourage material efficiency and high quality circularity; 2) "supply push" R&D and early commercialisation as well as "demand pull" to develop niche markets and help emerging technologies cross "the valley of death"; 3) GHG pricing or regulations with competitiveness provisions to trigger innovation and systemic GHG reduction; 4) long run, low cost finance mechanisms to enable investment and reduce risk; 5) infrastructure planning and construction (e.g. CO_2 transport and disposal, electricity and hydrogen transmission and storage), and institutional support (e.g. labour market training and transition support; electricity market reform). Wesseling et al. (2017b) and (Bataille et al. 2018a) further add a step to conduct ongoing stakeholder engagements, including stakeholders with effective "veto" power (i.e. firms, unions, government, communities, indigenous groups), to share and gather information, educate, debate, and build consensus for a robust, politically resilient policy package. This engagement of stakeholders can also bring on new supply chain collaborations and bridge the cost pass-through challenge (e.g., the Swedish HYBRIT steel project, or the ELYSIS consortium, with plans to bring fully commercialized inert electrodes for bauxite electrolysis to market by 2024).

Detailed sectoral roadmaps that assess the technical, economic, social and political opportunities and provide a clear path to low-GHG development are needed to guide policy designs. For example, the German state of North Rhine Westphalia passed a Climate Process Law that resulted in the adoption of a Climate Protection Plan that set subsector targets through a transparent stakeholder engagement process based on scenario development and identification of low GHG options (Lechtenböhmer et al. 2015), see Box 11.3. Another example is the UK set of Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050 as well as the UK Strategic Growth Plan, which are accompanied by Action Plans for each energy intensive subsector.

START BOX 11.3 HERE

Box 11.3 IN4Climate NRW – Initiative for a climate-friendly industry in North Rhine-Westphalia (NRW)

IN4Climate NRW (www.in4climate.nrw) was launched in September 2019 by the state government of North Rhine-Westphalia (IN4climate.NRW 2019) as a platform for collaboration between representatives from industry, science and politics. IN4climate.NRW offers a common space to develop innovative strategies for a carbon-neutral industrial sector, bringing together different perspectives and competencies.

North Rhine-Westphalia is Germany's industrial heartland. Around 19% of North Rhine-Westphalia's GHGs have their origin in the industry sector. Consequently, the sector bears a particular responsibility when it comes to climate protection, but the state is also a source of high-quality jobs and export value. The NRW government understands that the state's current competitive advantage can only be maintained if the regional industry positions itself as a frontrunner for becoming GHG-neutral.

In working together across different branches (more than 30 companies representing mainly steel, cement, chemical, aluminium industry, refineries and energy utilities) and enabling a direct interaction between industry and government officials, IN4Climate provides a benefit to the participating companies. People from the different areas are working together in so-called innovation teams and underlying working groups with a self-organized process of setting their milestones and working schedule while reflecting long-term needs as well as short-term requirements based on political or societal discussions.

The innovation teams aim to identify and set concrete impulses for development and implementation of breakthrough technologies, specify necessary infrastructures (e.g., for hydrogen production, storage and transport) and appropriate policy settings (i.e., integrated state, national, European policy mix). They also include an attempt to create a discourse between the public and the industry sectors as a kind of sounding board for the early detection of barriers and obstacles.

The initiative has been successful so far, for example having developed a clear vision for a hydrogen strategy and an associated policy framework as well as a broader decarbonisation strategy for the whole sector. It is present at the national level as well as at the European level. Being successful and unique IN4Climate is useful as a blueprint for other regions and is often visited by companies and administration staff from other German states.

It is particularly the so far missing intensive and dedicated cooperation across industrial sub-sectors that can be seen as success factor. Facing substantial transformation needs associated with structural changes and infrastructure challenges, very often solutions can't be provided and realised by single sector but need cooperation and coordination. Even more, chicken and egg problems like the construction of new infrastructures (e.g., for hydrogen and CO_2 disposal) require cooperation and new modes of collaboration. IN4Climate provides the necessary link for this.

END BOX 11.3 HERE

11.6.3 Technological research, development, and innovation

Policies for research, development, and innovation (RDI) for industry are present in most countries but it is only recently, and mainly in developed countries, that decarbonisation of emissions intensive industries has been prioritised (Nilsson et al. 2021; Åhman et al. 2017). Emission intensive industries are characterised by large dominant actors and mature process technologies with high fixed cost, long payback times and low profit margins on the primary production side of the value chain. Investments in RDI are commonly low and aimed at incremental improvements to processes and products (Wesseling et al. 2017).

11.6.3.1 Applied research

Investing in RDI for low-GHG process emissions is risky and uncompetitive in the absence of convincing climate policy. Research investment should be guided by assessing options, technology readiness levels, and roadmaps towards technology demonstration and commercialization. The potential GHG and environmental implications need to be assessed early on to assess the sustainability implications and to direct research needs (Zimmerman et al. 2020; Yao and Masanet 2018). Strategic areas for RDI can be focussed on a set of possible process options for producing basic materials using fossil-free energy and feedstock, or CCU and CCS (11.3.5 and 11.3.6). Policies to enhance RDI include public funding for applied research, technological and business model experimentation, pilot and demonstration projects, as well as support for education and training – which further have the positive side-effect of leading to spill-overs and network effects through labour market mobility and collaboration (Nemet et al. 2018). Innovative business models will not emerge if the transition is not considered along the full value chain with a focus on materials efficiency, circularity, and new roles for industry in a transitioning energy system, including possibly providing demand response for electricity through designed-in flexibility, for example, by combining electrolysis hydrogen production with substantial storage (Vogl et al. 2018).

Fostering collaborative innovation across sectors through the support of knowledge sharing and capabilities building is important as mitigation options involve new or stronger sectoral couplings (Tönjes et al. 2020). One example is linking chemicals to forestry in the upscaling of forest bio-refineries, although it has proven to be difficult to engage a diverse group of actors in such collaborations (Karltorp and Sandén 2012; Bauer et al. 2018). Heterogeneous collaboration and knowledge exchange can be encouraged through conscious design of RDI programs and by supporting network initiatives involving diverse actor groups (Van Rijnsoever et al. 2015; Söderholm et al. 2019).

11.6.3.2 Policy support from demonstration to market

Applied research is relatively inexpensive compared to piloting, demonstrations, and early commercialisation, and arguably a lot of it has already been done for the key technologies that need to climb the technology readiness ladder (see **Table 11.3**). This includes electricity and hydrogen-based processes, electro-thermal technologies, high temperature heat pumps, catalysis, lightweight building construction, low embodied carbon construction materials, etc. Demonstration to market strategies can be particularly successful when the complete supply chain is considered. A prominent example of such an integrated supply chain approach is the UK Offshore Wind Accelerator Project. Coordinated by the UK Carbon Trust and working with wind turbine manufacturers, the project looked across the potential supply chain for floating offshore wind and identified what components manufacturers could innovate and produce by themselves, and where there were gaps beyond the capability of any one firm. This process led to several key areas of work where the government and firms could work together; once the concepts were piloted and proven, the firms went back into a competitive mode. The project illustrates the potential importance of third parties, including government, in creating platforms and opportunities for cross-industry exchange and collaboration (Tönjes et al. 2020).

Pilot and demonstration projects funded through public - private partnerships contributes to risk mitigation for industries and helps inform on the feasibility, performance, costs and environmental impacts of decarbonization technologies. Most countries already maintain government research and deployment programs. For example, the Horizon Europe has a total budget of 95.5 billion EUR (117 billion USD) for 2021-2027, of which 30% will be directed to green technology research. The EU has conducted several demonstration projects for emission intensive industries, such as the Ultra-Low Carbon Steel (ULCOS) project (Abdul Quader et al. 2016), which lead to several small scale pilot that are now going to larger scale firm pilots (e.g., HISARNA, HYBRIT and SIDERWIN). Supported by the EU, several cement firms are working together on the cement LEILAC project, where a new form of limestone calciner is being developed to concentrate the process CO_2 emerging from quicklime production (about 60% of cement emissions) for eventual utilisation or geological storage (as one of many options for cement, see for example, Plaza et al. (2020)). If LEILAC works, it is conceivable that existing cement plants globally that are located near CCS opportunities could have their emissions reduced by 60% with one major retrofit of the kiln.

Once a technology has been demonstrated with scale up potential, the next stage is commercialization. This is a very expensive stage, where costs are not yet compensated by revenue (see, e.g., Åhman et al. (2018) and Nemet et al. (2018)). The H-DRI, SIDERWIN and LEILAC examples are all at the stage of scaling up. Given the resource requirement, a diversified portfolio of investors and support is required to share the risk. LEILAC includes several firms, as did the UK Offshore Wind Accelerator. Government funds are also required and could be refunded in the future through an equity position, royalty or tax. Fast growing economies, which are adding new industrial capacity, can provide opportunities to pilot, demonstrate and scale-up new technologies, as shown by the rapid expansion of electric vehicle and solar panel production in China, which contributed to driving down costs (Nemet 2019; Jackson et al. 2021; Hsieh et al. 2020).

Finally, large capital flows towards deployment of low GHG solutions will not materialise without a growing demand for low carbon materials and products that allows business opportunities. Policy will thus be needed to support the first niche markets which are essential for refining new decarbonized technologies, trouble shooting, and for building manufacturing economies of scale. Market creation does however go beyond the nurturing, shielding, and empowerment of early niches (Smith and Raven 2012; Raven et al. 2016) and must also consider how to significantly re-shape existing markets to create space for decarbonized solutions and crowd out fossil-based ones (Mazzucato 2016).

11.6.4 Market Pull

The perception of an increasing durable demand for low GHG products induces manufacturers to invest in decarbonisation strategies (Olatunji et al. 2019). Policies can support and accelerate this process by creating niche market, stimulating demand for low carbon products through procurement and financing and by addressing informational and other market barriers.

11.6.4.1 Public Procurement

Governments spend a large portion of their budget on the provision of products and material through infrastructure development, general equipment, and miscellaneous goods. The OECD estimates that an average of 30% of general government expenditure goes to public procurements in OECD countries, representing 12.6% of GDP, which makes government a powerful market actor (OECD 2021). Public procurement can therefore create a significant market pull and be used to pursue strategic environmental goals (Ghisetti 2017). Local, regional and national authorities can use their purchasing power to create niche markets and to guarantee demand for low GHG products and material (Wesseling and Edquist 2018; Muslemani et al. 2021). In some cases, governments will have to adapt government procurement policies that are not well suited for the procurement of products and services that focus on the decarbonisation benefits and longer-term procurement commitments of emissions reducing technologies and projects (Ghisetti 2017). Implementation can be challenged by the complexity of criteria, the lack of credible information to check GHG intensities and the added time needed for selection (Testa et al. 2012; Cheng et al. 2018; Geng and Doberstein 2008; Zhu et al. 2013; Liu et al. 2019b; Bratt et al. 2013; Lundberg et al. 2015). To ease these hurdles, the EU commission has developed environmental criteria that can be directly inserted in tender documents (Igarashi et al. 2015; European Commission 2016). These criteria are voluntary, and the extent of their application varies across public authorities (Bratt et al. 2013; Testa et al. 2016; Michelsen and de Boer 2009). In the Netherlands, companies achieving a desirable certification level under the national CO_2 Performance Ladder obtain a competitive advantage in public procurement (Rietbergen and Blok 2013; Rietbergen et al. 2015). Globally, many countries have implemented green product procurement or sustainable procurement following Sustainable Development Goal (SDG) 12 – Responsible consumption and production (UNEP 2017). Public procurement is also developing at subnational levels. For example, the state of California in the United States passed the Buy Clean California Act (AB 262) that establishes maximum acceptable global warming potentials for eligible steel and glass construction materials for public procurement (USGBC-LA 2018). See Box 11.4.

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Box 11.4 Buy Clean California Act

In October 2017, California passed Assembly Bill (AB) 262, the Buy Clean California Act, a new law requiring state-funded building projects to consider the global warming potential (GWP) of certain construction materials during procurement. The goal of AB 262 is to use California's substantial purchasing power to buy low-carbon products. Such low-carbon public procurement will directly reduce emissions by using lower-carbon products, and indirectly by sending a market signal to manufacturers to reduce their emissions in order to stay competitive in California.

The bill requirements are two-pronged: as of January 2020, manufacturers of eligible materials must submit a facility-specific environmental product declaration (EPD), and the eligible materials must demonstrate (through submitted EPDs) GWP below the product-specific compliance limits defined by the state Department of General Services (DGS), which will regulate policy implementation. The eligible materials include structural steel, carbon steel rebar, flat glass, and mineral wool insulation. In January 2021, the DGS published maximum acceptable GWP limits for each product category set at the industry average of facility specific GWP for each material. Beginning July 1, 2021, awarding authorities were required to verify GWP compliance for all eligible materials (DGS 2020; USGBC-LA 2018).

Prior to adoption of the Buy Clean California Act, the California Department of Transportation (Caltrans) had been evaluating the use of life-cycle assessment and EPDs in evaluating materials. In addition to the materials specified in Buy Clean California Act (noted above), the Caltrans project includes materials used extensively in transportation (concrete, asphalt, and aggregate). Also, the California High-Speed Rail project had begun using EPDs as part of its procurement process. The High-Speed Rail Sustainability Report states that the construction projects will: 1) require EPDs for construction materials including steel products and concrete mix designs, and 2) require "optimized life-cycle scores for major materials" and include additional strategies to reduce impacts across the life cycle of the project (Simonen et al. 2019).

Several other states such as Washington, Minnesota, Oregon, Colorado, New York and New Jersey are developing similar types of Buy Clean regulations (BGA 2020; Simonen et al. 2019).

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11.6.4.2 Private Procurement

The number of companies producing sustainability reports has increased rapidly over the last decade (Jackson and Belkhir 2018) and so has the number of pledges to carbon neutrality announced. This trend has mainly been driven by consumer concerns, investor requests, and as a business strategy to gain a competitive advantage (Koberg and Longoni 2019; Higgins and Coffey 2016; Ibáñez-Forés et al. 2016). For example, Apple and the governments of Québec and Canada are the financier and lead market maker in the Elysis consortium to bring inert electrodes to market for bauxite smelting to make zero GHG aluminium. Aluminium is a very small fraction of the cost of a laptop or smartphone, so even expensive low emissions aluminium adds to Apple's brand at very little cost per unit sold. Some countries are also requiring corporate to report their emissions. For example, the French government requires companies with 500 or more employees and financial institutions to report Corporate Social Responsibility (CSR) and disclose publically Scope 1 (direct emissions), Scope 2 (indirect emissions from purchased electricity) and Scope 3 (emissions from supply chain's 2 impacts and consumer's usage and end-of-life recycling practices) emissions (Mason et al. 2016).

The most common climate mitigation strategies used by corporates are to set emissions reduction targets in line with the Paris Agreement goals through science-based target (SBT) and to develop internal carbon pricing (Kuo and Chang 2021). The SBT initiative records that 338 SBT companies reduced their emissions by 302 $MtCO_2$ e between 2015 and 2019 (SBTI 2021). As of August 2021, 858 companies had set SBT and over 2,000 companies across the world currently use internal carbon pricing with a median internal carbon price of 25 USD per metric ton of CO_2-eq (Bartlett et al. 2021). The most determined companies have developed internal GHG abatement strategies that incorporate their supply chains' emissions (Martí et al. 2015; Tost et al. 2020; Gillingham et al. 2017) and design procurement contracts that encourage or require their suppliers to also improve their product GHG footprint (Liu et al. 2019a). For many corporations, the emissions impact within their supply chain far exceeds their operations direct emissions (CDP 2019). Therefore, the opportunities to reduce emissions through purchasing goods and services from the supply chain (scope 3) have much greater potentials than from direct emissions.

However, these trends have to be approached with caution as some of the emissions reductions are not direct emissions reductions from companies' operations, instead often from offset projects of varying quality (Chrobak 2021). There is a lack of consistency and comparability in the way firms are reporting emissions, which limits the possibilities to assess companies' actual ambition and progress (Blanco et al. 2016; Liu et al. 2015; Burritt and Schaltegger 2014; Sullivan and Gouldson 2012; Rietbergen et al. 2015). More research is needed to assess the current impacts of corporate voluntary climate actions and if these efforts meet the Paris agreement's goals (Rietbergen et al. 2015; Wang and Sueyoshi 2018). It will be critically important that the international corporate accounting frameworks, standards, and related guidance (e.g., GHG Protocol) be maintained and improved to reflect evolving needs in the global market and to allow for comparison of objectives and progress.

11.6.4.3 GHG content certifications

The development of GHG labels corresponds to a growing demand from consumers desiring information about the climate impacts of their consumption (Darnall et al. 2012; Feucht and Zander 2018; Tan et al. 2014). GHG labels fill this information gap by empowering consumers' purchasing decisions and creating higher value for low GHG products and materials (Cohen and Vandenbergh 2012; Vanclay et al. 2011). The willingness to pay for lower GHG products has been found to be positive but to depend on socioeconomic consumer characteristics, cultural preferences and the product considered (Li et al. 2017; Shuai et al. 2014; Tait et al. 2016; de-Magistris and Gracia 2016; Feucht and Zander 2018). Companies and governments that favour low GHG products and who are seeking to achieve environmental, social, and governance (ESG) goals also need readily available and reliable information about the GHG content of products and materials they purchase and produce (Munasinghe et al. 2016; Long and Young 2016).

Numerous methodologies have been developed by public and private organizations to meet the needs for credible and comparable environmental metrics at the product and organization levels. Most follow life cycle assessment standards as described in ISO 14040 and ISO 14044, ISO 14067 for climate change footprint only and ISO 14025 (2006) for environmental product declarations (EPD) but the way system boundaries are applied in practice varies (Liu et al. 2016; Wu et al. 2014). Adoption has been challenged by the complexity and the profusion of applications which contribute to confuse stakeholders (Guenther et al. 2012; Gadema and Oglethorpe 2011; Brécard 2014). The options of applying different system boundaries and allocation principles involve value judgements that in turn influence the results (McManus et al. 2015; Tanaka 2008; Overland 2019; Finnveden et al. 2009). A more systematic and coordinated international approach based on transparent and reliable data and methodologies is needed to induce global low GHG market development (Pandey et al. 2011; Tan et al. 2014; Darnall et al. 2012).

Within the context of GHG content certifications and EPD development, more transparency is needed to increase international comparability and to validate claims to meet consumers demand for low GHG material and products (Rangelov et al. 2021). Greater automation, publicly available reference databases, benchmarking systems and increased stakeholder collaboration can also support the important role of conveying credible emissions information between producers, traders and consumers.

11.6.4.4 Performance Standards and Codes

Policy makers can set minimum performance standards or maximum emission content specifications through legislation to increase the use of low GHG materials and products by mandating the adoption of low GHG production and construction processes while requiring material and resource efficiency aspects.

Construction of buildings represented 11% of energy and process-related carbon dioxide (CO_2) emissions globally in 2018 (IEA and UNEP 2019). The share of embodied emissions in construction is increasing as building energy efficiency is improving and energy supply is decarbonized (Chastas et al. 2016). As a result, jurisdictions are increasingly considering new requirements in building codes to reduce embodied emissions. This is the case of France's new building code which is shifting from a thermal regulation (RT 2012) to an environmental regulation (RE 2020) to include embodied GHG LCA metrics for encouraging use of low-GHG building materials (Schwarz et al. 2020; Ministère de la Transition écologique et solidaire 2018). The 2018 International Green Construction Code (IGCC) provides technical requirements that can be adopted by jurisdictions for encouraging low GHG building construction, which also covers minimum longevity and durability of structural, building envelope, and hardscape materials (Art. 1001.3.2.3) (Celadyn 2014). Low GHG Building Rating Systems, such as LEEDs, are voluntary standards which include specific requirements on material resources in their rating scale. Trade-offs between energy performance achievement and material used in building construction needs to be further assessed and considered as low GHG building code requirements develop. Local governments can also lead the way by adopting standards for construction. This is the case of the county of Marin in California which specifies maximum embodied carbon in $kgCO_{2\text{-eq}}\ m^{-3}$ and maximum ordinary Portland cement content in lbs/yd^3 for different levels of concrete compressive strength (Marin County 2021).

Governments are also turning their attention to developing standards to increase the durability of products and materials by requiring options for maintenance, reparability, reusability, upgradability, recyclability and waste handling. For example, the EU Eco-design directive includes new requirements for manufacturers to make available for a minimum of 7 to 10 years spare parts to repair household equipment (Talens Peiró et al. 2020; Nikolaou and Tsagarakis 2021; Calisto Friant et al. 2021). The European Commission plans to widen the resource efficiency requirements beyond energy-related products to cover products such as textiles, furniture as well as high impact intermediary products such as steel, cement and chemicals in a new sustainable product policy legislative initiative. (Polverini 2021; Domenech and Bahn-Walkowiak 2019; Llorente-González and Vence 2019; European Commission 2020).

Further research is needed to understand how different international and national frameworks, codes, and standards that focus on emissions can work in unison to amplify their mutually desired outcomes. Building performance and market instrument trading frameworks recognized globally do not always incentivize the same outcomes due to the differences in market approach. LCA metrics are a useful tool to help assess optimal options for ultimate emission reduction objectives (Röck et al. 2020; Shadram et al. 2020).

11.6.4.5 Financial Incentives

Fossil-free basic materials production will often lead to higher costs of production, for example, 20–40% more for steel, 70–115% more for cement, and potentially 15–60% for chemicals (Material Economics 2019). There is a nascent literature on what are effectively material "feed-in-tariffs" to bridge the commercialization "valley of death" (Wilson and Grubler 2011) of early development of low GHG materials (Neuhoff et al. 2018; Sartor and Bataille 2019; Wyns et al. 2019; Bataille et al. 2018a). Renewable electricity support schemes have typically been price-based (e.g., production subsidies and feed-in-tariffs) or volume-based (e.g., quota obligations and certificate schemes) and both principles can be applied when thinking about low GHG materials. Auction schemes are typically used for larger scale projects, for example, offshore wind parks.

Based on how feed-in-tariffs worked, a contract for difference (CfD) could guarantee a minimum and higher-than-market price for a given volume of early low GHG materials. CfDs could be based on a minimum effective GHG price reflecting parity with the costs of current higher emitting technologies, or directly on the higher base capital and operating costs for a lower GHG material (Richstein 2017; Chiappinelli et al. 2019; Sartor and Bataille 2019; Vogl et al. 2021a). CfDs can also be offered through low GHG material procurement where an agreed price offsets the incremental cost of buying low GHG content product or material. Private firms, by themselves or collectively, can also guarantee a higher than market price for low GHG materials from their supplier for marketing purposes (Bataille 2020a; Bataille et al. 2018a). Reverse auctions (by which the lowest bidder gets the production subsidy) for low GHG materials is also an option but it remains to be analyzed and explored. While these financial incentive schemes have been implemented for renewable energy, their application to incentivize and support low GHG material production have yet to be developed and implemented. The German government is currently developing a draft law which will allow companies that commit to cut GHG emissions by more than half using innovative technologies to bid for 10-year CfDs with a guaranteed price for low-carbon steel, chemical and cement products (Agora Energiewende and Wuppertal Institut 2019; BMU 2021).

New and innovative financial market contracts for basic materials that represent low-carbon varieties of conventional materials are emerging. This is the case of aluminium for which quantity of low GHG production already exist in countries where hydroelectric power is a common power source. Market developments will allow for low GHG aluminium to trade at a premium rate as demand develops. For example, Harbor Aluminium has launched a green aluminium spot premium at the end of October 2019 and the London Metal Exchange has introduced a "green aluminium" spot exchange contract. (LME 2020; Das 2021).

11.6.4.6 Extended producer responsibility

EPR systems are increasingly used by policy maker to require producers to take responsibility for the end life of their outputs and to cover the cost of recycling of materials or otherwise responsibly managing problematic wastes (Kaza et al. 2018). According to the OECD, there are about 400 EPR systems in operation worldwide, three-quarters of which have been established over the last two decades. One-third of EPR systems cover small consumer electronic equipment, followed by packaging and tyres (each 17%), vehicles, lead-acid batteries and a range of other products (OECD 2016).

While the economic value of some discarded materials such as steel, paper and aluminium is generally high enough to justify the cost and efforts of recycling, at current rates of 85% above 60% and 43% respectively (Cullen and Allwood 2013; Graedel et al. 2011), others like plastic or concrete have a much lower re-circularity value (Graedel et al. 2011). Most plastic waste ends up in landfills or dumped in the environment, with 9% recycled and 12% incinerated globally (UNEP 2018; Geyer et al. 2017)). Collected waste plastics from OECD countries were largely exported to China until a ban in 2018 required OECD countries to review their practices (Qu et al. 2019). EPR schemes may thus need to be strengthened to actually achieve a reduced use of virgin, GHG intensive materials. The potential for re-circularity of unreacted cement and aggregates in concrete is increasing as new standards and requirement develops. For example, concrete fines are now standardized as a new cement constituent in the European standardization CEN/TC 51 "cements and construction limes".

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Box 11.5 Circular economy policy

The implementation of a circular economy relies on the operationalization of the R-imperatives or strategies which extend from the original 3Rs: Reduce, Reuse and Recycle, with the addition of Refuse, Reduce, Re-sell/Re-use, Repair, Re-furbish, Re-manufacture, Re-purpose, Re-cycle, Recover (energy), Re-mine and more (Reike et al. 2018). The R implementation strategies are diverse across countries (Kalmykova et al. 2018; Ghisellini et al. 2016) but, in practice, the lower forms of retention of materials, such as recycling and recover (energy), often dominate. The lack of policies for higher retention of material use such as Reduce, Reuse, repair, remanufacture is due to institutional failures, lack of coordination and lack of strong advocates (Gonzalez Hernandez et al. 2018a).

Policies addressing market barriers to circular business development need to demonstrate that circular products meet quality performance standards, ensure that the full environmental costs are reflected in market prices and foster market opportunities for circular products exchange, notably through industrial symbiosis clusters and trading platforms (Hartley et al. 2020; Hertwich 2020; Kirchherr et al. 2018; OECD 2019a). Policy levels span from micro (such as consumer or company) to meso (eco-industrial parks) and macro (provinces, regions and cities) (Geng et al. 2019). The creation of eco-industry parks ("industrial clusters") has been encouraged by governments to facilitate waste exchanges between facilities, where by-products from one industry is used as a feedstock to another (Tian et al. 2014; Winans et al. 2017; Jiao and Boons 2014; Shi and Yu 2014; Ding and Hua 2012). Systematic assessment of wastes and resources is carried out to assess possible exchange between different supply chains and identify synergies of waste streams that include metal scraps, waste plastics, water heat, bagasse, paper, wood scraps, ash, sludge and others (Ding and Hua 2012; Shi and Yu 2014).

The development of data collection and indicators is nascent and need to ramp up to quantify the impacts and provide evidence to improve circular economy and materials efficiency policies. Policy makers needs to leverage the potential socio-economic opportunities of transitioning to circular economies (Llorente-González and Vence 2020) which shows positive GDP growth and job creation by shifting to more labor-intensive recycling plants and repair services than resource extraction activities (Cambridge Econometrics et al. 2018; WRAP and Alliance Green 2015). The International Labor Organization estimates that worldwide employment would grow by 0.1 per cent by 2030 under a circular economy scenario (ILO 2018). However questions remain if the type of jobs created are concentrated in low-wage labor-intensive circular activities which may need targeted policy instruments to improve working conditions (Llorente-González and Vence 2020).

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11.6.5 Knowledge and capacity

It is important that government bodies, academia and other actors strengthen their knowledge and capacities for the broad transformational changes envisioned for industry. In Japan, the industry has been voluntarily working on GHG reduction, under the Framework of Keidanren's Commitment to a Low-carbon Society since 2009. Government and scientific experts regularly review their commitments and discuss results, monitoring methods, and reconsidering goals. Industry federations/associations can obtain advice in the follow-up meetings from other industries and academics. The energy and transport sectors have decades of building institutions and expertise, whereas industrial decarbonisation is largely a new policy domain. Most countries have experience in energy efficiency policies, some areas of research and innovation, waste management, regulations for operational permits and pollution control, worker safety and perhaps fuel switching. There is less experience with market demand pull policies although low GHG public procurement is increasingly being tested. Circular economy policies are evolving but potential policies for managing material demand growth are less understood. Material efficiency policies through, for example, product standards or regulation against planned obsolescence are nascent but relatively unexplored (Gonzalez Hernandez et al. 2018a).

All this argues for active co-oversight, management and assessment by government, firms, sector associations and other actors, in effect the formation of an active industrial policy that includes decarbonisation in its broader mandate of economic and social development (OECD 2019b; Bataille 2020a). This could draw from the quadruple helix innovation model, which considers the role of government, universities, the private sector, the natural environment and social systems to foster collaboration in innovation (Durán-Romero et al. 2020; Carayannis and Campbell 2019). Important aspects of governance include mechanisms for monitoring, transparency, and accountability. It may involve the development of new evaluation approaches, including a greater focus on ex-ante evaluations and assessment of, for example, readiness and capacities, rather than ex-post evaluations of outcomes. Such organisational routines for learning have been identified as a key aspect of policy capacity to govern evolutionary processes (Karo and Kattel 2018; Kattel and Mazzucato 2018). Although many governments have adopted ideas of focusing resources on the mission or challenge of climate change mitigation, comparisons between Western and East-Asian contexts show significant differences in the implementation of governance structures (Wanzenböck et al. 2020; Mazzucato et al. 2020; Karo 2018). Overall, improved knowledge and stronger expertise is important also to handle information asymmetries and the risk of regulatory capture.

11.6.6 Policy coherence and integration

Industrial net zero transitions, while technically feasible, involves not just a shift in production technology but major shifts in demand, material efficiency, circularity, supply chain structure and geographic location, labour training and adaptation, finance, and industrial policy. This transition must also link decarbonisation to larger environmental and social goals (e.g. air and water quality, low GHG growth, poverty alleviation, sustainable development goals) (OECD 2019b).

Although there is little evidence of carbon leakage so far it will be ever more important to strive for coherence in climate and trade policies as some countries take the lead in decarbonising internationally traded basic materials (Jakob 2021b). At the time of writing the previously academic debate on this issue is shifting to real policy making through debates and negotiations around carbon border adjustment (see 11.6.1) and sectoral agreements or climate clubs (Nordhaus 2015; Nilsson et al. 2021; Åhman et al. 2017; Jakob 2021a). The climate and trade policy integration should also consider what is sometimes called positive leakage, i.e., that heavy industry production moves to where it is easier to reach zero emissions. As a result, policy should go beyond border measures to include, for example, international technology cooperation and transfer and development of shared lead markets.

Energy intensive production steps may move where clean resources are most abundant and relatively inexpensive (Bataille et al. 2021a; Gielen et al. 2020). For example, steel making has historically located itself near iron ore and coal resources whereas in the future it may be located near iron ore and zero GHG electricity or close to carbon storage sites (Fischedick et al. 2014b; Vogl et al. 2018; Bataille 2020a). This indicates large changes in industrial and supply chain structure, with directly associated needs for employment and skills. Some sectors will grow, and some will shrink, with differing skill needs. Each new workforce cohort needs the general specific skill to provide the employment that is needed at each stage in the transition, implicating a need for co-ordination with policies for education and retraining.

Depending on what mixes of deep decarbonisation strategies are followed in a given region (e.g. material efficiency, electrification, hydrogen, biomass, CCU, CCS), infrastructure will need to be planned, financed and constructed The UKCCC Net-zero Technical Report describes the infrastructure needs for achieving net zero GHG in the UK by 2050 for every sector of the economy (UKCCC 2019b). Transportation would be facilitated with pipelines or ships to allow transfer of captured CO_2 for utilisation and disposal, and associated institutional frameworks (IEAGHG 2021). Electrification will require market design and transmission to support increased generation, transmission, and flexible demand. Hydrogen, CCU, and CCS will require significant new or adapted infrastructure. Hydrogen and CO_2 pipelines, and expanded electricity transmission, have natural monopoly characteristics which are normally governed and planned by national and regional grid operators and their regulators. Industrial clustering (a.k.a. eco-parks), such as those planned in Rotterdam and Teeside, UK, would allow more physical and cost-effective sharing of electricity, CCU, CCS, and hydrogen infrastructure but is dependent on physical planning, permitting, and infrastructure policies.

Costing analysis (see Chapter 15) indicates an increased upfront need for financial capital which require policies to encourage long term, patient capital that reflects society's preferences for investment in industrial decarbonisation and the minimum 10 or more years horizon before there are significant new commercially available processes.

All the above indicate the need for general industrial policy as part of a coherent general economic, taxation, investment, employment and social policy for climate change mitigation (Wyns et al. 2019; Wesseling et al. 2017; Bataille et al. 2018a; Nilsson et al. 2021).

11.6.7 Roles and responsibilities

While all climate policy requires topic specific adaptive governance for long term effectiveness (Mathy et al. 2016), deep decarbonisation of heavy industry has special governance challenges, different from those for the electricity, transport or buildings sectors (Åhman et al. 2017; Wesseling et al. 2017; Bataille et al. 2018a). Competition is strong, investments are rare, capital intensive and very "lumpy". In an atmosphere where transformative innovation is required the process is very capital focussed with non-diversifiable risks unless several companies are involved. There are significant infrastructure needs for electricity, hydrogen, and CCS and CCU. Given there is no "natural" market for low emissions materials, there is a need to manage both the supply and demand sides of the market, especially in early phase through lead supplier and markets. Finally, there is a very high probability of surprises and substantial learning, which could affect policy choice, direction, and stringency.

Different types of actors thus have to play different, but coordinated roles and responsibilities in developing, supporting, and implementing policies for an industrial transition. Table 11.6 below shows how the different core parts of integrated policy making for an industrial transition may depend on efforts from different actors groups and highlights the responsibility of these actor groups in developing a progressive and enabling policy context for the transition. This includes policy makers at local, national, and international arenas as well as civil society organisations, industry firms, and interest organisations.

Table 11.6 Examples of the potential roles of different actors in key policy and governance areas for a low GHG transition to indicate the importance of agency and wide stakeholder engagement in the governance of industrial decarbonisation

Actors	Direction: Planning and strategising pathways to net zero	Innovation: RD&D for new technologies and other solutions	Market creation: Create and shape demand-pull for various solutions	Knowledge and capacity: Build institutional capacity across various actors	Coherence: Establish international and national policy coherence
International bodies and multilateral collaboration	More attention to industry in NDCs. Monitor progress and identify gaps. Develop international roadmaps.	Include heavy industry decarbonisation in technology cooperation (e.g., Mission Innovation).	International standards, benchmarking systems, and GHG labels. Allow for creation and protection of lead markets.	Support knowledge building and sharing on industrial decarbonisation.	Align other Conventions and arenas (e.g., WTO) with climate targets and include heavy industry transitions in negotiations.
Regional and national government, and cities	Require net zero strategies in permitting. Set targets and facilitate roadmaps at various levels. Sunset clauses and phase-out agreements for polluting plants.	Experimentation for recycling, materials efficiency, and demand management. Hydrogen, electrification, and other infrastructure.	Public procurement for innovation and lead markets. Green infrastructure investments.	Develop policy expertise for industrial transformation. Support and facilitate materials efficient and circular solutions through design standards, building codes, recycling, and waste policy.	Support vertical policy coherence (i.e., international, national, city level).
Civil society	Monitor and evaluate leaders and laggards. Support transparency.	Engage in responsible innovation programs, experimentation, and social innovation.	Progressive labelling, standards and criteria for low emissions materials and products (e.g., LCA-based), including updating.	Engage in policy processes and build capacity on industrial decarbonisation. Support consumer information and knowledge.	Monitor and support policy coherence and coordination across policy domains (trade, climate, waste, etc.).
Industrial sectors and associations	Adopt net zero emissions targets, roadmaps, and policy strategies for reaching them. Assess whole value chains, scope 3 emissions and new business models.	Share best practice. Coordination and collaboration. Efficient markets for new technology (e.g., licensing).	Work across (new) value chains to establish lead markets for low emissions materials as well as for materials efficiency and circularity.	Education and retraining for designers, engineers, architects, etc. Information sharing and transparency to reduce information asymmetry.	Coordination across policy domains (trade, climate, waste, etc.). Explore sectoral couplings, new value chains and location of heavy industry.

Corporations and companies	Set zero emissions targets and develop corporate and plant level roadmaps for reaching targets.	Lead and participate in R&D, pilots, and demonstrations. Increase and direct R&D efforts at reaching net zero.	Marketing and procurement of low emissions materials and products. Include scope 3 emissions to assess impact and mitigation strategies.	Engage in value chains for increased recycling and materials efficiency. Build knowledge and capacity for reorientation and transformation.	MNCs avoid race to the bottom, and strategically account for high carbon price as part of transition strategy.

11.7 Knowledge gaps

An increasing body of research proposes deep decarbonisation pathways for energy intensive industries including mitigation options such as materials efficiency, circular economy and new primary processes. These options are underrepresented in climate change scenario modelling and integrated assessment models, some of which do not even reflect evolution of demand for basic materials, which is a key driver behind energy consumption and GHGs emissions in the industrial sector. As a result, no agreement is reached so far between bottom-up and top-down studies on the effectiveness and costs for many promising mitigation options, their respective roles, sequencing and packaging within various mitigation pathways.

A significant shift is needed from the transition process of the past mainly based on marginal and incremental changes, with a strong focus on energy efficiency efforts, to one grounded in transformational change where there is limited knowledge of how to implement such change effectively.

There is a knowledge gap on comparable, comprehensive, and detailed quantitative information on costs and potentials associated with the mitigation options for deep decarbonisation in industry, as cost estimates are not often comparable due to the regional or country focus, differences in costs metrics, currencies, discount rates, and energy prices across studies and regions.

A very large and important uncertainty is the availability of biomass for deep decarbonisation pathways due to competition for biomass feedstock with other priorities and the extent to which electrification can reduce the demand for bioenergy in the industry, transport and energy sectors.

CCS and CCU are important mitigation options in industry, for which the potentials and costs vary considerably depending on the diversity of industrial processes, the volume and purity of carbon dioxide flows, the energy requirements, the lifetime of utilisation products and the production route.

The effectiveness of mitigation policies in industry is poorly known as so far the sector has largely been sheltered from the impacts of climate policy due to the concerns of competitiveness and carbon leakage. There is a lack of integration of material efficiency and circularity with energy and climate policies which partly results from the inadequacy of monitored indicators to inform policy debates and set targets, a lack of high-level political focus, a history of strong industrial lobbying, uncoordinated policy across subsectors and institutions, and the sequential nature of decision-making along supply chains.

Industry as a whole is a very complex web of sectors, sub-sectors and inter-sectoral interactions and dependence, with diverse associated mitigation opportunities and co-benefits and costs. Additional knowledge is needed to understand sectoral interactions in the transformation processes.

Industrial climate mitigation policy is supplemental to many other policy instruments developed to reach multiple industrial goals, for the range of stakeholders with their interest and priorities reflecting the assessment of co-benefits and risk and affecting decision-making processes and behaviour of stakeholders. Better knowledge is needed to identify the co-benefits for the adoption of climate change mitigation strategies.

Frequently Asked Questions

FAQ 11.1 What are the key options to reduce industrial emissions?

Industry has a diverse set of GHG emission sources across sub-sectors. To decarbonise industry requires that we pursue several options simultaneously. These include energy efficiency, materials demand management, improving materials efficiency, more circular material flows, electrification, as well as CCU and CCS. Improved materials efficiency and recycling reduces the need for primary resource extraction and the energy intensive primary processing steps. Future recycling may include chemical recycling of plastics if quality requirements make mechanical recycling difficult. One approach, albeit energy intensive, is to break down waste plastics to produce new monomer building blocks, potentially based on biogenic carbon and hydrogen instead of fossil feedstock. Hydrogen can also be used as a reduction agent instead of coke and coal in ironmaking. Process emissions from cement production can be captured and stored or used as feedstock for chemicals and materials. Electricity and hydrogen needs can be very large but the potential for renewable electricity, possibly in combination with other low carbon options, is not a limiting factor.

FAQ 11.2 How costly is industrial decarbonisation and will there be synergies or conflicts with sustainable development?

In most cases and in early stages of deployment, decarbonisation through electrification or CCS will make the primary production of basic materials such as cement, steel, or polyethylene more expensive. However, demand management, energy and materials efficiency, and more circular material flows can dampen the effect of such cost increases. In addition, the cost of energy intensive materials is typically a very small part of the total price of products, such as an appliance, a bottle of soda or a building, so the effect on consumers is very small. Getting actors to pay more for zero emission materials is a challenge in supply chains with a strong focus on competitiveness and cutting costs, but it is not a significant problem for the broader economy. Reduced demand for services such as square meters of living space or kilometres of car travel is an option where material living standards are already high. If material living standards are very low, increased material use is often needed for more sustainable development. The options of materials and energy efficiency, and more circular material flows, generally have synergies with sustainable development. Increased use of electricity, hydrogen, CCU and CCS may have both positive and negative implications for sustainable development and thus require careful assessment and implementation for different contexts.

FAQ 11.3 What needs to happen for a low carbon industry transition?

Broad and sequential policy strategies for industrial development and decarbonisation that pursue several mitigation options at the same time are more likely to result in resource-efficient and cost-effective emission reductions. Industrial decarbonisation is a relatively new field and thus building capacity for industrial transition governance is motivated. For example, policy to support materials efficiency or fundamental technology shifts in primary processes is less developed than energy efficiency policy and carbon pricing. Based on shared visions or pathways for a zero-emission industry, industrial policy needs to support development of new technologies and solutions as well as market creation for low and zero emission materials and products. This implies coordination across several policy domains including research and innovation, waste and recycling, product standards, digitalisation, taxes, regional development, infrastructure, public procurement, permit procedures and more to make the transition to a carbon neutral industry. International competition means that trade rules must be evolved to not conflict with industrial decarbonisation. Some local and regional economies may be disadvantaged from the transition which can motivate re-education and other support.

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Chapter 12: Cross-sectoral perspectives

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Date of Draft: 28/11/2021

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Executive summary

The total emission mitigation potential achievable by the year 2030, calculated based on sectoral assessments, is sufficient to reduce global greenhouse gas emissions to half of the current (2019) level or less (*robust evidence, high agreement*). This potential (32 to 44 $GtCO_2$-eq) requires implementation of a wide range of mitigation options. Options with mitigation costs lower than 20 USD tCO_2^{-1} make up more than half of this potential and are available for all sectors {12.2, Table 12.3}

Carbon Dioxide Removal (CDR) is a necessary element to achieve net zero CO_2 and GHG emissions both globally and nationally, counterbalancing residual emissions from hard-to-transition sectors. It is a key element in scenarios likely to limit warming to 2°C or lower by 2100 (*robust evidence, high agreement*). Implementation strategies need to reflect that CDR methods differ in terms of removal process, timescale of carbon storage, technological maturity, mitigation potential, cost, co-benefits, adverse side-effects, and governance requirements. All Illustrative Mitigation Pathways (IMPs) use land-based biological CDR (primarily Afforestation/Reforestation, A/R) and/or bioenergy with carbon capture and storage (BECCS) and some include direct air carbon capture and storage (DACCS). As a median value (5–95% range) across the scenarios likely limiting warming to 2°C or lower, cumulative volumes of BECCS, net CO_2 removal on managed land (including A/R), and DACCS reach 328 (168–763) $GtCO_2$, 252 (20–418) $GtCO_2$, and 29 (0–339) $GtCO_2$ for the 2020-2100 period, with annual volumes at 2.75 (0.52–9.45) $GtCO_2$ yr^{-1} for BECCS and 2.98 (0.23–6.38) $GtCO_2$ yr^{-1} for the net CO_2 removal on managed land (including A/R), and 0.02 (0–1.74) $GtCO_2$ yr^{-1} for DACCS, in 2050. {12.3, Cross-Chapter Box 8 in this chapter}

Despite limited current deployment, moderate to large future mitigation potentials are estimated for Direct Air Carbon Capture and Sequestration (DACCS), enhanced weathering (EW) and ocean-based CDR methods (including ocean alkalinity enhancement and ocean fertilisation) (*medium evidence, medium agreement*). The potential for DACCS (5–40 $GtCO_2$ yr^{-1}) is limited mainly by requirements for low-carbon energy and by cost (100-300 (full range: 84–386) USD tCO_2^{-1}). DACCS is currently at a medium technology readiness level. EW has the potential to remove 2–4 (full range: <1 to ~100) $GtCO_2$ yr^{-1}, at costs ranging from 50 to 200 (full range: 24–578) USD tCO_2^{-1}. Ocean-based methods have a combined potential to remove 1–100 $GtCO_2$ yr^{-1} at costs of 40–500 USD tCO_2^{-1}, but their feasibility is uncertain due to possible side-effects on the marine environment. EW and ocean-based methods are currently at a low technology readiness level. {12.3}

Realising the full mitigation potential from the food system requires change at all stages from producer to consumer and waste management, which can be facilitated through integrated policy packages (*robust evidence, high agreement*). Some 23-42% of global GHG emissions are associated with food systems, while there is still wide-spread food insecurity and malnutrition. Absolute GHG emissions from food systems increased from 14 to 17 $GtCO_2$-eq yr^{-1} in the period 1990-2018. Both supply and demand side measures are important to reduce the GHG intensity of food systems. Integrated food policy packages based on a combination of market-based, administrative, informative, and behavioural policies can reduce cost compared to uncoordinated interventions, address multiple sustainability goals, and increase acceptance across stakeholders and civil society *(limited evidence, medium agreement).* {7.2, 7.4, 12.4}

Diets high in plant protein and low in meat and dairy are associated with lower GHG emissions *(robust evidence, high agreement*). Ruminant meat shows the highest GHG intensity. Beef from dairy systems has lower emissions intensity than beef from beef herds (8-23 and 17-94 $kgCO_2$-eq (100g protein)$^{-1}$, respectively) when a share of emissions is allocated to dairy products. The wide variation in emissions reflects differences in production systems, which range from intensive feedlots with stock raised largely on grains through to rangeland and transhumance production systems. Where appropriate, a shift to diets with a higher share of plant protein, moderate intake of animal-source foods and reduced intake of added sugars, salt and saturated fats could lead to substantial decreases in GHG emissions. Benefits would also include reduced land occupation and nutrient losses to the surrounding environment, while at the same time providing health benefits and reducing mortality from diet-related non-communicable diseases. {7.4.5, 12.4}

Emerging food technologies such as cellular fermentation, cultured meat, plant-based alternatives to animal-based food products, and controlled environment agriculture, can bring substantial reduction in direct GHG emissions from food production *(limited evidence, high agreement)*. These technologies have lower land, water, and nutrient footprints, and address concerns over animal welfare. Access to low-carbon energy is needed to realize the full mitigation potential, as some emerging technologies are relatively more energy intensive. This also holds for deployment of cold chain and packaging technologies, which can help reduce food loss and waste, but increase energy and materials use in the food system. (*limited evidence, high agreement*). {11.4.1.3, 12.4}

Scenarios that likely to limit warming to 2°C or lower by 2100 commonly involve extensive mitigation in the AFOLU sector that at the same time provides biomass for mitigation in other sectors. Bioenergy is the most land intensive renewable energy option, but the total land occupation of other renewable energy options can become significant in high deployment scenarios *(robust evidence, high agreement)*. Growing demands for food, feed, biomaterials, and non-fossil fuels increase the competition for land and biomass while climate change creates additional stresses on land, exacerbating existing risks to livelihoods, biodiversity, human and ecosystem health, infrastructure, and food systems. Appropriate integration of bioenergy and other biobased systems, and of other mitigation options, with existing land and biomass uses can improve resource use efficiency, mitigate pressures on natural ecosystems and support adaptation through measures to combat land degradation, enhance food security, and improve resilience through maintenance of the productivity of the land resource base (*medium evidence, high agreement*). {3.2.5, 3.4.6, 12.5}

Bio-based products as part of a circular bioeconomy have potential to support adaptation and mitigation. Key to maximizing benefits and managing trade-offs are sectoral integration, transparent governance, and stakeholder involvement *(high confidence)*. A sustainable bioeconomy relying on biomass resources will need to be supported by technology innovation and international cooperation and governance of global trade to disincentivize environmental and social externalities (medium confidence). {12.5, Cross-Working Group Box 3}

Coordinated, cross-sectoral approaches to climate change mitigation should be adopted to target synergies and minimize trade-offs between sectors and with respect to sustainable development *(robust evidence, high agreement)*. This requires integrated planning using multiple-objective-multiple-impact policy frameworks. Strong inter-dependencies and cross-sectoral linkages create both opportunities for synergies and the need to address trade-offs related to mitigation options and technologies. This can only be done if coordinated sectoral approaches to climate change mitigations policies that mainstream these interactions are adopted. Integrated planning and cross-sectoral alignment of climate change policies are particularly evident in developing countries' NDCs pledged under the Paris Agreement, where key priority sectors such as agriculture and energy are closely aligned between the proposed mitigation and adaptation actions in the context of sustainable development and the SDGs. {12.6.2}

Carbon leakage is a critical cross-sectoral and cross-country consequence of differentiated climate policy *(robust evidence, medium agreement)*. Carbon leakage occurs when mitigation measures implemented in one country/sector lead to increased emissions in other countries/sectors. Global commodity value chains and associated international transport are important mechanisms of carbon leakage. Reducing emissions from the value chain and transportation can offer opportunities to mitigate three elements of cross-sectoral spill-overs and related leakage: 1) domestic cross-sectoral spill-overs within the same country; 2) international spill-overs within a single sector resulting from substitution of domestic production of carbon-intensive goods with their imports from abroad; and 3) international cross-sectoral spill-overs among sectors in different countries. {12.6.3}

Cross-sectoral considerations in mitigation finance are critical for the effectiveness of mitigation action as well as for balancing the often conflicting social, developmental, and environmental policy goals at the sectoral level *(medium evidence, medium agreement)*. True resource mobilisation plans that properly address mitigation costs and benefits at sectoral level cannot be developed in isolation of their cross-sectoral implications. There is an urgent need for multilateral financing institutions to align their frameworks and delivery mechanisms including the use of blended financing to facilitate cross-sectoral solutions as opposed to causing competition for resources among sectors. {12.6.4}

Understanding the co-benefits and trade-offs associated with mitigation is key to supporting societies to prioritize among the various sectoral policy options (*medium evidence, medium agreement*). For example, CDR options can have positive impacts on ecosystem services and the SDGs, but also potential adverse side-effects; transforming food systems has potential co-benefits for several SDGs, but also trade-offs; and land-based mitigation measures may have multiple co-benefits but may also be associated with trade-offs among environmental, social, and economic objectives. Therefore, the possible implementation of the different sectoral mitigation options would depend on how societies prioritise mitigation versus other products and services including food, material wellbeing, nature conservation and biodiversity protection, as well as on other considerations such as society's future dependence on CDR and on carbon-based energy and materials. {12.3, 12.4, 12.5, 12.6.1}

Governance of CDR, food systems and land-based mitigation can support effective and equitable policy implementation (*medium evidence, high agreement*). Effectively responding to climate change while advancing sustainable development will require coordinated efforts among a diverse set of state- and non-state-actors on global, multi-national, national, and sub-national levels. Governance arrangements in public policy domains that cut through traditional sectors are confronted with specific challenges, such as establishing reliable systems for monitoring, reporting and verification (MRV) that allow evaluation of mitigation outcomes and co-benefits. Effectively integrating CDR into mitigation portfolios can build on already existing rules, procedures and instruments for emissions abatement. Additionally, to accelerate research, development, and demonstration, and to incentivise CDR deployment, a political commitment to formal integration into existing climate policy frameworks is required, including reliable MRV of carbon flows. Food systems governance may be pioneered through local food policy initiatives complemented by national and international initiatives, but governance on the national level tends to be fragmented, and thus have limited capacity to address structural issues like inequities in access. The governance of land-based mitigation, including land-based CDR, can draw on lessons from previous experience with regulating biofuels and forest carbon; however, integrating these insights requires governance that goes beyond project-level approaches and emphasizes integrated land use planning and management within the frame of the SDGs. {7.4 Box 7.2, 7.6, 12.3.3, 12.4, 12.5}

12.1 Introduction

12.1.1 Chapter overview

The scope of this chapter was motivated by the need for a succinct bottom-up cross-sectoral view of greenhouse gas (GHG) emissions mitigation coupled with the desire to provide systemic perspectives of critical mitigation potentials and options that go beyond individual sectors and cover cross-sectoral topics such as food systems, land systems, and carbon dioxide removal (CDR) methods. Driven by this motivation, Chapter 12 provides a focused thematic assessment of CDR methods and food systems, followed by consideration of land-related impacts of mitigation options (land-based CDR and other mitigation options that occupy land) and other cross-sectoral impacts of mitigation, with emphasis on synergies and trade-offs between mitigation options, and between mitigation and other environmental and socio-economic objectives. The systems focus is unique to AR6 and is of critical policy relevance as it informs coordinated approaches to planning interventions that deliver multiple benefits and minimise trade-offs, and coordinated policy approaches to support such planning, to tap relatively under-explored areas for the strengthening and acceleration of mitigation efforts in the short to medium term, and for dealing with residual emissions in hard-to-transition sectors in the medium to long term.

Table 12.1 presents an overview of the cross-sectoral perspectives addressed in Chapter 12, mapping the chapter main themes to the sectoral and global chapters in this report. These mappings reflect the cross-sectoral aspects of mitigation options in the context of sustainable development, sectoral policy interactions, governance, implications in terms of international trade, spill-over effects, and competitiveness, and cross-sectoral financing options for mitigation. While some cross-sector technologies are covered in more detail in sectoral chapters, this chapter covers important cross-sectoral linkages and provides synthesis concerning costs and potentials of mitigation options, and co-benefits and trade-offs that can be associated with deployment of mitigation options. Additionally, Chapter 12 covers CDR methods and specific considerations related to land use and food systems, complementing Chapter 7. The literature assessed in the chapter includes both peer-reviewed and grey literature post IPCC AR5 including IPCC SR1.5, IPCC SRCCL and IPCC SROCC. Knowledge gaps are identified and reflected where encountered, as well as in a separate section. Finally, a strong link is maintained with sectoral chapters and the relevant global chapters of this report to ensure consistency.

12.1.2 Chapter content

Chapters 5 to 11 assess outcomes from mitigation measures that are applicable in individual sectors, and potential co-benefits and adverse side effects of these individual measures. Chapter 12 brings together the cross-sectoral aspects of these assessments including synergies and trade-offs as well as the implications of measures that have application in more than one sector and measures whose implementation in one sector impacts implementation in other sectors.

Taking stock of the sectoral mitigation assessments, Chapter 12 provides a summary synthesis of sectoral mitigation costs and potentials in the short and long term along with comparison to the top-down IAM assessment literature of Chapter 3 and the national/regional assessment literature of Chapter 4.

In the context of cross-sectoral synergies and trade-offs, the chapter identifies a number of mitigation measures that have application in more than one sector. Examples include measures involving product and material circularity, which contribute to mitigation of GHG emissions in a number of ways, such as treatment of organic waste to reduce methane emissions, avoid emissions through generation of renewable energy, and reduce emissions through substitution of synthetic fertilisers. Low carbon energy technologies such as solar and wind may be used for grid electricity supply, as embedded generation in the buildings sector (e.g., rooftop solar) and for energy supply in the agriculture sector. Nuclear and bio-based thermal electric generation can provide multiple synergies including base load to augment solar and wind, district heating, and seawater desalination. Grid-integrated hydrogen systems can buffer variability of solar and wind power and is being explored as a mitigation option in the transport and industry sectors. Carbon Capture and Storage (CCS) has potential application in a number of industrial processes (cement, iron and steel, petroleum refining and pulp and paper) and the fossil fuel electricity sector. When coupled with energy recovery from biomass (BECCS), CCS can help to provide CO_2 removal from the atmosphere. On the demand side, electric vehicles are also considered an option for balancing variable power, energy efficiency options find application across the sectors, as does reducing demand for goods and services, and improving material use efficiency. Focused inquiry into these areas of cross-sectoral perspectives is provided for CDR, food systems, and land-based mitigation options.

A range of examples of where mitigation measures result in cross-sectoral interactions and integration is identified. The mitigation potential of electric vehicles, including plug-in hybrids, is linked to the extent of decarbonisation of the electricity grid, as well as to the liquid fuel supply emissions profile. Making buildings energy positive, where excess energy is used to charge vehicles, can increase the potential of electric and hybrid vehicles. Advanced process control and process optimisation in industry can reduce energy demand and material inputs, which in turn can reduce emissions linked to resource extraction and manufacturing. Trees and green roofs planted to counter urban heat islands reduce the demand for energy for air conditioning and simultaneously sequester carbon. Material and product circularity contributes to mitigation, such as treatment of organic waste to reduce methane emissions, generate renewable energy, and to substitute for synthetic fertilisers.

The chapter also discusses cross-sectoral mitigation potential related to diffusion of General-Purpose Technologies (GPT), such as electrification, digitalisation, and hydrogen. Examples include the use of hydrogen as an energy carrier, which, when coupled with low carbon energy, has potential for driving mitigation in energy, industry, transport, and buildings (Box 12.5), and digitalisation has the potential for reducing GHG emissions through energy savings across multiple sectors.

The efficient realisation of the above examples of cross-sectoral mitigation would require careful design of government interventions across planning, policy, finance, governance, and capacity building fronts. In this respect, Chapter 12 assesses literature on cross-sectoral integrated policies, cross-sectoral financing solutions, cross-sectoral spill-overs and competitiveness effects, and on cross-sectoral governance for climate change mitigation.

Finally, in the context of cross-sectoral synergies and trade-offs, the chapter assesses the non-climate mitigation co-benefits and adverse effects in relation to SDGs, building on the fast-growing literature on the non-climate impacts of mitigation.

12.1.3 Chapter layout

The chapter is mapped into seven sections. Cost and potentials of mitigation technologies are discussed in Section 12.2, where a comparative assessment and a summary of sectoral mitigation cost and potentials is provided in coordination with the sectoral Chapters 5 to 11, along with a comparison to aggregate cost and potentials based on IAM outputs presented in Chapter 3.

Section 12.3 provides a synthesis of the state and potential contribution of CDR methods for addressing climate change. CDR options associated with the AFOLU and Energy sectors are dealt with in Chapters 6 and 7 and synthesised in Section 12.3. Other methods, not dealt with elsewhere, are covered in more detail. A comparative assessment is provided for the different CDR options in terms of costs, potentials, governance, impacts and risks, and synergies and trade-offs.

Section 12.4 assesses the literature on food systems and GHG emissions. The term 'food system' refers to a composite of elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities that relate to the production, processing, distribution, preparation and consumption of food, and the outputs of these activities, including socio-economic and environmental outcomes. Climate change mitigation opportunities and related implications for sustainable development and adaptation are assessed, including those arising from food production, landscape impacts, supply chain and distribution, and diet shifts.

Section 12.5 provides a cross-sectoral perspective on land occupation and related impacts, risks and opportunities associated with land-based mitigation options as well as mitigation options that are not designated land-based, yet occupy land. It builds on SRCCL and Chapter 7 in this report, which covers mitigation in agriculture, forestry and other land use (AFOLU), including biomass production for mitigation in other sectors. In addition to an assessment of biophysical and socioeconomic risks, impacts and opportunities, this section includes a cross-chapter box (WGII and WGIII) on Mitigation and Adaptation via the Bioeconomy, and a box on Land Degradation Neutrality as a framework to manage trade-offs in land-based mitigation.

Section 12.6 provides a cross-sectoral perspective on mitigation, co-benefits, and trade-offs, including those related to sustainable development and adaptation. The synthesised sectoral mitigation synergies and trade-offs are mapped into options/technologies, policies, international trade, and finance domains. Cross-sectoral mitigation technologies fall into three categories in which the implementation of the technology: (i) occurs in parallel in more than one sector; (ii) could involve interaction between sectors, and/or (iii) could create resource competition among sectors. Policies that have direct sectoral effects include specific policies for reducing GHG emissions and non-climate policies that yield GHG emissions reductions as co-benefits. Policies may also have indirect cross-sectoral effects, including synergies and trade-offs that may, in addition, spill over to other countries.

Section 12.7 provides an overview of knowledge gaps, which could be used to inform further research.

Table 12.1 An overview of cross-sector perspectives addressed in Chapter 12

	Sectoral chapters							***Global chapters***				
Chapter 12 Themes	**Chapter 5**	**Chapter 6**	**Chapter 7**	**Chapter 8**	**Chapter 9**	**Chapter 10**	**Chapter 11**	**Chapter 13**	**Chapter 14**	**Chapter 15**	**Chapter 16**	**Chapter 17**
Costs & Potentials	Change in demand	Renewables CCU CCS Nuclear	Land-use Change	Urban planning Cities Demographics	Standards Electrification	Hybridisation Electric vehicles Fuel economy Decoupling	Technology Biomass CCU CCS	Enabling of mitigation		Finance of mitigation		Synergies and trade-offs to SDGs
CDR		BECCS	Land-based CDR		C storage in buildings				International Governance			
Food Systems	Food demand Wellbeing	Energy demand of some emerging mitigation options	Agricultural production Demand side measures	Urban food systems; controlled environment agriculture		Food transport	Food processing & packaging	Food system transformation	Governance			Food system and SDGs

Mitigation & land use		Land use/ occupation: bioenergy, hydro, solar, wind, nuclear	A/R, Biomass production, Bioenergy, Biochar		Land use and biomass supply	Land use and biomass supply	Land use and biomass supply		Governance			Co-benefits and adverse side effects
Cross-sectoral perspectives	Electrification, Hydrogen, Digitalisation , Circularity, Synergies, Trade-offs, Spill-overs							Policy interactions Policy packages Case studies Value chain & carbon leakage	Governance Leakage	Blended financing	General Purpose Technologies Electrification Hydrogen	SDGs Co-benefits Trade-offs Adaptation

12.2 Aggregation of sectoral costs and potentials

The aim of this section is to provide a consolidated overview of the net emissions reduction potentials and costs for mitigation options available in the various sectors dealt with in the sectoral chapters 6, 7, 9, 10 and 11 of this assessment report. This overview provides policy-makers with an understanding of which options are more or less important in terms of mitigating emissions in the short term (here interpreted as 2030), and which ones are more or less costly. The intention is not to provide a high level of accuracy for each technology cost or potential, but rather to indicate relative importance on a global scale and whether costs are low, intermediate or high. The section starts with an introduction (Section 12.2.1), providing definitions and the background. Next, ranges of net emission reduction potentials and the associated costs for the year 2030 are presented (Section 12.2.2) and compared to earlier estimates and with the outputs of integrated assessment models (IAMs) (Section 12.2.3). Finally, an outlook to the year 2050 is provided (Section 12.2.4).

12.2.1 Introduction

The term 'mitigation potential' is used here to report the quantity of net greenhouse gas emissions reductions that can be achieved by a given mitigation option relative to specified reference scenario. The net greenhouse gas emission reduction is the sum of reduced emissions and enhanced sinks. Several types of potential can be distinguished. The technical potential is the mitigation potential constrained by theoretical limits in addition to the availability of technology and practices. Quantification of technical potentials primarily takes into account technical considerations, but social, economic and/or environmental considerations are sometimes also considered, if these represent strong barriers for the deployment of an option. The economic potential, being the potential reported in this section, is the proportion of the technical potential for which the social benefits exceed the social costs, taking into account a social discount rate and the value of externalities (see glossary). In this section, only externalities related to greenhouse gas emissions are taken into account. They are represented by using different cost cut-off levels of options in terms of USD per tonne of avoided CO_2-eq emissions. Other potentials, such as market potentials, could also be considered, but they are not included in this section.

The analysis presented here is based, as far as possible, on information contained in Chapters 6, 7, 9, 10 and 11, where costs and potentials, referred to here as 'sectoral mitigation potentials' have been discussed for each individual sector. In the past, these were designated as bottom-up potentials, in contrast to the top-down potentials that are obtained from integrated energy-economic models and IAMs. However, IAMs increasingly include 'bottom-up' elements, which makes the distinction less clear. Still, sectoral studies often have more technical and economic detail than IAMs. They may also provide more up-to-date information on technology options and associated costs. However, aggregation of results from sectoral studies is more complex, and although interactions and overlap are corrected for as far as possible in this analysis, it is recognised that such systemic effects are much more rigorously taken into account in IAMs. A comparison is made between the sectoral results and the outcomes of the IAMs in Section 12.2.3.

Costs of mitigation options will change over time. For many technologies, costs will reduce as a result of technological learning. An attempt has been made to take into account the average, implementation-weighted costs until 2030. However, the underlying literature did not always allow such costs to be presented. For the year 2030, the results are presented similarly to AR4, with a breakdown of the potential in "cost bins". For the year 2050, a more qualitative approach is provided. The origins of the cost data in this section mostly are based on studies carried out in the period 2015-2020. Given the wide range of the cost bins that are used in this section it is not meaningful (and often not possible) to convert to USD-values for one specific year. This may lead to some extra uncertainty, but this is expected to be relatively small.

As indicated previously, net emission reduction potentials are presented based on comparison with a reference scenario. Unfortunately, not all costs and potentials found in the literature are determined against the same reference scenarios. In this assessment reference scenarios are based on what were assumed current-policy scenarios in the period 2015-2019. Typical reference scenarios are the SSP2 scenarios (Fricko et al. 2017) and the Current Policies scenario from the World Energy Outlook 2019 (IEA 2019). They can both be considered scenarios with middle-of-the-road expectations on population growth and economic development, but there are still some differences between the two (Table 12.2). The net emission reduction potentials reported here were generally based on analyses carried out before 2020, so the impact of the COVID-19 pandemic was not taken into account. For comparison, the Stated Policies scenario of the World Energy Outlook 2020 (IEA 2020a) is also shown, one of the scenarios in which the impact of COVID-19 was considered. Variations of up to 10% between the different reference scenarios exist with respect to macro-variables such as total primary energy use and total GHG emissions. The potential estimates presented below should be interpreted against this background. The total emissions under the reference scenarios in 2030 are expected to be in the range of 54 to 68 $GtCO_2$-eq yr^{-1} with a median of 60 $GtCO_2$-eq yr^{-1} (Chapter 4, Table 4.1).

For the energy sector the potentials are determined using the World Energy Outlook 2019 Current Policies Scenario as a reference (IEA 2019). However, for the economic assessment more recent LCOEs for different electricity generating technologies were used (IEA 2020a). For the agriculture, forestry and other land use (AFOLU) sector, the potentials were derived from a variety of studies. It may be expected that the best estimates, as averages, match with the reference in a middle-of-the-road scenario. For the buildings sector the Current Policies scenario of World Energy Outlook 2019 (IEA 2019) was used as a reference. For the transport sector, the references of the underlying sources were used. For the industry sector, the scenarios used have emissions that are slightly higher than in the Current Policies scenario from the World Energy Outlook 2019 (IEA 2019).

Table 12.2: Key characteristics of the scenarios that are used as a reference for determining costs and potentials. The values are for the year 2030.

	SSP2 reference (MESSAGE-GLOBIOM) (Fricko et al. 2017)	All reference scenarios median (25/75 per-centiles in parenthesis) (AR6 scenarios database)	WEO-2019 (Current Policies) (IEA 2019)	WEO-2020 (Stated Policies) (IEA 2020a)	AR6 Chapter 4 (Chapter 4, Table 4.1)
Real GDP (PPP) (10^{12} USD)	158 (USD_{2010})	159 (154–171)	3.6% p.a.↑ (2018 to 2030)	2.9% p.a.↑ (2019 to 2030)	
Population (billion)	8.30	8.30 (8.20–8.34)	8.60		
Total primary energy use (EJ)	627	670 (635–718)	710	660	
Total final energy use (EJ)	499	480 (457–508)	502	472	
Energy-related CO_2 emissions (Gt)	33.0	37.9 (34.7–41.4)	37.4	33.2*	37 (35–45)
CO_2 emissions energy and industry (Gt)	37.9	42.3 (39.0–45.8)		36.0	
Total CO_2 (emissions Gt)	40.6	45.7 (41.8–49.4)			43 (38–51)
Total greenhouse gas emissions ($GtCO_2$-eq)	52.7	59.7 (55.0–65.8)			60 (54-68)

*The difference between WEO-2020 and WEO-2019 is partly explained by the fact that WEO-2019 had two different reference scenarios: Current Policies and Stated Policies. WEO-2020 has only one reference: the Stated Policies Scenario (STEPS), which "is based on today's policy settings". The Stated Policy scenario in WEO-2019 had energy-related emissions of 34.9 $GtCO_2$.

12.2.2 Costs and potentials of options for 2030

In this section, we present an overview of mitigation options per sector. An overview of net emission reduction potentials for different mitigation options is presented in Table 12.3.

Firstly, a brief overview of the process of data collection is presented, with a more detailed overview being found in Supplementary Material SM 12.A.2. For the energy sector, the starting point for the determination of the emission reduction potentials was the Emissions Gap Report (UNEP 2017), but new literature was also assessed, and a few studies that provide updated estimates of the mitigation potentials were included. It was found that higher mitigation potentials than in the UNEP report are now reported for solar and wind energy, but at the same time electricity production by solar and wind energy in the reference scenario has increased, compared to earlier versions of the World Energy Outlook. The net effect is a modest increase of the average value of the potential, and a wider uncertainty range. Costs of electricity generating technologies are discussed in Chapter 6, (Section 6.4.7) with a summary of LCOEs from the literature being presented in Section 6.4.7. Mitigation costs of electricity production technology depend on local conditions and on the baseline technology being displaced, and it is difficult to determine the distribution over the cost ranges used in this assessment. However, it is possible to indicate a broad cost range for these technologies. These cost ranges are presented in Table 12.3. For onshore wind and utility scale solar energy, there is strong evidence that despite regional difference in resource potential and cost, a large part of the mitigation potential can be found in the negative cost category or at cost parity with fossil fuel based options. This is also the case for nuclear energy in some regions. Other technologies show mostly positive mitigation potentials, the highest mitigation costs are for CCS, bioelectricity with CCS, for details see Supplementary Material SM 12.A.2.

For the AFOLU sector, assessments of global net emission reduction studies were provided by Chapter 7 (Table 7.3). The number of studies depends on the type of mitigation action, but ranges from 5 to 9. Each of these studies relies on a much larger number of underlying data sources. From these studies, emission reduction ranges and best estimates were derived. The studies presented refer to different years in the period 2020 to 2050, and the mitigation potential presented for AFOLU primarily refers to the average over the period 2020 to 2050. However, because most of the activities involve storage of carbon in stocks that accumulate carbon, or conversely decay over time (e.g., forests, mangroves, peatland soils, agricultural soils, wood products), the 2020 to 2050 average provides a good approximation of the amount of permanent atmospheric CO_2 mitigation that could be available at a given price in 2030. The exception is BECCS which is in an early upscaling phase, so the potential estimated by Chapter 7 as an average for the 2020 to 2050 period is not included in Table 12.3. Note that for the energy sector a mitigation potential for BECCS is provided in Table 12.3.

The emission reduction potentials for the buildings sector were based on the analysis by Chapter 9 authors of a large number of sectoral studies for individual countries or regions. In total, the chapter analysed the results of 67 studies that assess the potential of technological energy efficiency and onsite renewable energy production and use, and the results of 11 studies that assess the potential of sufficiency measures helping avoid demand for energy and materials. The sufficiency measures were included in models by reorganization of human activities, efficient design, planning, and use of building space, higher density of building and settlement inhabitancy, redefining and downsizing goods and equipment, limiting their use to health, living, and working standards, and their sharing. Most of these studies targeted 2050 for the decarbonisation of buildings; the potentials in 2030 reported here rely on the estimates for 2030 provided by these studies or on the interpolated estimates targeting these 2050 figures. Based on these individual country studies, regional aggregate emission reduction percentages were found. The potential estimates were assembled in the order sufficiency, efficiency, renewable options, correcting the amount of the potential at each step for the interaction with preceding measures. Note that the option 'Enhanced use of wood products' was analysed by Chapter 7, but is listed under the buildings sector in Table 12.3, as such enhanced use of wood takes place predominantly in the construction sector.

For the transport sector, Chapter 10 provided data on the emission reduction potential for shipping. For the other transportation modes, additional sources were used to achieve a complete overview of emission reduction potentials (for further details, see Supplementary Material 12.A.2). A limited number of estimates for global emission reduction potential is available: the total number of sources is about 10, and some estimates rely on just one source. The data have been coordinated with Chapter 10 authors.

For the industrial sector, global emission reduction potentials per technology class per sector were derived by Chapter 11 authors, using primarily sectoral or technology-oriented literature. The analysis is based on about 75 studies, including sectoral assessments (Sections 11.4.1, 11.4.2, Figure 11.13).

For methane emission reduction from oil and gas operations, coal mining, waste treatment and wastewater, an analysis was done, based on three major data sources in this area (US EPA 2019; Harmsen et al. 2019; Höglund-Isaksson et al. 2020), and for oil and gas operations complemented by (IEA 2021a). A similar analysis for reductions of emissions of fluorinated gases was carried out based on analysis by the same institutes (Purohit and Höglund-Isaksson 2017; US EPA 2019; Harmsen et al. 2019). Data for CDR options not discussed previously (such as DACCS and enhanced weathering) were taken from Section 12.3. For more details about data sources and data processing, see Supplementary Material 12.A, Section SM 12.A.2.

In Table 12.4 mitigation potentials for all gases are presented in $GtCO_2$-eq. For most sectors the mitigation potentials (notably for methane emissions reductions from coal, oil and gas, waste and wastewater) have been converted to CO_2-eq using global warming potentials (GWP) values as presented in the 6[th] Assessment Report (Cross-Chapter Box 2 in Chapter 2). However, the underlying literature did not always accommodate this, in which cases older GWP values apply. Given the uncertainty ranges in the mitigation potentials in Table 12.3, the impact on the results of using different GWP values is considered to be very small.

Table 12.3: Detailed overview of global net GHG emission reduction potentials ($GtCO_2$-eq) in the various cost categories for the year 2030. Note that potentials within and across sectors cannot be summed, as the adoption of some options may affect the mitigation potentials of other options. Only monetary costs and benefits of options are taken into account. Negative costs occur when the benefits are higher than the costs. For wind energy, for example, this is the case if production costs are lower than those of the fossil alternatives. Ranges are indicated for each option separately, or indicated for the sector as a whole (see column "Notes"); they reflect full ranges. Cost ranges are not cumulative, e.g., to obtain the full potential below 50 USD tCO_2-eq^{-1}, the potentials in the cost bins <0, 0–20 and 20–50 USD tCO_2-eq^{-1} need to be summed together.

Emission reduction options (including carbon sequestration options)	**Cost categories (USD tCO_2-eq^{-1})**					**Notes**
	<0	**0–20**	**20–50**	**50–100**	**100–200**	
Energy sector						*Cost ranges are derived as ranges of LCOEs for different electricity generating technologies and the potentials are updated from UNEP (2017).*
Wind energy	2.1–5.6 (majority in <0 range)					Costs for system integration of intermittent renewables are not included, but these are expected to have limited impact until 2030 and will depend on market design and cross-sectoral integration
Solar energy	2.0–7.0 (majority in <0 range)					Ibid.
Nuclear energy	0.88 ±50%					
Bioelectricity				0.86 ±50%		Biomass use for indoor heating and industrial heat is not included here. Currently, about 90% of renewable industrial heat consumption is biobased, mainly in industries that can use their own biomass waste and residues (IEA, 2020)
Hydropower		0.32 ±50%				Mitigation costs show large variation and may end up beyond these ranges.

Geothermal energy			0.74 ±50%			Mitigation costs show large variation and may end up beyond these ranges.
Carbon capture and storage (CCS)				0.54 ±50%		
Bioelectricity with CCS				0.30 ±50%		
CH_4 emission reduction from coal mining	0.04 (0.01–0.06)	0.41 (0.15–0.64)	0.03 (0.02–0.05)	0.02 (0.01–0.03)		
CH_4 emission reduction from oil and gas operations	0.31 (0.12–0.56)	0.61 (0.23–1.30)	0.07 (0.03–0.20)	0.06 (0.00–0.29)	0.10 (0–0.29)	
Land-based mitigation options (including agriculture and forestry)						*Potentials for AFOLU are averages for the period 2020–2050, and represent a proxy for mitigation in 2030.* *Technical potentials listed below include the potentials already listed in the previous columns.* *Note that in Table 7.3 the same potentials are listed, but they are cumulative over the cost bins.*
Carbon sequestration in agriculture (soil carbon sequestration, agroforestry and biochar application)		0.50 (0.38–0.60)	0.73 (0.5–1.0)	2.21 (0.6–3.9)		Technical potential: 9.5 (range 1.1–25.3)
CH_4 and N_2O emission reduction in agriculture (reduced enteric fermentation, improved		0.35	-	0.28		Technical potential: 1.7 (range 0.5–3.2)

manure management, nutrient management, rice cultivation)		(0.11–0.84)		(0.19–0.46)		GWPs used from AR4 and AR5
Protection of natural ecosystems (avoid deforestation, loss and degradation of peatlands, coastal wetlands and grasslands)		2.28 (1.7–2.9)	0.12 (0.06–0.18)	1.63 (1.3–4.2)	0.22 (0.09–045	Technical potential 6.2 (range 2.8–14.4)
Restoration (afforestation, reforestation, peatland restoration, coastal wetland restoration)		0.15	0.57 (0.2–1.5)	1.46 (0.6–2.3)	0.66 (0.4–1.1)	Technical potential 5.0 (range 1.1–12.3)
Improved forest management, fire management		0.38 (0.32–0.44)	-	0.78 (0.32–1.44)		Technical potential 1.8 (range 1.1–2.8)
Reduce food loss and food waste						Feasible potential 0.5 (0.1–0.9) Technical potential 0.7 (0.1–1.6) Estimates reflect direct mitigation from diverted agricultural production only, not including land-use effects
Shift to sustainable healthy diets						Feasible potential 1.7 (1.0–2.7) Technical potential 3.5 (2.1–5.5) Estimates reflect direct mitigation from diverted agricultural production only, not including land-use effects

Buildings						*The numbers were corrected for the potential overlap between options in the order "sufficiency, efficiency, renewable measures" and they could be therefore added up. In 2050, much larger and cheaper potential is available (see 9.6 in Chapter 9); the potential in 2030 is lower and more expensive mostly due to various feasibility constrains.*
Sufficiency to avoid demand for energy services (e.g., efficient building use and increased inhabitancy and density)	0.56 (0.28–0.84)					
Efficient lighting, appliances and equipment, including ICT, water heating and cooking technologies	0.73 (0.54–0.91)					
New buildings with very high energy performance (change in construction methods, management and operation of buildings, efficient heating, ventilation and air conditioning)			0.35 (0.26–0.53)		0.83 (0.62–1.24)	
Onsite renewable production and use (often backed-up with demand-side flexibility and digitalization measures, typically installed in very new high energy performance buildings)			0.20 (0.15–0.30)		0.27 (0.20–0.40)	

Improvement of existing building stock (thermal efficiency of building envelopes, management and operation of buildings, and efficient heating, ventilation and air conditioning leading to "deep" energy savings)		0.27 (0.20–0.34)				Additionally, there is 0.50 (range 0.37–0.62) $GtCO_2$-eq of potential above a price of 200 USD tCO_2-eq^{-1}
Enhanced use of wood products						Technical potential 1.0 (range 0.04–3.7) Economic potential 0.38 (range 0.3–0.5) (varying carbon prices). Potential is mainly in the construction sector.
Transport						Options for the transportation sector have an uncertainty of ±50%.
Light duty vehicles – fuel efficiency	0.6					
Light duty vehicles – electric vehicles	0.5–0.7					Depending on the carbon intensity of the electricity supplied to the vehicles.
Light duty vehicles – shift to public transport	0.5					
Light duty vehicles – shift to bikes and e-bikes	0.2					
Heavy duty vehicles – fuel efficiency	0.4					
Heavy duty vehicles – electric vehicles	0.2					
Heavy duty vehicles – shift to rail						No data available.
Shipping – efficiency, optimisation, biofuels	0.5 (0.4–0.7)					

Aviation – energy efficiency	0.12–0.32					Limited evidence
Biofuels		0.6–0.8				
Industry						*The numbers for the industry sector typically have an uncertainty of ±25%.* *The numbers are corrected for overlap between the options, except for the 0.15 $GtCO_2$ potential in the highest cost bin. For the rest they can be aggregated to provide full potentials.*
Energy efficiency		1.14				This only applies to more efficient use of fuels. More efficient use of electricity is not included.
Material efficiency			0.93			
Circularity (enhanced recycling)			0.48			
Fuel switching			1.28	0.67	0.15	
Feedstock decarbonisation, process change				0.38		
Carbon capture, utilization and storage (CCU and CCS)					0.15	
Cementitious material substitution			0.28			
Reduction of non-CO_2 emissions		0.2				

Cross-sectorial						
Emission reduction of fluorinated gases	0.26 (0.01–0.50)	0.68 (0.55–0.90)	0.18 (0.01–0.42)	0.09 (0–0.20)	0.03 (0–0.05)	GWPs not updated
Reduction of CH_4 emissions from solid waste	0.33 (0.24–0.43)	0.11 (0.03–0.15)	0.06 (0.03–0.08)	0.04 (0.01–0.10)	0.08 (0.02–0.12)	
Reduction of CH_4 emissions from wastewater	0.02 (0–0.05)	0.03 (0.01–0.05)	0.04 (0.01–0.07)	0.03 (0.02–0.04)	0.07 (0.01–0.16)	
Direct air carbon capture and storage					very small	There is potential in these categories, but given the current technology readiness levels, for 2030 the potential is limited. Also, it is not certain whether the costs will already drop below 200 USD tCO_2^{-1} before 2030. In the longer term, much larger potentials are projected, see Section 12.3.1.
Enhanced weathering					very small	

For all options, uncertainty ranges of the mitigation potentials are given in Table 12.3. As far as possible, the ranges represent the variation in assessments found in the literature. This is the case for wind and solar energy, for the AFOLU options, for the methane mitigation options (coal, oil and gas, waste and wastewater) and for fluorinated gas mitigation. For the latter options, some variability exists for each cost bin, but aggregated over cost ranges the variation is much smaller, typically ±50%. For the buildings sector and the industrial sector options, the uncertainty in the mitigation potential is estimated by the lead authors of Chapters. For options for which only limited sources were available an uncertainty range of ±50% was used. Overall, the uncertainty range per option is typically in the range of ±20% to ±60%.

Despite these uncertainties, clearly a number of options with high potentials can be identified, including solar energy, wind energy, reducing conversion of forests and other natural ecosystems, and restoration of forests and other natural ecosystems. As mid-range values, they each represent 4 to 7% of total reference emissions for 2030. Soil carbon sequestration in agriculture and fuel switching in industry can also be considered as options with high potential, although it should be noted that these options consist of a number of discernible sub-options, see Table 12.3. It can be observed that for each sector, a variety of options is available. Many of the smaller options each make up 1 to 2% of the reference emissions for 2030. Within this group of smaller options there are some categories that, summed together, stand out as substantial: the energy efficiency options and the methane mitigations options.

Costs are highly variable across the options. All sectors have several options for which at least part of the potential has mitigation costs below 20 USD tCO_2^{-1}. The only exception is the industrial sector, in which only energy efficiency is available below this cost level. At the same time, a substantial part of the emission reduction potential comes at higher cost, much being in the 20 to 100 USD tCO_2^{-1} cost ranges. All sectors have substantial additional potential in these cost ranges; only for transportation is this limited. Aggregation of the potentials per cost bin shows that the potential in these cost bins is marginally smaller than in the two cheapest cost bins. For some options, potential was identified in the 100 to 200 tCO_2^{-1} cost bin. The mitigation potentials identified in this cost range make up only a small part of the total mitigation potential. It could be that there is limited potential in this range; however, a more plausible explanation, supported by several authors of sectoral chapters, is that this cost range is relatively unexplored.

In this assessment, the emphasis is on the specific mitigation costs of the various options, and these are often considered as an indicator to prioritise options. However, in such a prioritisation, other elements will also play a role, like the development of technology for the longer term (Section 12.2.4) and the need to optimise investments over longer time periods, see for example Vogt-Schilb et al. (2018) who argue that sometimes it makes sense to start with implementing the most expensive option.

In this section, an overview of emission mitigation options for the year 2030 was presented. The overview of the mitigation potential is based on a variety of approaches, relying on a large number of sources, and the number of sources varied strongly from sector to sector. The main conclusions from this section are: i) there is a variety of options per sector, ii) per sector the options combined show significant mitigation potential, iii) there are a few major options and a lot of smaller ones, and iv) more than half of the potential comes at costs below 20 USD tCO_2^{-1} (between sectors: *medium to robust evidence, high agreement*).

12.2.3 Aggregation of sectoral results and comparison with earlier analyses and Integrated Assessment Models

In this section, the mitigation potentials are aggregated per sector, and then to the global economy. These potentials, which are based on sectoral analysis, are then compared to the results from earlier assessments and the results from Integrated Assessment Models (IAMs). Given the incompleteness of data on the mitigation potential at mitigation costs larger than 100 USD tCO_2^{-1}, the focus will be on options with mitigation costs below 100 USD tCO_2^{-1}.

As suggested previously, the overview presented in Table 12.3 should be interpreted with care, as the implementation of one option may affect the mitigation potential of another option. Most sectoral chapters have supplied mitigation potentials that were already adjusted for overlap and mutual influences (industry, buildings, AFOLU). For the energy sector, interactions between the options will occur, but parallel implementation of all the options seems to be possible; if all options at costs levels below 100 USD tCO_2^{-1} would be implemented, this would lead to an additional power generation with no direct CO_2 emissions of 41% of the total projected generation in 2030. This seems to be possible, but as higher penetrations are relatively unexplored, we apply a smaller uncertainty range at the high end. For the calculation of the aggregate potentials in the energy sector, error propagation rules were applied. For the transport sector, there will be interaction between the technical measures on the one hand and the modal shift measures on the other hand. Given the small mitigation contribution of the modal shift options, these interactions will be negligible. The resulting aggregate mitigation potentials and their uncertainty ranges per (sub)sector are given in Table 12.4 (columns indicated as 'AR6'). This overview confirms the large potentials per sector, even when taking the uncertainty ranges into account.

Calculating aggregated mitigation potentials for the global economy requires that interactions between sectors also need to be taken into account (Section 12.6). First of all, there may be overlap between the electricity supply sector and the electricity demand sectors: if the electricity sector is extensively decarbonized, the avoided emissions due to electricity efficiency measures and local electricity production will be significantly reduced. Therefore, this demand-side mitigation potential is only taken into account for 25% (reflecting the degree of further decarbonisation of the power sector) in the cross-sectoral aggregation. For the other demand sectors, this problem does not arise. The industry sector did not provide estimates for electricity efficiency improvement and in the transport sector the utilization of electricity to date is very low. Electrification options may occur in all sectors, but this enhances the mitigation potential in combination with a decreased carbon intensity of the power sector. For other energy sector options, methane emission reduction from coal, oil and natural gas operations, the situation is more complex. The total emission reduction potential for fossil fuels in the other sectors is high. Should this potential be realised, this would lead to a reduction of the potential reported here. However, reducing fossil fuel use also leads to a reduction in the upstream CH_4 emissions, so in the case of reducing fossil fuel use, these upstream emissions will also be avoided, so no overestimate of the aggregate emission reduction potential occurs.

The total potential, given these corrections for overlap, leads to a mid-range value for the total mitigation potential at costs below 100 USD $tCO_2\text{-eq}^{-1}$ of 38 $GtCO_2$-eq. Given the fact that it is not to be expected that mitigation potentials of the various sectors are mutually correlated, i.e. it is not to be expected that mitigation potentials are all on the high side or all on the low side), the ranges are aggregated using error propagation rules, which leads to a range for the mitigation potential of 32 to 44 $GtCO_2$-eq.

Table 12.4 Overview of aggregate sectoral net GHG emission reduction potentials ($GtCO_2$-eq) for the year 2030 at costs below 100 USD tCO_2-eq^{-1}. Comparisons with earlier assessments are also provided. Note that sectors are not entirely comparable across the three different estimates.

Sector	**Mitigation potentials at costs less than 100 USD tCO_2-eq^{-1}**				
	AR6 best estimate	AR6 range	AR4 (Barker et al. 2007)	UNEP-2017 best estimate (UNEP 2017)	UNEP- 2017 range (UNEP 2017)
Electricity sector	11.0	7.9–12.5	6.2–9.3	10.3	9.5–11.0
Other energy sector (methane)	1.6	1.1–2.1		2.2	1.7–2.6
Agriculture	4.1	1.7–6.7	2.3–6.4	4.8	3.6–6.0
Forestry and other land-use related options	7.3	3.9–13.1	1.3–4.2	5.3	4.1–6.5
AFOLU demand-side options (estimates reflect direct mitigation from **diverted agricultural production only, not including land-use effects)**	2.2	1.1–3.6			1.3–3.4
Buildings (potentials up to 200 USD tCO_2-eq^{-1} **in parentheses)**	Dir 0.7 (1.1) Ind 1.3 (2.1) Tot 2.0 (3.2)	0.5–1.0 (0.7–1.5) 0.9–1.8 (1.5–3.1) 1.4–2.9 (2.3–4.6)	Dir 2.3–2.9 Ind 3.0–3.8 Tot 5.4–6.7	Dir 1.9 Ind 4.0 Tot 5.9	Dir 1.6–2.1

Transport	3.8	1.9–5.7	1.6–2.5	4.7	4.1–5.3
Industry	Dir 5.4	4.0–6.7	Dir 2.3–4.9 Ind 0.83 Tot 3.1–5.7	Dir 3.9 Ind 1.9 Tot 5.8	Dir 3.0–4.8
Fluorinated gases (all sectors)	1.2	0.7–1.5	NE	1.5	1.2–1.8
Waste and wastewater	0.7	0.6–0.8	0.4–1.0	0.4	0.3–0.5
Enhanced weathering	-	-	-	1.0	0.7–1.2
Total of all sectors	**38**	**32–44**	**15.8–31.1**	**38**	**35–41**

Dir = reduction of direct emissions, Ind = reduction of indirect emissions (related to electricity production), Tot = reduction of total emissions, NA = not applicable, NE = not estimated, AR4: Table 11.3, UNEP-2017: Chapter 4.

Mitigation costs and potentials for 2030 have been presented previously, notably in the AR4 Chapter 11 on Mitigation from a cross-sectoral perspective (Barker et al. 2007) and the Emissions Gap Report (UNEP 2017). Note that AR5 did not provide emission reduction potentials in this form. The aggregated potentials reported here are higher than those estimated in AR4. Note however, that AR4 suggested the potentials were underestimated by 10 to 15%, but a higher potential still remains in the current assessment. In a sector-by-sector comparison, higher potentials than in AR4 can be observed especially for the energy sector and the forestry sector, and to a more limited extent for the industry sector and the transport sector. For the energy sector, the change can largely be explained by the higher estimates for wind and solar energy and the improved understanding of how to integrate high shares of intermittent renewable energy sources into power systems. For industry and transport, the higher potentials can be partly explained by the inclusion of more options, like recycling and material efficiency (for industry) and electric transportation and modal shifts for transport. For buildings a lower potential can be observed compared to AR4, one reason is that the 2030 reference direct and indirect emissions were estimated as 45% and 11% higher in AR4 than they were in AR6 (signalling a much quicker actual switch to electricity than was thought 15 to 20 years ago, among other reasons). The other reason for a difference is that the scenarios considered in AR4 had 25 to 30 years between their start year until the target year of 2030 and the scenarios reviewed in AR6 has only 10 to 15 years before 2030. The current retrofitting rates of existing buildings and penetration rates of nearly zero energy buildings do not allow decarbonizing the sector over 10-15 years, but they do over a longer time period. A much larger potential than reported here for 2030 can still be realized in the timeframe up to 2050 (Section 9.6.2).

Another global analysis was done by McKinsey (2009) which presents a marginal abatement cost curve for 2030, suggesting a total potential of 38 $GtCO_2$-eq (note that the reference for this study is 70 $GtCO_2$-eq, which is at the high end of the reference range used in this assessment).

The potentials reported here are comparable with UNEP (2017). Note that material for the energy sector from the UNEP report was partly reused in this analysis. Furthermore, some options for the transport sector (aviation and biofuels) were identical to the estimates in the UNEP report. The remaining mitigation potentials are all based on new – and much more extended – assessment. There are some notable changes. The AR6 mitigation potential for forestry is substantially larger. For buildings the potential is smaller, mainly related to the smaller mitigation potential for electric appliances than in the UNEP report. But overall, the estimates of the total mitigation potential are well aligned, which confirms there is substantial consistency across various emissions estimates.

The results of the sectoral mitigation potentials are also compared with mitigation impacts as calculated by IAMs. To this end, cumulative sectoral potentials over cost ranges were determined, based on the information in Table 12.3. For options that are in various cost ranges, we assumed that they are evenly distributed over these cost ranges. The only exception is wind and solar energy, for which it is indicated that the majority of the mitigation potential is in the negative cost range. It was assumed that the fraction in the negative cost range was 60%; the remainder is evenly distributed over the other cost ranges. These cumulative potentials were compared with emission reductions realized in IAMs at certain price levels for CO_2. Note that these price levels selected in IAMs are average price levels – not all IAMs use globally uniform carbon prices, so underlying these cost levels, there may be regional differentiation. Data were taken from the AR6 scenarios database. Note that, strictly speaking, not all models in the database are IAMs; in this analysis all models in the database were used, but the term IAMs is used as shorthand in the text that follows. All scenarios likely to limit warming to 2˚C or lower are included for the comparison (i.e., the categories of scenarios C1-C3 in Chapter 3). A comparison per sector is provided in Figure 12.1. It is important to note that two different things are compared in this figure: on the one hand emission reduction potentials and on the other hand realisations of (part of) the potential within the context of a certain scenario. Having said that, a number of lessons can be learned from the comparison of both.

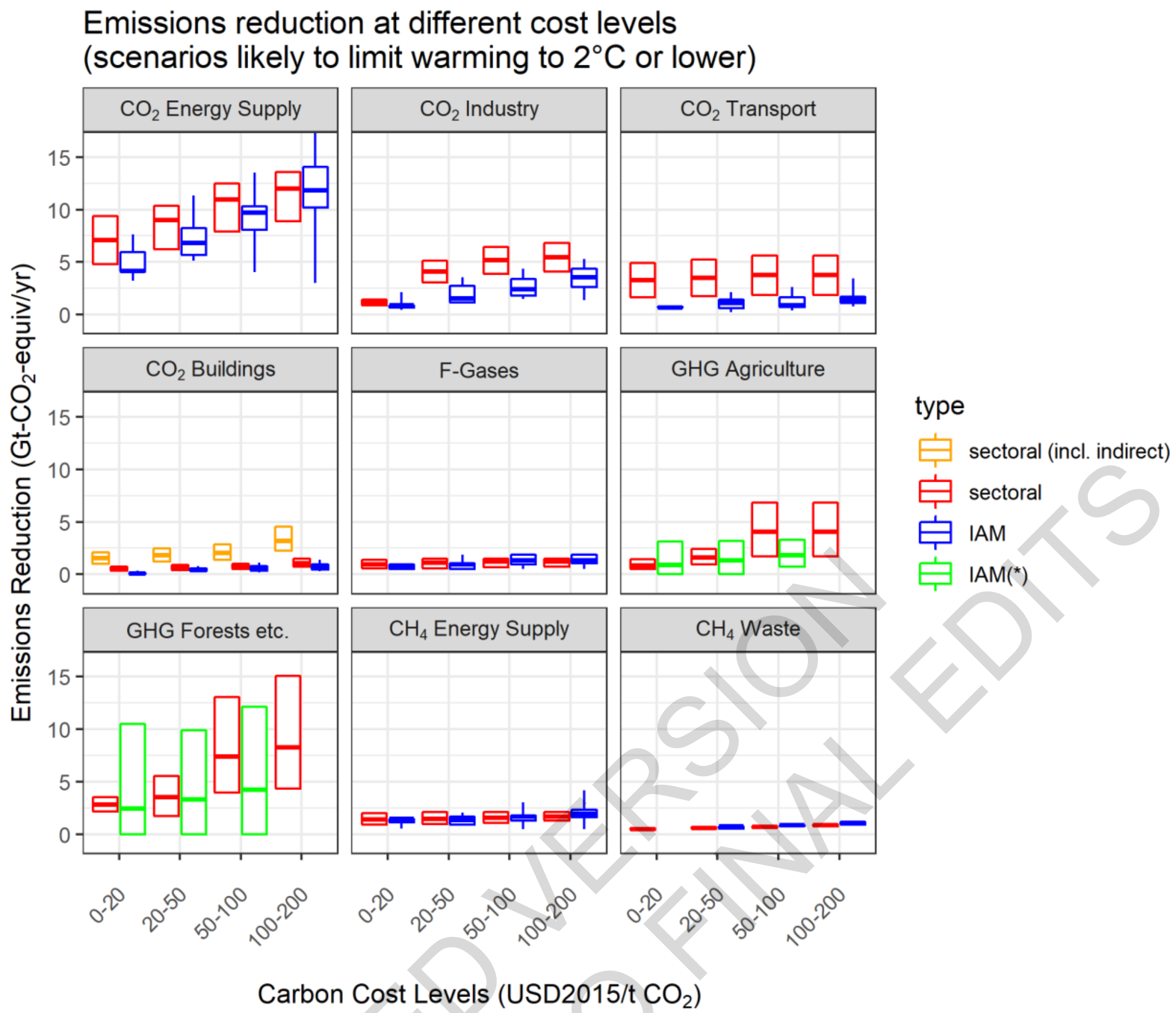

Figure 12.1 Comparison of sectoral estimates for the emission reduction potential with the emission reductions calculated using IAMs.

The latter are given as box plots of global emissions reduction for each sector (blue and green) at different global carbon cost levels (horizontal axis) for 2030, based on all scenarios likely limiting warming to 2°C or lower (see Chapter 3) in the AR6 scenarios database (IPCC 2021). **For IAMs, the cost levels correspond to the levels of the carbon price. Hinges in the blue box plots represent the interquartile ranges and whiskers extend to 5th and 95th percentiles while the hinges in the green box plots describe the full range, and the middle point indicates the mean, not the median. In red, the estimates from the sectoral analysis are given. In all cases, only direct emission reductions are presented, except for the orange boxes (for buildings), which include indirect emission reductions. The orange boxes are only given for reasons of completeness, also for buildings the blue boxes should be compared with the red boxes. Orange and red boxes represent the full ranges of estimates. For IAMs, global carbon prices are applied, which are subject to significant uncertainty.**

For the energy supply sector, the emission reductions projected by the IAMs are for the higher cost levels comparable with the potentials found in the sectoral analysis. But at lower cost levels, the emission reductions as projected by IAMs are smaller than for the sectoral analysis. This is likely due to the fact that high costs for solar energy and wind energy are assumed in IAM models (Krey et al. 2019; Shiraki and Sugiyama 2020). This is not surprising, as the scenario database comprises studies dating back to 2015. A more detailed comparison for the power sector is given in Figure 12.2. Both the sectoral analysis and the IAMs find that both solar and wind energy in particular show strong growth potential, although there is a continuing role for other low-carbon technologies, like nuclear energy and hydropower.

For the AFOLU sector, the sectoral studies provide net emission reduction potentials comparable with projections from the IAMs at costs levels up to 50 USD tCO_2-eq^{-1}. However, beyond that level the mitigation potential found in the sectoral analysis is larger than in the IAMs. For agriculture, it can be explained by the fact that carbon sequestration options, like soil carbon, biochar and agroforestry have little to no representation in IAMs. Similarly, for forestry and other land-use related options, the protection and restoration of other ecosystems than forests (peatland, coastal wetlands and savannas) are not represented in IAMs. Also note that some IAM baselines already have small carbon prices which induce land-based mitigation, while in others, mitigation, particularly from reduced deforestation is part of the storyline even without an implemented carbon price. Both of these effects dampen the mitigation potential available in the USD 100 tCO_2-eq^{-1} carbon price scenario from IAMs. Furthermore, estimates of mitigation through forestry and other land use related options from the AR6 IAM scenario database represent the net emissions from A/R and deforestation, thus are likely to be lower than the sectoral estimates of A/R potential expressed as gross removals.

For the buildings and transport sectors, the sectoral mitigation potentials are higher than those projected by the IAMs. The difference in the transport sector is particularly significant. One possible explanation is that options with negative costs are already included in the reference. In addition, some options, like avoiding demand for energy services in the building sector and model shift in transportation are less well represented in IAMs.

For the industry sector, the sectoral emission reduction potentials are somewhat higher than those reported on average by IAMs. The difference can well be explained by the fact that most IAMs do not include circularity options like material efficiency and recycling; these options together account for 1.5 $GtCO_2$-eq at costs levels from 20 USD tCO_2-eq^{-1} onwards.

For mitigation of emissions of methane and fluorinated gases, the comparability between the sectoral results and IAMs is good.

Overall, it is concluded that there are differences between the sectoral analysis and the IAM outcomes, but most of the differences can be explained by the exclusion of specific options in most IAMs. This comparability confirms the reliability of the sectoral analysis of emission reduction potential. It also demonstrates the added value of sectoral analyses of mitigation potentials: they can more rapidly adapt to changes in price levels of technologies and adopt new options for emission mitigation.

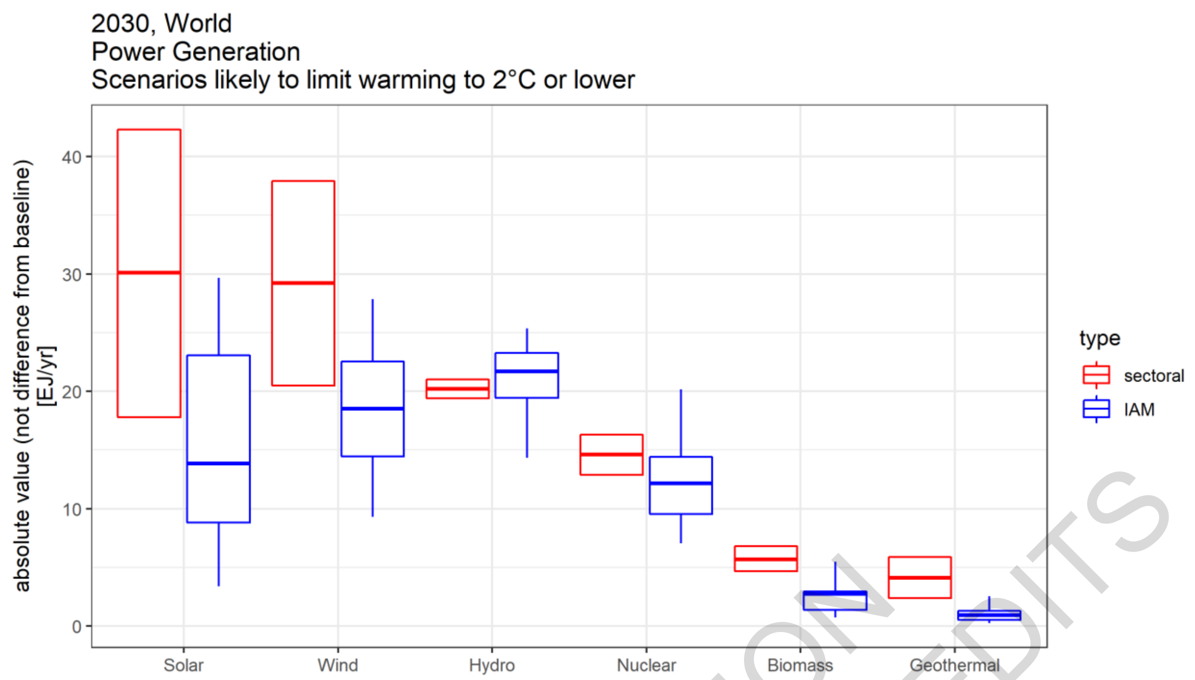

Figure 12.2 Electricity production in 2030 as calculated by Integrated Assessment Models (blue), compared with electricity production potentials found in the sectoral analysis (red).

In both cases cost cut-offs at 100 USD tCO_2^{-1} are applied. Hinges in the blue box plots represent the interquartile ranges and whiskers extend to 5 and 95 percentiles while the hinges in the red box plots describe the full range.

In this section, the information on individual options reported in Section 12.2.2 to sectoral and economy-wide totals has been aggregated. It is concluded that, based on the sectoral analysis, the global mitigation potential is in the range of 32 to 44 $GtCO_2$-eq. This mitigation potential is substantially higher than that reported in AR4, but it is comparable to the more recent estimate by UNEP (2017). Differences exist with the results of IAMs, but most of these can be well explained. The conclusion that the global potential is in this range can be drawn with *high agreement and robust evidence*.

Given the median projection of the reference emissions of 60 $GtCO_2$-eq in 2030, the range of mitigation potentials presented here is sufficient to bring down global emissions in the year 2030 to a level of 16 to 28 $GtCO_2$-eq. Taking into account that there is a range in reference projections for 2030 of 54 to 68 $GtCO_2$-eq, the resulting emissions level shows a wider range: 12 to 31 $GtCO_2$-eq. This is about at or below half of the most recent (2019) emission value of 59±6.6 $GtCO_2$-eq (*high confidence*).

12.2.4 Sectoral findings on emission pathways until 2050

As noted previously, a more qualitative approach is followed and less quantitative information is presented for 2050. The sectoral results are summarised in Table 12.5. In addition to the many technologies that already play a role by 2030 (Table 12.3) additional technologies may be needed for deep decarbonisation, for example for managing power systems with high shares of intermittent renewable sources and for providing new fuels and associated infrastructure for sectors that are hard to decarbonise. New processes also play an important role, notably for industrial processes. In general, stronger sector coupling is needed, particularly increased integration of energy end-use and supply sectors.

Table 12.5: Mitigation options and their characteristics for 2050

Sector	Major options	Degree to which net zero-GHG is possible
Energy sector	Range of supply side options possible (see 2030 overview). Increased share of electricity in final energy use Potentially important role for hydrogen, ammonia, etc.	Zero CO_2 energy system is possible
Agriculture, forestry and other land use	Options comparable to those in 2030. Permanence is important.	Some hard-to-abate activities will still have positive emissions, but for the sector as a whole, net negative emissions are possible through carbon sequestration in agriculture and forestry
Buildings	Sufficiency, high performance new and existing buildings with efficient HVAC esp. heat pumps, building management and operation, efficient appliances, onsite renewables backed up with demand flexibility and digitalisation measures	At least 8.2 $GtCO_2$ or 61% reduction, as compared to the baseline is possible with options on demand-side. This is a low estimate, because in some developing regions literature is not sufficient to derive a comprehensive estimate. Nearly net zero CO_2 emissions are possible if grid electricity will also be decarbonised. Carbon storage in buildings provides CDR.
Transport	Electrification can become a major option for many transport modes. For long-haul trucking, ships and aviation, in addition biofuels, hydrogen and potentially synthetic fuels can be applied.	To a large extent if the electricity sector is fully decarbonized and the deployment of alternative fuels for long-haul trucking, aviation and shipping is successful.
Industry	Stronger role for material efficiency and recycling. Full decarbonisation through new processes, CCS, CCU and hydrogen can become dominant	Approx. 85% reduction is possible. Net zero CO_2 emissions are possible with retrofitting and early retirement.

Cross-sectoral	Direct air carbon capture and storage Enhanced weathering Ocean-based methods	Contributes CDR to support net zero GHG by counterbalancing sectoral emissions

12.3 Carbon dioxide removal (CDR)

CDR refers to a cluster of technologies, practices, and approaches that remove and sequester carbon dioxide from the atmosphere and durably store the carbon in geological, terrestrial, ocean reservoirs, or in products. Despite the common feature of removing carbon dioxide, CDR methods can be very different (Smith et al. 2017). There are proposed methods for removal of non-CO_2 greenhouse gases such as methane (Jackson et al. 2019, 2021) but scarcity of literature on these methods prevents assessment here.

A number of CDR methods (e.g., Afforestation/Reforestation (A/R), Bioenergy with carbon capture and storage (BECCS), soil carbon sequestration (SCS), biochar, wetland/peatland restoration and coastal restoration) are dealt with elsewhere in this report (Chapters 6 and 7). These methods are synthesised in Section 12.3.2. Others, not dealt with elsewhere, i.e., Direct Air Carbon Capture and Storage (DACCS), enhanced weathering of minerals (EW) and ocean-based approaches including ocean fertilisation (OF) and alkalinity (OA) enhancement, are discussed in Sections 12.3.1.1 to 12.3.1.3 below (see also IPCC SROCC and WGI, Section 5.6). Some methods such as BECCS and DACCS involve carbon storage in geological formations, which is discussed in Chapter 6. The climate system and the carbon cycle responses to CDR deployment and each method's physical and biogeochemical characteristics such as storage form and duration are assessed in Chapters 4 and 5 of the WGI report.

START CROSS-CHAPTER BOX 8 HERE

Cross-Chapter Box 8 Carbon Dioxide Removal: Key characteristics and multiple roles in mitigation strategies

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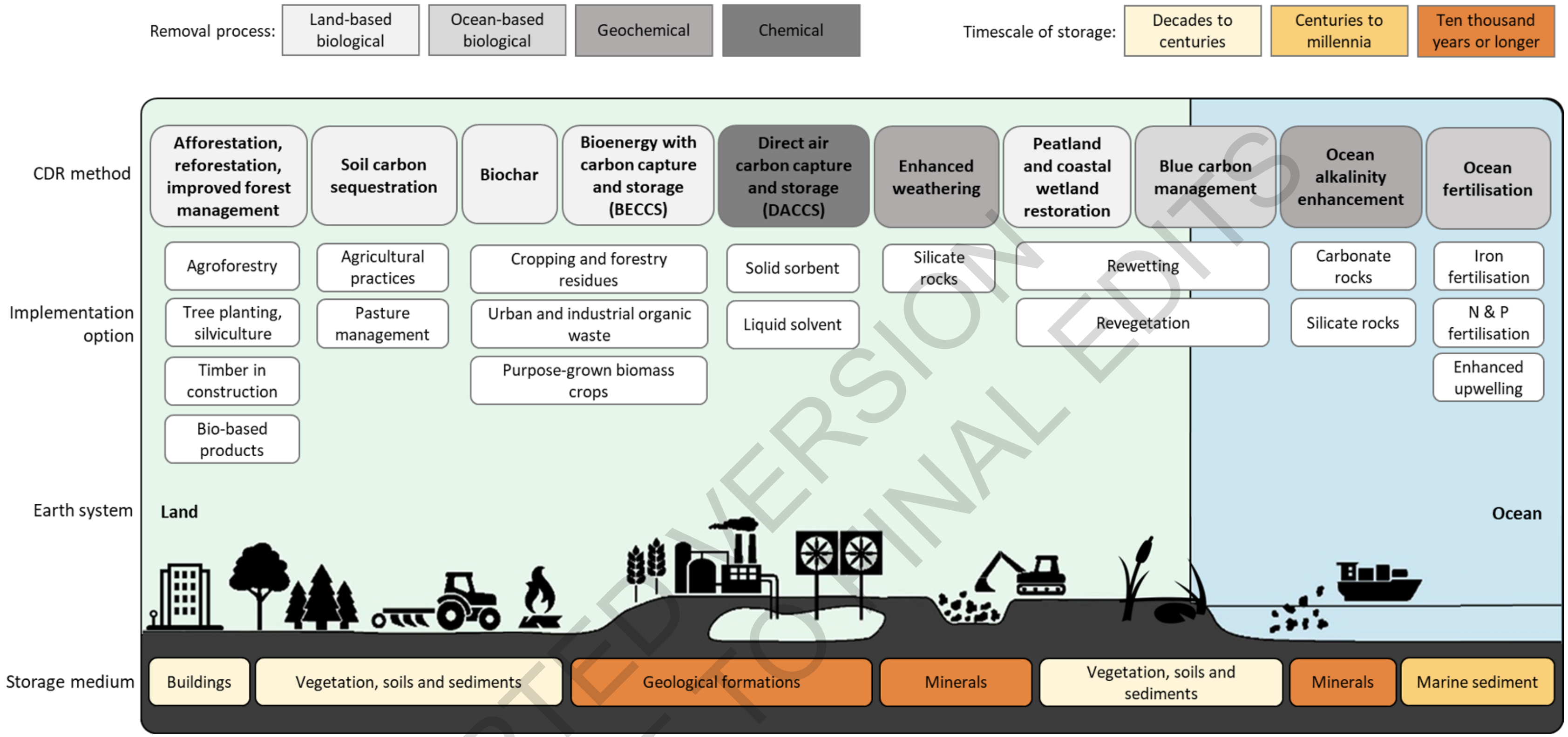
Carbon Dioxide Removal (CDR) is a necessary element of mitigation portfolios to achieve net zero CO_2 and GHG emissions both globally and nationally, counterbalancing residual emissions from 'hard-to-transition' sectors such as industry, transport and agriculture. CDR is a key element in scenarios likely to limit warming to 2°C or lower, regardless of whether global emissions reach near-zero, net zero or net-negative levels (Sections 3.3, 3.4, 3.5 in Chapter 3 and Section 12.3 in this chapter). While national mitigation portfolios aiming at net zero or net-negative emissions will need to include some level of CDR, the choice of methods and the scale and timing of their deployment will depend on the ambition for gross emission reductions, how sustainability and feasibility constraints are managed, and how political preferences and social acceptability evolve (Section 12.3.3). This box gives an overview of CDR methods, presents a categorisation based on the key characteristics of removal processes and storage timescales, and clarifies the multiple roles of CDR in mitigation strategies. The term *negative emissions* is used in this report only when referring to the net emissions outcome at a systems level (e.g., *net negative emissions* at global, national, sectoral or supply chain levels).

Categorisation of the main CDR methods

CDR refers to anthropogenic activities that remove CO_2 from the atmosphere and store it durably in geological, terrestrial, or ocean reservoirs, or in products. It includes anthropogenic enhancement of biological, geochemical or chemical CO_2 sinks, but excludes natural CO_2 uptake not directly caused by human activities. Increases in land carbon sink strength due to CO_2 fertilisation or other indirect effects of human activities are not considered CDR (see Glossary). Carbon Capture and Storage (CCS) and Carbon Capture and Utilisation (CCU) applied to CO_2 from fossil fuel use are not CDR methods as they do not remove CO_2 from the atmosphere. CCS and CCU can, however, be part of CDR methods if the CO_2 has been captured from the atmosphere, either indirectly in the form of biomass or directly from ambient air, and stored durably in geological reservoirs or products (Sections 11.3.6 in Chapter 11 and Section 12.3 in this chapter).

There are many different CDR methods and associated implementation options (Cross-Chapter Box 8, Figure 1). Some of these methods (including afforestation and improved forest management, wetland restoration and SCS) have been practiced for decades to millennia, although not necessarily with the intention of removing carbon from the atmosphere. Conversely, methods such as Direct Air Carbon Capture and Storage (DACCS), Bioenergy with Carbon Capture and Storage (BECCS) and Enhanced Weathering are novel, and while experience is growing, their demonstration and deployment are limited in scale. CDR methods have been categorised in different ways in the literature, highlighting different characteristics. In this report, as in AR6 WGI, the categorisation is based on the role of CDR methods in the carbon cycle, i.e., on the removal process (*land-based biological*; *ocean-based biological*; *geochemical*; *chemical*) and on the timescale of storage (*decades to centuries*; *centuries to millennia*; *ten thousand years or longer*). The timescale of storage is closely linked to the storage medium: carbon stored in ocean reservoirs (through enhanced weathering, ocean alkalinity enhancement or ocean fertilisation) and in geological formations (through BECCS or DACCS) generally has longer storage times and is less vulnerable to reversal through human actions or disturbances such as drought and wildfire than carbon stored in terrestrial reservoirs (vegetation, soil). Furthermore, carbon stored in vegetation or through SCS has shorter storage times and is more vulnerable than carbon stored in buildings as wood products; as biochar in soils, cement and other materials; or in chemical products made from biomass or potentially through direct air capture (WGI, Section 5.6, Figure 5.36; WGIII, Section 11.3.6; Fuss et al. 2018; Minx et al. 2018; NAS 2019). Within the same category (e.g., land-based biological CDR) options often differ with respect to other dynamic or context-specific dimensions such as mitigation potential, cost, potential for co-benefits and adverse side-effects, and technology readiness level (Section 12.3, Table 12.6).



Cross-Chapter Box 8, Figure 1: Carbon Dioxide Removal taxonomy.

Methods are categorised based on removal process (grey shades) and storage medium (for which timescales of storage are given, yellow/brown shades). Main implementation options are included for each CDR method. Note that specific land-based implementation options can be associated with several CDR methods, e.g., agroforestry can support soil carbon sequestration and provide biomass for biochar or BECCS.

Source: This figure is an extended version of Figure 2 in (Minx et al. 2018).

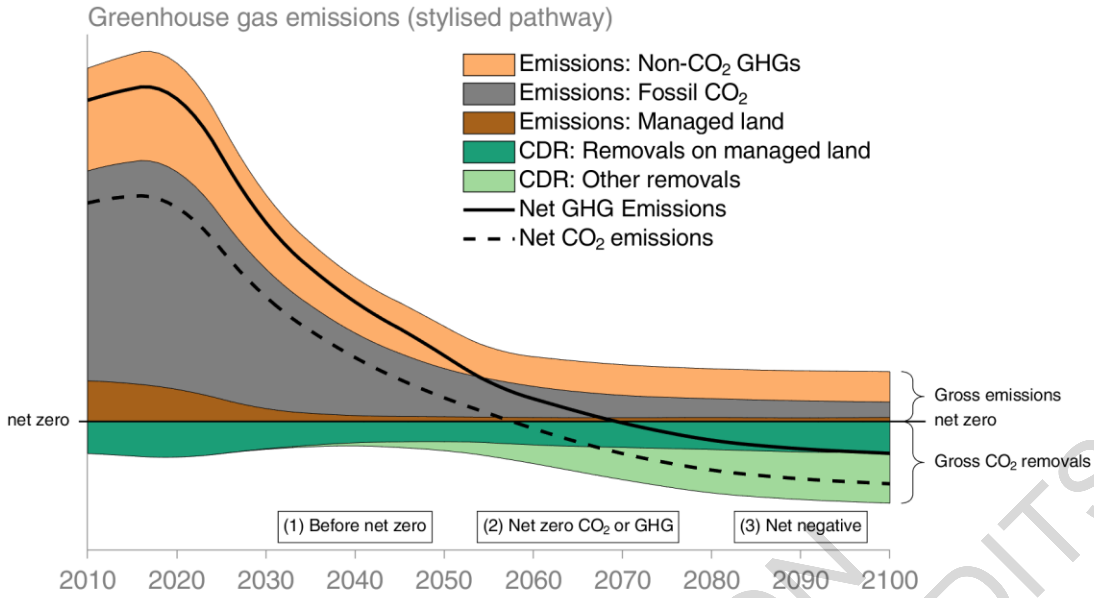
Roles of CDR in mitigation strategies

Within ambitious mitigation strategies at global or national levels, CDR cannot serve as a substitute for deep emissions reductions but can fulfil multiple complementary roles: (1) further reduce net CO_2 or GHG emission levels in the near-term; (2) counterbalance residual emissions from 'hard-to-transition' sectors , such as CO_2 from industrial activities and long-distance transport (e.g., aviation, shipping), or methane and nitrous oxide from agriculture, in order to help reach net zero CO_2 or GHG emissions in the mid-term; (3) achieve and sustain net-negative CO_2 or GHG emissions in the long-term, by deploying CDR at levels exceeding annual residual gross CO_2 or GHG emissions (Sections 2.7.3 in Chapter 2, 3.3 and 3.5 in Chapter 3).

In general, these roles of CDR are not mutually exclusive and can exist in parallel. For example, achieving net zero CO_2 or GHG emissions globally might involve some countries already reaching net-negative levels at the time of global net zero, allowing other countries more time to achieve this. Equally, achieving net-negative CO_2 emissions globally, which could address a potential temperature overshoot by lowering atmospheric CO_2 concentrations, does not necessarily involve all countries reaching net-negative levels (Cross-Chapter Box 3 in Chapter 3; Rajamani et al. 2021; Rogelj et al. 2021).

Cross-Chapter Box 8, Figure 2 shows these multiple roles of CDR in a stylised ambitious mitigation pathway that can be applied to global and national levels. While such mitigation pathways will differ in their shape and exact composition, they include the same basic components: CO_2 emissions from fossil sources, CO_2 emissions from managed land, non-CO_2 emissions, and various forms of CDR. Figure 2 also illustrates the importance of distinguishing between gross CO_2 removals from the atmosphere through deployment of CDR methods and the net emissions outcome (i.e., gross emissions minus gross removals).

CDR methods currently deployed on managed land, such as afforestation or reforestation and improved forest management, lead to CO_2 removals already today, even when net emissions from land use are still positive, e.g., when gross emissions from deforestation and draining peatlands exceed gross removals from afforestation or reforestation and ecosystem conservation (Sections 2.2 in Chapter 2, 7.2 in Chapter 7, Cross-Chapter Box 6 in Chapter 7). As there are currently no removal methods for non-CO_2 gases that have progressed beyond conceptual discussions (Jackson et al. 2021), achieving net zero GHG implies gross CO_2 removals to counterbalance residual emissions of both CO_2 and non-CO_2 gases, applying GWP100 as the metric for reporting CO_2-equivalent emissions, as required for emissions reporting under the Rulebook of the Paris Agreement (Cross-Chapter Box 2 in Chapter 2).



Cross-Chapter Box 8, Figure 2: Roles of CDR in global or national mitigation strategies. Stylised pathway showing multiple functions of CDR in different phases of ambitious mitigation: (1) further reducing net CO_2 or GHG emission levels in near-term; (2) counterbalancing residual emissions to help reach net zero CO_2 or GHG emissions in the mid-term; (3) achieve and sustain net-negative CO_2 or GHG emissions in the long-term.

Net zero CO_2 emissions will be achieved earlier than net zero GHG emissions. As volumes of residual non-CO_2 emissions are expected to be significant, this time-lag could reach one to several decades, depending on the respective size and composition of residual GHG emissions at the time of net zero. Furthermore, counterbalancing residual non-CO_2 emissions by CO_2 removals will lead to net-negative CO_2 emissions at the time of net zero GHG emissions (Cross-Chapter Box 3 in Chapter 3).

END CROSS-CHAPTER BOX 8 HERE

While many governments have included A/R and other forestry measures into their NDCs under the Paris Agreement (Moe and Røttereng 2018; Fyson and Jeffery 2019; Mace et al. 2021), and a few countries also mention BECCS, DACCS and enhanced weathering in their mid-century low emission development strategies (Buylova et al. 2021), very few are pursuing the integration of a broad range of CDR methods into national mitigation portfolios so far (Box 12.1 in Section 12.3.3) (Schenuit et al. 2021). There are concerns that the prospect of large-scale CDR could, depending on the design of mitigation strategies, obstruct near-term emission reduction efforts (Lenzi et al. 2018; Markusson et al. 2018), mask insufficient policy interventions (Geden 2016; Carton 2019), might lead to an overreliance on technologies that are still in their infancy (Anderson and Peters 2016; Larkin et al. 2018; Grant et al. 2021), could overburden future generations (Lenzi 2018; Shue 2018; Bednar et al. 2019) might evoke new conflicts over equitable burden-sharing (Pozo et al. 2020; Lee et al. 2021; Mohan et al. 2021), could impact food security, biodiversity or land rights (Buck 2016; Boysen et al. 2017; Dooley and Kartha 2018; Hurlbert et al. 2019; Dooley et al. 2021), or might be perceived negatively by stakeholders and broader public audiences (Royal Society and Royal Academy of Engineering 2018; Colvin et al. 2020). Conversely, without considering different timescales of carbon storage (Fuss et al. 2018; Hepburn et al. 2019) and implementation of reliable measurement, reporting and verification of carbon flows (Mace et al. 2021), CDR deployment might not deliver the intended benefit of removing CO_2 durably from the atmosphere. Furthermore, without appropriate incentive schemes and market designs

(Honegger et al. 2021b), CDR implementation options could see under-investment. The many challenges in research, development and demonstration of novel approaches, to advance innovation according to broader societal objectives and to bring down costs, could delay their scaling up and deployment (Nemet et al. 2018). Depending on the scale and deployment scenario, CDR methods could bring about various co-benefits and adverse side effects (see below). All this highlights the need for appropriate CDR governance and policies (Section 12.3.3).

The volumes of future global CDR deployment assumed in IAM-based mitigation scenarios are large compared to current volumes of deployment, which presents a challenge since rapid and sustained upscaling from a small base is particularly difficult (de Coninck et al. 2018; Nemet et al. 2018; Hanna et al. 2021). All Illustrative Mitigation Pathways (IMPs) likely to limit warming to 2°C or lower use some form of CDR. Across the full range of similarly ambitious IAM scenarios (scenario categories C1-C3; see Section 3.3.), the annual net CO_2 removal (i.e., gross removals, including A/R, minus gross emissions) on managed land reaches 0.86 [0.01–4.11] $GtCO_2$ yr^{-1} by 2030, 2.98 [0.23–6.38] $GtCO_2$ yr^{-1} by 2050, and 4.19 [0.1–6.91] $GtCO_2$ yr^{-1} by 2100 (values are the medians and bracketed values denote the 5-95 percentile range). The annual BECCS deployment is 0.08 [0–1.09] $GtCO_2$ yr^{-1}, 2.75 [0.52–9.45] $GtCO_2$ yr^{-1}, and 8.96 [2.63–16.15] $GtCO_2$ yr^{-1} for these years, respectively. The annual DACCS deployment reaches 0 [0–0.02] $GtCO_2$ yr^{-1} by 2030, 0.02 [0–1.74] $GtCO_2$ yr^{-1} by 2050, and 1.02 [0–12.6] $GtCO_2$ yr^{-1} by 2100 (Figure 12.3)[1]. Cumulative volumes of BECCS, net CO_2 removal on managed land, and DACCS reach 328 [168–763] $GtCO_2$, 252 [20–418] $GtCO_2$, and 29 [0–339] $GtCO_2$ for the 2020-2100 period, respectively. Reaching the higher end of CDR volumes is subject to issues regarding their feasibility (see below), especially if achieved with only a limited number of CDR methods. Recent studies have identified some drivers for large-scale CDR deployment in IAM scenarios, including insufficient representation of variable renewables, a high discount rate that tends to increase initial carbon budget overshoot and therefore inflates usage of CDR to achieve net-negative emissions at later times, omission of CDR methods aside from BECCS and A/R (Köberle 2019; Emmerling et al. 2019; Hilaire et al. 2019), and limited deployment of demand-side options (Grubler et al. 2018; Daioglou et al. 2019; van Vuuren et al. 2018). The levels of CDR in IAMs in modelled pathways would change depending on the allowable overshoot of policy targets such as temperature or radiative forcing and the costs of non-CDR mitigation options (Johansson et al. 2020; van der Wijst et al. 2021).(see also Section 3.2.2)

FOOTNOTE[1] We use representative options for labels of each variable reported in the AR6 scenarios database.

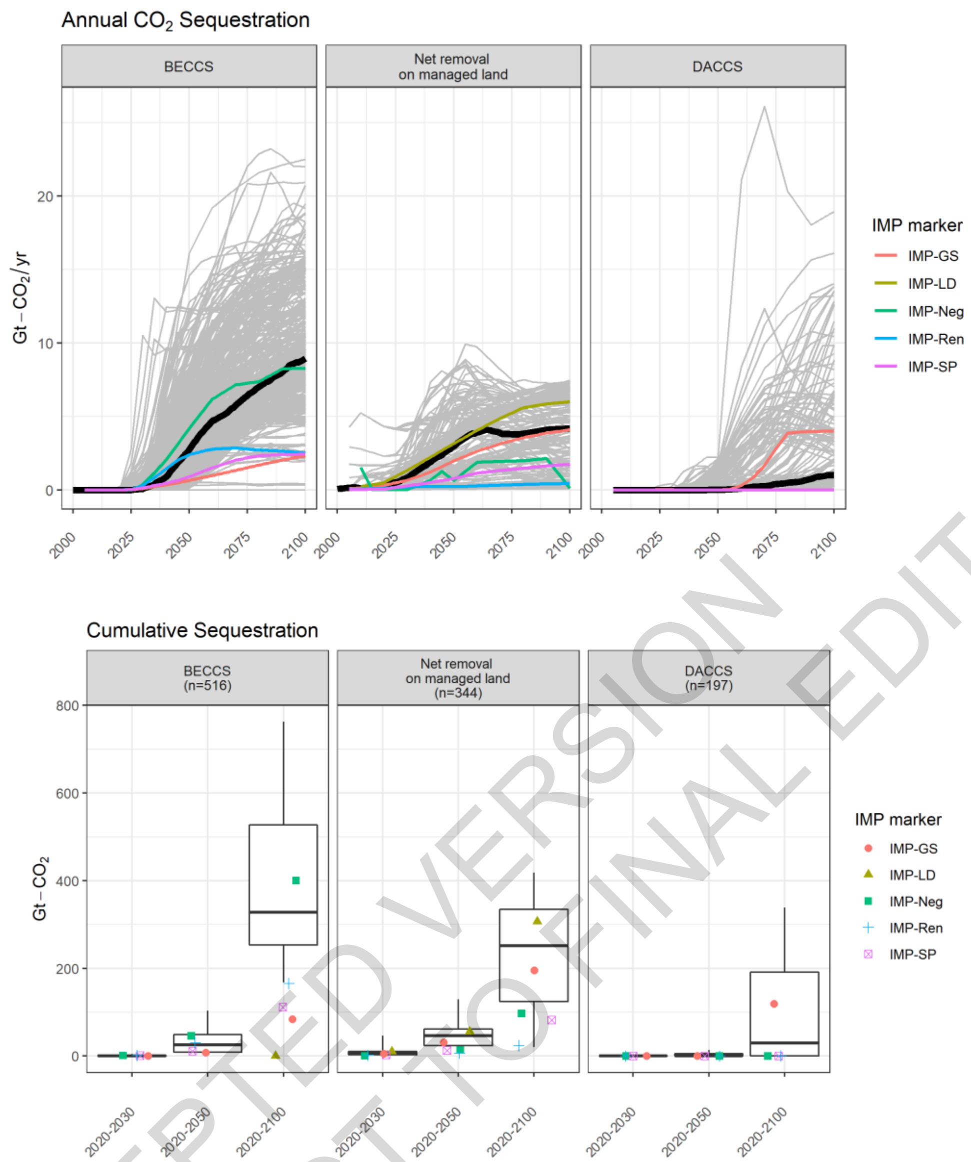


Figure 12.3 Sequestration of three predominant CDR methods: BECCS, net CO_2 removal on managed land (that is, gross removal through A/R minus emissions from deforestation) , and DACCS (upper panels) annual sequestration and (lower panels) cumulative sequestration.

The IAM scenarios correspond to those likely limiting warming to 2°C or lower. The black line in each of the upper panels indicates the median of all the scenarios in categories C1-C3. Hinges in the lower panels represent the interquartile ranges while whiskers extend to 5th and 95th percentiles. The IMPs are highlighted with colours, as shown in the key. The number of scenarios is indicated in the header of each panel. The number of scenarios with a non-zero DACCS value is 146.

While many CDR methods are gradually being explored, IAM scenarios have focused mostly on BECCS and A/R (Tavoni and Socolow 2013; Fuhrman et al. 2019; Rickels et al. 2019; Calvin et al. 2021; Diniz Oliveira et al. 2021) Although some IAM studies have also included other methods such as DACCS (Chen and Tavoni 2013; Marcucci et al. 2017; Realmonte et al. 2019; Akimoto et al. 2021; Fuhrman et al. 2020, 2021a), enhanced weathering (Strefler et al. 2021), SCS and biochar (Holz et al. 2018) there is much less literature compared to studies on BECCS (Hilaire et al. 2019). A large scale, coordinated IAM study on BECCS ("EMF-33") has been conducted (Muratori et al. 2020; Rose et al. 2020a) but none exists for other CDR methods. A recent review proposes a combination of various CDR methods (Fuss et al. 2018) but more in-depth literature on such a portfolio approach is limited

(Strefler et al. 2021). A multi-criteria analysis has identified pathways with CDR portfolios different from least-cost pathways often dominated by BECCS and A/R (Rueda et al. 2021).

At the national and regional level, the role of land-based biological CDR methods has long been analysed, but there is little detailed technoeconomic assessment of the role of other CDR. There is a small but emerging literature providing such assessments for developed countries (Baik et al. 2018; Sanchez et al. 2018; Patrizio et al. 2018; Larsen et al. 2019; Daggash et al. 2018; Kato and Kurosawa 2019; Kraxner et al. 2014; Breyer et al. 2019; McQueen et al. 2020; Bistline and Blanford 2021; Jackson et al. 2021; Kato and Kurosawa 2021; García-Freites et al. 2021; Negri et al. 2021) while the literature outside of developed countries is limited (Alatiq et al. 2021; Fuhrman et al. 2021b; Weng et al. 2021).

In IAMs, CDR is contributed mainly by the energy sector (through BECCS) and AFOLU sector (through A/R) (See Figure 12.3). IAMs are starting to include other CDR methods, such as DACCS and enhanced weathering (Section 12.3.1), which are yet to be attributed to specific sectors in IAMs. Following IPCC guidance for UNFCCC inventories, A/R and SCS are reported in LULUCF, while BECCS would be reported in the sector where the carbon capture occurs, that is, the energy sector in the case of electricity and heat production, and the industry sector for BECCS linked to manufacturing (e.g., steel or hydrogen) (Tanzer et al. 2020; Bui et al. 2021; Tanzer et al. 2021).

12.3.1 CDR methods not assessed elsewhere in this report: DACCS, enhanced weathering and ocean-based approaches

This section assesses the CDR methods that are not carried out solely within conventional sectors and so are not covered in other parts of the report: direct air carbon capture and storage, enhanced weathering, and ocean-based approaches. It provides an overview of each CDR method, costs, potentials, risks and impacts, co-benefits, and their role in mitigation pathways. Since these processes, approaches and technologies have medium to low technology readiness levels, they are subject to significant uncertainty.

12.3.1.1 Direct Air Carbon Capture and Storage (DACCS)

Direct air capture (DAC) is a chemical process to capture ambient CO_2 from the atmosphere. Captured CO_2 can be stored underground (direct air capture carbon and storage, DACCS) or utilised in products (direct air capture carbon and utilisation, DACCU). DACCS shares with conventional CCS the transport and storage components but is distinct in its capture part. Because CO_2 is a well-mixed GHG, DACCS can be sited relatively flexibly, though its locational flexibility is constrained by the availability of low-carbon energy and storage sites. Capturing the CO_2 involves three basic steps: a) contacting the air, b) capturing on a liquid or solid sorbent or a liquid solvent, c) regeneration of the solvent or the sorbent (with heat, moisture and/or pressure). After capture, the CO_2 stream can be stored underground or utilised. The duration of storage is an important consideration; geological reservoirs or mineralisation result in removal for > 1000 years. The duration of the removal through DACCU (Breyer et al. 2019) varies with the lifetime of respective products (Wilcox et al. 2017; Gunnarsson et al. 2018; Bui et al. 2018; Creutzig et al. 2019; Royal Society and Royal Academy of Engineering 2018; Fuss et al. 2018), ranging from weeks to months for synthetic fuels to centuries or more for building materials (e.g., concrete cured using mineral carbonation) (Hepburn et al. 2019). The efficiency and environmental impacts of DACCS and DACCU options depend on the carbon intensity of the energy input (electricity and heat) and other life-cycle assessment (LCA) considerations (Jacobson 2019; Global CO2 Initiative 2018). See Chapters 6 and 11 for further details regarding carbon capture and utilisation. Another key consideration is the net carbon CO_2 removal of DACCS over its life cycle (Madhu et al. 2021). Deutz and Bardow (2021) and Terlouw et al. (2021) demonstrated that the life-cycle net emissions of DACCS systems can be negative, even for existing supply chains and some current energy mixes. They found that the GHG-intensity of energy sources is a key factor.

DAC options can be differentiated by the specific chemical processes used to capture ambient CO_2 from the air and recover it from the sorbent (Fasihi et al. 2019). The main categories are a) liquid solvents with high-temperature regeneration, b) solid sorbents with low temperature regeneration and c) regenerating by moisturising of solid sorbents. Other approaches such as electro-swing (Voskian and Hatton 2019) have been proposed but are less developed. Compared to other CDR methods, the primary barrier to upscaling DAC is its high cost and large energy requirement (*high confidence*) (Nemet et al. 2018), which can be reduced through innovation. It has therefore attracted entrepreneurs and private investments (IEA 2020b).

Status: There are some demonstration projects by start-up companies and academic researchers, who are developing various types of DAC, including aqueous potassium solvent with calcium carbonation and solid sorbents with heat regeneration (NASEM 2019). These projects are supported mostly by private investments and grants or sometimes serve utilisation niche markets (e.g., CO_2 for beverages, greenhouses, enhanced oil recovery). As of 2021, there are more than ten plants worldwide, with a scale of $ktCO_2$ yr^{-1} or smaller (IEA 2020b; NASEM 2019; Larsen et al. 2019). Because of the fundamental difference in the CO_2 concentration in the capture stage, DACCS does not benefit directly from RD&D of conventional CCS. Public RD&D programs dedicated to DAC have therefore been proposed (NASEM 2019; Larsen et al. 2019). Possible research topics include development of new liquid solvents, novel solid sorbents, and novel equipment or system designs, and the need for third-party evaluation of techno-economic aspects has also been emphasized (NASEM 2019). However, since basic research does not appear to be a primary barrier, both NASEM (2019) and Larsen et al. (2019) argue for a stronger focus on demonstration in the US context. Though the US and UK governments have begun funding DACCS research (IEA 2020b), the scale of R&D activities is limited.

Costs: As the process captures dilute CO_2 (~0.04%) from the ambient air, it is less efficient and more costly than conventional carbon capture applied to power plants and industrial installations (*high confidence*) (with a CO_2 concentration of ~10%). The cost of a liquid solvent system is dominated by the energy cost (because of the much higher energy demand for CO_2 regeneration, which reduces the efficiency) while capital costs account for a significant share of the cost of solid sorbent systems (Fasihi et al. 2019). The range of the DAC cost estimates found in the literature is wide (60–1000 USD tCO_2^{-1}) (Fuss et al. 2018) partly because different studies assume different use cases, differing phases (first plant vs. *n*th plant) (Lackner et al. 2012), different configurations, and disparate system boundaries. Estimates of industrial origin are often on the lower side (Ishimoto et al. 2017). Fuss et al. (2018) suggest a cost range of 600–1000 USD tCO_2^{-1} for first-of-a-kind plants, and 100–300 USD tCO_2^{-1} as experience accumulates. An expert elicitation study found a similar cost level for 2050 with a median of around 200 USD tCO_2^{-1} (Shayegh et al. 2021) (*medium evidence, medium agreement*). NASEM (2019) systematically evaluated the costs of different designs and found a range of 84–386 USD_{2015} tCO_2^{-1} for the designs currently considered by active technology developers. This cost range excludes the site-specific costs of transportation or storage.

Potentials: There is no specific study on the potential of DACCS but the literature has assumed that the technical potential of DACCS is virtually unlimited provided that high energy requirements could be met (*medium evidence, high agreement*) (Lawrence et al. 2018; Marcucci et al. 2017; Fuss et al. 2018) since DACCS encounters less non-cost constraints than any other CDR method. Focusing only on the Maghreb region, Breyer et al. (2020) reported an optimistic potential 150 $GtCO_2$ at less than 61 USD tCO_2^{-1} for 2050. Fuss et al. (2018) suggest a potential of 0.5–5 $GtCO_2$ yr^{-1} by 2050 because of environmental side effects and limits to underground storage. In addition to the ultimate potentials, Realmonte et al. (2019) noted the rate of scale-up as a strong constraint on deployment. Meckling and Biber (2021) discuss a policy roadmap to address the political economy for upscaling. More systematic analysis on potentials is necessary; first and foremost on national and regional levels, including the requirements for low-carbon heat and power, water and material demand, availability of geological storage and the need for land in case of low-density energy sources such as solar or wind power.

Risks and impacts: DACCS requires a considerable amount of energy (*high confidence*), and depending on the type of technology, water, and make-up sorbents, while its land footprint is small compared to other CDR methods (Smith et al. 2016), but depending on the source of energy for DACCS (e.g., renewables vs. nuclear), it could require a significant land footprint (NASEM 2019; Sekera and Lichtenberger 2020). The theoretical minimum energy requirement for separating CO_2 gas from the air is ~0.5 GJ tCO_2^{-1} (Socolow et al. 2011). Fasihi et al. (2019) reviewed the published estimates of energy requirements and found that for the current technologies, the total energy requirement is ~4–10 GJ tCO_2^{-1} , with heat accounting for about 80% and electricity about 20% (McQueen et al. 2021). At a 10 $GtCO_2$ yr^{-1} sequestration scale, this would translate into 40–100 EJ yr^{-1} of energy consumption (32–80 EJ yr^{-1} for heat and 8–20 EJ yr^{-1} electricity), which can be contrasted with the current primary energy supply of ~600 EJ yr^{-1} and electricity generation of ~100 EJ yr^{-1}. For the solid sorbent technology, low-temperature heat could be sourced from heat pumps powered by low-carbon sources such as renewables (Breyer et al. 2020), waste heat (Beuttler et al. 2019), and nuclear energy (Sandalow et al. 2018). Unless sourced from a clean source, this amount of energy could cause environmental damage (Jacobson 2019). Because DACCS is an open system, water lost from evaporation must be replenished. Water loss varies, depending on technology (including adjustable factors such as the concentration of the liquid solvent) as well as environmental conditions (e.g., temperate vs. tropical climates). For a liquid solvent system, it can be 0–50 tH_2O tCO_2^{-1} (Fasihi et al. 2019). A water loss rate of ~1–10 tH_2O tCO_2^{-1} (Socolow et al. 2011) would translate into ~10–100 GtH_2O = 10–100 km^3 to capture 1ma0 $GtCO_2$ from the atmosphere. Some solid sorbent technologies actually produce water as a by-product, for example 0.8–2 tH_2O tCO_2^{-1} for a solid-sorbent technology with heat regeneration (Beuttler et al. 2019; Fasihi et al. 2019). Large-scale deployment of DACCS would also require a significant quantity of materials, and energy to produce them (Chatterjee and Huang 2020). Hydroxide solutions are currently being produced as a by-product of chlorine but replacement (make-up) requirement of such materials at scale exceeds the current market supply (Realmonte et al. 2019). The land requirements for DAC units are not large enough to be of concern (Madhu et al. 2021). Furthermore, these can be placed on unproductive lands, in contrast to biological CDR. Nevertheless, to ensure that CO_2-depleted air does not enter the air contactor of an adjacent DAC system, there must be enough space between DAC units, similar to wind power turbines. Considering this, Socolow et al. (2011) estimated a land footprint of 1.5 km^2 $MtCO_2^{-1}$. In contrast, large energy requirements can lead to significant footprints if low-density energy sources (e.g., solar PV) are used (Smith et al. 2016). For the issues associated with CO_2 utilisation and storage, see Chapter 6.

Co-benefits: While Wohland et al. (2018) proposed solid sorbent-based DAC plants as a Power-to-X technology that could use excess renewable power (at the time of low or even negative prices), such operation would add additional costs. Installations would need to be designed for intermittent operations (i.e., at low load factors) which would negatively affect capital and operation costs (Sandalow et al. 2018; Daggash et al. 2018) as a high time-resolution model suggests a high utilisation rate (Breyer et al. 2020). Solid sorbent DAC designs can potentially remove more water from the ambient air than needed for regeneration, thereby delivering surplus water that would contribute to Sustainable Development Goal (SDG) 6 (*Clean Water and Sanitation*) in arid regions (Sandalow et al. 2018; Fasihi et al. 2019).

Trade-offs and spill over effects: Liquid solvent DACCS systems need substantial amounts of water (Fasihi et al. 2019), although much less than BECCS systems (Smith et al. 2016), which could negatively affect SDG 6 (*Clean Water and Sanitation*). Although the high energy demand of DACCS could affect SDG 7 (*Affordable and Clean Energy*) negatively through potential competition or positively through learning effects (Beuttler et al. 2019), its impact has not been thoroughly assessed yet.

Role in mitigation pathways: There are a few IAM studies that have explicitly incorporated DACCS. Stringent emissions constraints in these studies lead to high carbon prices, allowing DACCS to play an important role in mitigation. Chen and Tavoni (2013) examined the role of DACCS in an IAM (WITCH) and found that incorporating DACCS in their IAM reduces the overall cost of mitigation and tends to postpone the timing of mitigation. The scale of capture goes up to 37 $GtCO_2$ yr^{-1} in 2100. (Akimoto et al. 2021) introduced DACCS in the integrated assessment model DNE21+, and also found the long-term marginal cost of abatement is significantly reduced by DACCS. Marcucci et al. (2017) ran MERGE-ETL, an integrated model with endogenous learning, and showed that DACCS allows for a model solution for the 1.5°C target, and that DACCS substitutes for BECCS under stringent targets. In their analysis, DACCS captures up to 38.3 $GtCO_2$ yr^{-1} in 2100. Realmonte et al. (2019) modelled two types of DACCS (based on liquid and solid sorbents) with two IAMs (TIAM-Grantham and WITCH), and showed that in deep mitigation scenarios, DACCS complements, rather than substitutes, other CDR methods such as BECCS, and that DACCS is effective at containing mitigation costs. At the national scale, Larsen et al. (2019) utilised the Regional Investment and Operations (RIO) Platform coupled with the Energy PATHWAYS model, and explicitly represented DAC in US energy systems scenarios. They found that in a scenario that reaches net zero emissions by 2045, about 0.6 $GtCO_2$ or 1.8 $GtCO_2$ of DACCS would be deployed, depending on the availability of biological carbon sinks and bioenergy. The modelling supporting the European Commission's initial proposal for net zero GHG emissions by 2050 incorporated DAC, whose captured CO_2 is used for both synthetic fuel production (DACCU) and storage (DACCS) (Capros et al. 2019). Fuhrman et al. (2021a) evaluated the role of DACCS across 5 shared socioeconomic pathways with the GCAM modelling framework and identified a substantial role of DACCS in mitigation and a decreased pressure on land and water resources from BECCS, even under the assumption of limited energy efficiency improvement and conservative cost declines of DACCS technologies. The newest iteration of the World Economic Outlook by IEA (2021b) deploys CDR on a limited scale, and DACCS removes 0.6 $GtCO_2$ in 2050 for its Net Zero CO_2 Emissions scenario.

Status, costs, potentials, risk and impacts, co-benefits, trade-offs and spillover effects and the role in mitigation pathways of DACCS are summarised in Table 12.6.

12.3.1.2 Enhanced weathering

Enhanced weathering involves a) the mining of rocks containing minerals that naturally absorb CO_2 from the atmosphere over geological timescales (as they become exposed to the atmosphere through geological weathering), b) the comminution of these rocks to increase the surface area, and c) the spreading of these crushed rocks on soils (or in the ocean/coastal environments; Section 12.3.1.3) so that they react with atmospheric CO_2 (Schuiling and Krijgsman 2006; Hartmann et al. 2013; Beerling et al. 2018; Goll et al. 2021). Construction waste, and waste materials from mining can also be used as a source material for enhanced weathering. Silicate rocks such as basalt, containing minerals rich in calcium and magnesium and lacking metal ions such as nickel and chromium, are most suitable for enhanced weathering (Beerling et al. 2018); they reduce soil solution acidity during dissolution, and promote the chemical transformation of CO_2 to bicarbonate ions. The bicarbonate ions can precipitate in soils and drainage waters as a solid carbonate mineral (Manning 2008), or remain dissolved and increase alkalinity levels in the ocean when the water reaches the sea (Renforth and Henderson 2017).

The modelling study by Cipolla et al. (2021) found that rate of weathering is greater in high rainfall environments, and was increased by organic matter amendment.

Status: Enhanced weathering has been demonstrated in the laboratory and in small scale field trials (TRL 3–4) but has yet to be demonstrated at scale (Beerling et al. 2018; Amann et al. 2020). The chemical reactions are well understood (Gillman 1980; Gillman et al. 2001; Manning 2008), but the behaviour of the crushed rocks in the field and potential co-benefits and adverse-side effects of enhanced weathering require further research (Beerling et al. 2018). Small scale laboratory experiments have calculated weathering rates that are orders of magnitude slower than the theoretical limit for mass transfer-controlled forsterite (Renforth et al. 2015; Amann et al. 2020) and basalt dissolution (Kelland et al. 2020). Uncertainty surrounding silicate mineral dissolution rates in soils, the fate of the released products, the extent of legacy reserves of mining by-products that might be exploited, location and availability of rock extraction sites, and the impact on ecosystems remain poorly quantified and require further research to better understand feasibility (Renforth 2012; Moosdorf et al. 2014; Beerling et al. 2018). Closely monitored, large-scale demonstration projects would allow these aspects to be studied (Smith et al. 2019a; Beerling et al. 2020).

Costs: Fuss et al. (2018), in a systematic review of the costs and potentials of CDR methods including enhanced weathering, note that costs are closely related to the source of the rock, the technology used for rock grinding and material transport (Hartmann et al. 2013; Renforth 2012; Strefler et al. 2018). Due to differences in the methods and assumptions between studies, literature ranges are highly uncertain and range from 15–40 USD tCO_2^{-1} to 3460 USD tCO_2^{-1} (Köhler et al. 2010; Taylor et al. 2016). Renforth (2012) reported operational costs in the UK of applying mafic rocks (rocks with high magnesium and iron silicate mineral concentrations) of 70–578 USD tCO_2^{-1}, and for ultramafic rocks (rocks rich in magnesium and iron silicate minerals but with very low silica content - the low silica content enhances weathering rates) of 24–123 USD tCO_2^{-1}. Beerling et al. (2020) combined a spatially resolved weathering model with a technoeconomic assessment to suggest costs of between 54–220 USD tCO_2^{-1} (with a weighted mean of 118–128 USD tCO_2^{-1}). Fuss et al. (2018) suggested an author judgement cost range of 50–200 USD tCO_2^{-1} for a potential of 2–4 $GtCO_2$ yr^{-1} from 2050, excluding biological storage.

Potentials: In a systematic review of the costs and potentials of enhanced weathering, Fuss et al. (2018) report a wide range of potentials (*limited evidence, low agreement*). The highest reported regional sequestration potential, 88.1 $GtCO_2$ yr^{-1}, is reported for the spreading of pulverised rock over a very large land area in the tropics, a region considered promising given the higher temperatures and greater rainfall (Taylor et al. 2016). Considering cropland areas only, the potential carbon removal was estimated by Strefler et al. (2018) to be 95 $GtCO_2$ yr^{-1} for dunite and 4.9 $GtCO_2$ yr^{-1} for basalt. Slightly lower potentials were estimated by Lenton (2014) where the potential of carbon removal by enhanced weathering (including adding carbonate and olivine to both oceans and soils) was estimated to be 3.7 $GtCO_2$ yr^{-1} by 2100, but with mean annual removal an order of magnitude less at 0.2 GtC-eq yr^{-1} (Lenton 2014). The estimates reported in Smith et al. (2016) are based on the potential estimates of Lenton (2014). Beerling et al. (2020) estimate that up to 2 $GtCO_2$ yr^{-1} could be removed by 2050 by spreading basalt onto 35-59% (weighted mean 53%) of agricultural land of 12 countries. Fuss et al. (2018) provide an author judgement range for potential of 2–4 $GtCO_2$ yr^{-1} for 2050.

Risks and impacts: Mining of rocks for enhanced weathering will have local impacts and carries risks similar to that associated with the mining of mineral construction aggregates, with the possible additional risk of greater dust generation from fine comminution and land application. In addition to direct habitat destruction and increased traffic to access mining sites, there could be adverse impacts on local water quality (Younger and Wolkersdorfer 2004).

Co-benefits: Enhanced weathering can improve plant growth by pH modification and increased mineral supply (Kantola et al. 2017; Beerling et al. 2018), can enhance SCS in some soils (Beerling et al. 2018) thereby protecting against soil erosion (Wrigth and Upadhyaya 1998), and increasing the cation exchange capacity, resulting in increased nutrient retention and availability (Baldock and Skjemstad 2000; Yu et al. 2017; Guntzer et al. 2012; Tubana et al. 2016; Manning 2010; Haque et al. 2019; Smith et al. 2019a; Gillman 1980; Gillman et al. 2001). Through these actions, it can contribute to the UN SDGs 2 *Zero Hunger*, 15 *Life of Land* (by reducing land demand for croplands), 13 *Climate Action* (through CDR), 14 *Life Below Water* (by ameliorating ocean acidification) and 6 *Clean Water and Sanitation* (Smith et al. 2019a). To more directly ameliorate ocean acidification while increasing CDR and reducing impacts on land ecosystems, alkaline minerals could instead be directly added to the ocean (Section 12.3.1.3). There are potential benefits in poverty reduction through employment of local workers in mining (Pegg 2006).

Trade-offs and spill over effects: Air quality could be adversely affected by the spreading of rock dust (Edwards et al. 2017), though this can partly be ameliorated by water-spraying (Grundnig et al. 2006). As noted above, any significant expansion of the mining industry would require careful assessment to avoid possible detrimental effects on biodiversity (Amundson et al. 2015). The processing of an additional 10 billion tonnes of rock would require up to 3000 TWh, which could represent approximately 0.1-6 % of global electricity in 2100. The emissions associated with this additional energy generation may reduce the net carbon dioxide removal by up to 30% with present day grid average emissions, but this efficiency loss would decrease with low-carbon power (Beerling et al. 2020).

Role in mitigation pathways: Only one study to date has included enhanced weathering in an integrated assessment model to explore mitigation pathways (Strefler et al. 2021).

Status, costs, potentials, risk and impacts, co-benefits, trade-offs and spill over effects and the role in mitigation pathways of enhanced weathering are summarised in Table 12.6.

12.3.1.3 Ocean-based methods

The ocean, which covers over 70% of the Earth's surface, contains ~38,000 GtC, some 45 times more than the present atmosphere, and oceanic uptake has already consumed close to 30-40% of anthropogenic C emissions (Gruber et al. 2019, Sabine et al. 2004). The ocean is characterised by diverse biogeochemical cycles involving carbon, and ocean circulation has much longer timescales than the atmosphere, meaning that additional anthropogenic carbon could potentially be stored in the ocean for centuries to millennia for methods that increase deep ocean dissolved carbon concentrations or temporarily bury the carbon; or essentially permanently (over ten thousand years) for methods that store the carbon in mineral forms or as ions by increasing alkalinity (Siegel et al., 2021) (Cross-Chapter Box 8 Figure 1). A wide range of methods and implementation options for marine CDR have been proposed (Gattuso et al. 2018; Hoegh-Guldberg et al. 2018; GESAMP 2019). The most studied ocean-based CDR methods are ocean fertilisation, alkalinity enhancement (including electrochemical methods) and intensification of biologically driven carbon fluxes and storage in marine ecosystems, referred to as "blue carbon". The mitigation potentials, costs, co-benefits and trade-offs of these three options are discussed below. Less well studied are methods including artificial upwelling, terrestrial biomass dumping into oceans, direct CO_2 removal from seawater (with CCS), and sinking marine biomass into the deep ocean or harvesting it for bioenergy (with CCS) or biochar (GESAMP 2019). These methods are summarized briefly below. Potential climate response and influence on the carbon budget of ocean-based CDR methods are discussed in Chapter 5 in WGI AR6.

Ocean fertilisation (OF). One natural mechanism of carbon transfer from the atmosphere to the deep ocean is the ocean biological pump, which is driven by the sinking of organic particles from the upper ocean. These particles derive ultimately from primary production by phytoplankton and most of them are remineralised within the upper ocean with only a small fraction reaching the deep ocean where the carbon can be sequestered on centennial and longer timescales**.** Increasing nutrient availability would stimulate uptake of CO_2 through phytoplankton photosynthesis producing organic matter, some of which would be exported into the deep ocean, sequestering carbon. In areas of the ocean where macronutrients (nitrogen, phosphorus) are available in sufficient quantities (about 25% of the total area), the growth of phytoplankton is limited by the lack of trace elements such as iron. Thus, OF CDR can be based on two implementation options to increase the productivity of phytoplankton (Minx et al. 2018): macronutrient enrichment and micronutrient enrichment. A third option highlighted in GESAMP (2019) is based on fertilisation for fish stock enhancement, for instance, as naturally occurs in eastern boundary current systems. Iron fertilisation is the best studied OF option to date, but knowledge so far is still inadequate to predict global ecological and biogeochemical consequences.

Status: OF has a natural analogue: periods of glaciation in the geological past are associated with changes in deposition of dust containing iron into the ocean. Increased formation of phytoplankton has also been observed during seasonal deposition of dust from the Arabian Peninsula and ash deposition on the ocean surface after volcanic eruptions (Jaccard et al., 2013; Achterberg et al. 2013; Olgun et al. 2013; Martínez-García et al. 2014). OF options may appear technologically feasible, and enhancement of photosynthesis and CO_2 uptake from surface waters is confirmed by a number of field experiments conducted in different areas of the ocean, but there is scientific uncertainty about the proportion of newly formed organic carbon that is transferred to deep ocean, and the longevity of storage (Blain et al. 2008; Williamson et al. 2012; Trull et al. 2015). The efficiency of OF also depends on the region and experimental conditions, especially in relation to the availability of other nutrients, light and temperature (Aumont and Bopp 2006). In the case of macronutrients, very large quantities are needed and the proposed scaling of this technique has been viewed as unrealistic (Williamson and Bodle 2016).

Costs: Ocean fertilisation costs depend on nutrient production and its delivery to the application area (Jones 2014). The costs range from 2 USD tCO_2^{-1} for fertilisation with iron (Boyd 2008) to 457 USD tCO_2^{-1} for nitrate (Harrison 2013). Reported costs for macronutrient application at 20 USD tCO_2^{-1} (Jones 2014), contrast with higher estimates by (Harrison 2013) reporting that low costs are due to overestimation of sequestration capacity and underestimation of logistical costs. The median of OF cost estimates, 230 USD tCO_2^{-1} (Gattuso et al., 2021) indicates low cost-effectiveness, albeit uncertainties are large.

Potentials: Theoretical calculations indicate that organic carbon export increases 2–20 kg per gram of iron added, but experiments indicate much lower efficiency: a significant part of the CO_2 can be emitted back the atmosphere because much of the organic carbon produced is remineralised in the upper ocean. Efficiency also varies with location (Bopp et al. 2013). Between studies, there are substantial differences in the ratio of iron added to carbon fixed photosynthetically, and in the ratio of iron added to carbon eventually sequestered (Trull et al. 2015), which has implications both for the success of this strategy, and its cost. Estimates indicate potentially achievable net sequestration rates of 1–3 $GtCO_2\ yr^{-1}$ for iron fertilisation, translating into cumulative CDR of 100–300 $GtCO_2$ by 2100 (Ryaboshapko and Revokatova 2015; Minx et al. 2018), whereas OF with macronutrients has a higher theoretical potential of 5.5 $GtCO_2\ yr^{-1}$ (Harrison 2017; Gattuso et al. 2021). Modelling studies show a maximum effect on atmospheric CO_2 of 15–45 ppmv in 2100 (Zeebe and Archer 2005; Aumont and Bopp 2006; Keller et al. 2014; Gattuso et al. 2021).

Risks and impacts: Several of the mesoscale iron enrichment experiments have seen the emergence of potentially toxic species of diatoms (Silver et al. 2010; Trick et al. 2010). There is also (limited) evidence of increased concentrations of other GHGs such as methane and nitrous oxide during the subsurface decomposition of the sinking particles from iron-stimulated blooms (Law 2008). Impacts on marine biology and food web structure are not well known, however OF at large scale could cause changes in nutrient distributions or anoxia in subsurface water (Fuhrman and Capone 1991; DFO 2010). Other potential risks are perturbation to marine ecosystems via reorganisation of community structure, enhanced deep ocean acidification (Oschlies et al. 2010) and effects on human food supply.

Co-benefits: Co-benefits of OF include a potential increase in fish biomass through enhanced biological production (Minx et al. 2018) and reduced ocean acidification in the short term in the upper ocean (by CO_2 removal), though it could be enhanced in the long term in the ocean interior (by CO_2 release) (Oschlies et al., 2010; Gattuso et al. 2018).

Trade-offs and spill-over effects: Potential drawbacks include subsurface ocean acidification and deoxygenation (Oschlies et al., 2010; Cao and Caldeira 2010; Williamson et al. 2012); altered regional meridional nutrient supply and fundamental alteration of food webs (GESAMP 2019); and increased production of N_2O and CH_4 (Jin and Gruber 2003; Lampitt et al. 2008). Ocean fertilisation is considered to have negative consequences for eight SDGs, and a combination of both positive and negative consequences for seven SDGs (Honegger et al. 2020).

Ocean Alkalinity enhancement (OAE). CDR through 'ocean alkalinity enhancement' or 'artificial ocean alkalinisation' (Renforth and Henderson 2017) can be based on: 1) the dissolution of natural alkaline minerals that are added directly to the ocean or coastal environments; 2) the dissolution of such minerals upstream from the ocean (e.g., 'enhanced weathering', Section 12.3.1.2); 3) the addition of synthetic alkaline materials directly to the ocean or upstream; and 4) electrochemical processing of seawater. In the case of 2), minerals are dissolved on land and the dissolution products are conveyed to the ocean through runoff and river flow. These processes result in chemical transformation of CO_2 and sequestration as bicarbonate and carbonate ions (HCO_3^-, CO_3^{2-}) in the ocean. Imbalances between the input and removal fluxes of alkalinity can result in changes in global oceanic alkalinity and therefore the capacity of the ocean to store C. Such alkalinity-induced changes in partitioning of C between atmosphere and ocean are thought to play an important role in controlling climate change on timescales of 1000 years and longer (e.g., Zeebe 2012). The residence time of dissolved inorganic carbon in the deep ocean is around 100,000 years. However, residence time may decrease if alkalinity is reduced by a net increase in carbonate minerals by either increased formation (precipitation) or reduced dissolution of carbonate (Renforth and Henderson 2017). The alkalinity of seawater could potentially also be increased by electrochemical methods, either directly by reactions at the cathode that increase the alkalinity of the surrounding solution that can be discharged into the ocean, or by forcing the precipitation of solid alkaline materials (e.g., hydroxide minerals) that can then be added to the ocean (e.g., Rau et al. 2013; La Plante et al. 2021).

Status: OAE has been demonstrated by a small number of laboratory experiments (in addition to enhanced weathering, Section 12.3.1.2). The use of enhanced ocean alkalinity for C storage was first proposed by Kheshgi (1995) who considered the creation of highly reactive lime that would readily dissolve in the surface ocean and sequester CO_2. An alternative method proposed the dissolution of carbonate minerals (e.g., $CaCO_3$) in the presence of waste flue gas CO_2 and seawater as a means capturing CO_2 and converting it to bicarbonate ions (Rau and Caldeira 1999; Rau 2011). House et al. (2007) proposed the creation of alkalinity in the ocean through electrolysis. The fate of the stored carbon is the same for these proposals (i.e., HCO_3^- and CO_3^{2-} ions), but the reaction pathway is different. Enhanced weathering of silicate minerals such as olivine could add alkalinity to the ocean, for example, by placing olivine sand in coastal areas (Montserrat et al. 2017; Meysman and Montserrat 2017)**.** Some authors suggest use of maritime transport to discharge calcium hydroxide (slaked lime, SL) (Caserini et al. 2021).

Costs: Techno-economic assessments of OAE largely focus on quantifying overall energy and carbon balances. Cost ranges are 40–260 USD tCO_2^{-1} (Fuss et al. 2018). Considering life cycle carbon and energy balances for various OA options, adding lime (or other reactive calcium or magnesium oxide/hydroxides) to the ocean would cost 64–260 USD tCO_2^{-1} (Renforth et al. 2013; Renforth & Kruger 2013; Caserini et al. 2019). Rau (2008) and Rau et al. (2018) estimate that electrochemical processes for increasing ocean alkalinity may have a net cost of 3–160 USD tCO_2^{-1}, largely depending on energy cost and co-product (H_2) market value. In the case of direct addition of alkaline minerals to the ocean (i.e., without calcination), the cost is estimated to be 20–50 USD tCO_2^{-1} (Harvey 2008; Köhler et al. 2013; Renforth and Henderson 2017).

Potentials: For OAE, the ocean theoretically has the capacity to store thousands of $GtCO_2$ (cumulatively) without exceeding pre-industrial levels of carbonate saturation (Renforth and Henderson 2017) if the impacts were distributed evenly across the surface ocean. The potential of increasing ocean alkalinity may be constrained by the capability to extract, process, and react minerals (Section 12.3.1.2); the demand for co-benefits (see below), or to minimise impacts around points of addition. Important challenges with respect to the detailed quantification of the CO_2 sequestration efficiency include nonstoichiometric dissolution, reversed weathering and potential pore water saturation in the case of adding minerals to shallow coastal environments (Meysman and Montserrat 2017). Fuss et al. (2018) suggest storage potentials of 1–100 $GtCO_2$ yr^{-1}. (González and Ilyina 2016) suggested that addition of 114 Pmol of alkalinity to the surface ocean could remove 3400 $GtCO_2$ from the atmosphere.

Risks and impacts: For OAE, the local impact of increasing alkalinity on ocean chemistry can depend on the speed at which the impacted seawater is diluted/circulated and the exchange of CO_2 from the atmosphere (Bach et al. 2019)**.** Also, more extreme carbonate chemistry perturbations due to non-equilibrated alkalinity could affect local marine biota (Bach et al. 2019), although biological impacts are largely unknown . Air-equilibrated seawater has a much lower potential to perturb seawater carbonate chemistry. However, seawater with slow air-sea gas exchange, in which alkalinity increases, consumes CO_2 from the surrounding water without immediate replenishment from the atmosphere, which would increase seawater pH and saturation states and may impact marine biota (Meysman and Montserrat 2017; Montserrat et al. 2017). It may be possible to use this effect to ameliorate ocean acidification. Like enhanced weathering, some proposals may result in the dissolution products of silicate minerals (e.g., Si, Fe, K, Ni) being supplied to ocean ecosystems (Meysman and Montserrat 2017; Montserrat et al. 2017). Ecological and biogeochemical consequences of OA largely depend on the minerals used. When natural minerals such as olivine are used, the release of additional Si and Fe could have fertilising effects (Bach et al. 2019). In addition to perturbations to marine ecosystems via reorganisation of community structure, potentially adverse effects of OA that should be studied include the release of toxic trace metals from some deposited minerals (Hartmann et al. 2013).

Co-benefits: Intentional addition of alkalinity to the oceans through OAE would decrease the risk to ocean ecosystems caused by the CO_2-induced impact of ocean acidification on marine biota and the global carbon cycle (Doney et al. 2009; Köhler et al. 2010; Rau et al. 2012; Williamson and Turley 2012; Albright et al. 2016; Bach et al. 2019). OA could be jointly implemented with enhanced weathering (see section 12.3.1.2), spreading the finely crushed rock in the ocean rather than land. Regional alkalinisation could be effective in protecting coral reefs against acidification (Feng et al. 2016) (Mongin et al., 2021) and coastal OA could be part of a broader strategy for geochemical management of the coastal zone, safeguarding specific coastal ecosystems from the adverse impact of ocean acidification, such as important shellfisheries (Meysman and Montserrat 2017).

Trade-offs and spill-over effects: There is a paucity of research on biological effects of alkalinity addition. The very few studies that have explored the impact of elevated alkalinity on ocean ecosystems have largely been limited to single species experiments (Cripps et al. 2013; Gore et al. 2019) and a constrained field study quantifying the net calcification response of a coral reef flat to alkalinity enhancement (Albright et al. 2016). The addition rate would have to be great enough to overcome mixing of the local seawater with the ambient environment, but not sufficient to detrimentally impact ecosystems. More research is required to assess locations in which this may be feasible, and how such a scheme may operate (Renforth and Henderson 2017). The environmental impact of large-scale release of natural dissolution products into the coastal environment will strongly depend on the scale of olivine application, the characteristics of the coastal water body (e.g., residence time) and the particular biota present (e.g., coral reefs will react differently compared with seagrasses) (Meysman and Montserrat 2017). Model simulations (González et al. 2018) suggest that termination of OA implemented on a massive scale under a high CO_2 emission scenario (RCP8.5) might pose high risks to biological systems sensitive to rapid environmental changes because it would cause a sharp increase in ocean acidification. For example, OA termination would lead to a decrease in surface pH in warm shallow regions where vulnerable coral reefs are located, and a drop in the carbonate saturation state. However, other studies with lower levels of OA have shown no termination effect (Keller et al., 2014).

Blue carbon management. The term “blue carbon” was used originally to refer to biological carbon sequestration in all marine ecosystems, but it is increasingly applied to CDR associated with rooted vegetation in the coastal zone, such as tidal marshes, mangroves and seagrasses. Potential for carbon sequestration in other coastal and non-coastal ecosystems, such as macroalgae (e.g., kelp), is debated (Krause-Jensen et al., 2018; Krause-Jensen and Duarte, 2016). In this report, blue carbon refers to CDR through coastal blue carbon management.

Status: In recent years, there has been increasing research on the potential, effectiveness, risks, and possibility of enhancing CO_2 sequestration in shallow coastal ecosystems (Duarte, 2017). About 20% of the countries that are signatories to the Paris Agreement refer to blue carbon approaches for climate change mitigation in their NDCs and are moving toward measuring blue carbon in inventories. About 40% of those same countries have pledged to manage shallow coastal ecosystems for climate change adaptation (Kuwae and Hori 2019).

Costs: There are large differences in cost of CDR applying blue carbon management methods between different ecosystems (and at the local level). Median values are estimated as 240, 30,000, and 7,800 USD tCO_2^{-1}, respectively for mangroves, salt marsh and seagrass habitats (Gattuso et al. 2021). Currently estimated cost effectiveness (for climate change mitigation) is very low (Siikamäki et al. 2012; Bayraktarov et al. 2016; Narayan et al. 2016).

Potentials: Globally, the total potential carbon sequestration rate through blue carbon CDR is estimated in the range 0.02–0.08 $GtCO_2\ yr^{-1}$ (Wilcox et al. 2017; National Academies of Sciences 2019). Gattuso et al. (2021) estimate the theoretical cumulative potential of coastal blue carbon management by 2100 to be 95 $GtCO_2$, taking into account the maximum area that can be occupied by these habitats and historic losses of mangroves, seagrass and salt marsh ecosystems.

Risks and impacts: For blue carbon management, potential risks relate to the high sensitivity of coastal ecosystems to external impacts associated with both degradation and attempts to increase carbon sequestration. Under expected future warming, sea-level rise and changes in coastal management, blue carbon ecosystems are at risk, and their stored carbon is at risk of being lost (Bindoff et al. 2019).

Co-benefits: Blue carbon management provides many non-climatic benefits and can contribute to ecosystem-based adaptation, also reducing emissions associated with habitat degradation and loss (Howard et al. 2017; Hamilton and Friess 2018). Shallow coastal ecosystems have been severely affected by human activity; significant areas have already been deforested or degraded and continue to be denuded. These processes are accompanied by carbon emissions. The conservation and restoration of coastal ecosystems, which will lead to increased carbon sequestration, is also essential for the preservation of basic ecosystem services, and healthy ecosystems tend to be more resilient to the effects of climate change.

Trade-offs and spill-over effects: Blue carbon management schemes should consist of a mix of restoration, conservation and areal increase, including complex engineering interventions that enhance natural capital, safeguard their resilience and the ecosystem services they provide, and decrease the sensitivity of such ecosystems to further disturbances.

Overview of other ocean-based CDR approaches

Artificial Upwelling This concept uses pipes or other methods to pump nutrient-rich deep ocean water to the surface where it has a fertilizing effect (see OF section). To achieve CO_2 removal at a Gt magnitude, modelling studies have shown that artificial upwelling would have to be implemented on a massive scale (over 50% of the ocean to deliver maximum rate of 10GtCO_2 yr^{-1} under RCP 8.5) (Oschlies et al., 2010, Keller et al. 2014). Because the deep water is much colder than surface water, at massive scale this could cool the Earth's surface by several degrees, but the cooling effect would cease as the deeper ocean warms, and would reverse, leading to rapid warming, if the pumping ceased (Oschlies et al., 2010, Keller et al. 2014).

Furthermore, the cooling would also severely alter atmospheric circulation and precipitation patterns (Kwiatkowski et al. 2015). Several upwelling approaches have been developed and tested (Pan et al., 2016) and more R&D is underway.

Terrestrial biomass dumping There are proposals to sink terrestrial biomass (crop residues or logs) into the deep ocean as a means of sequestering carbon (Strand and Benford 2009). Sinking biochar has also been proposed (Miller and Orton, 2021). Decomposition would be inhibited by the cold and sometimes hypoxic/anoxic environment on the ocean floor, and absence of bacteria that decompose terrestrial lignocellulosic biomass, so storage timescale is estimated at hundreds to thousands of years (Strand and Benford 2009)(Burdige 2005). Potential side-effects on marine ecosystems, chemistry, or circulation have not been thoroughly assessed. Neither have these concepts been evaluated with respect to the impacts on land from enhanced transfer of nutrients and organic matter to the ocean, nor the relative merits of alternative applications of residues and biochar as an energy source or soil amendment (Chapter 7).

Marine biomass CDR options Proposals have been made to grow macroalgae (Duarte et al., 2017) for BECCS (N'Yeurt et al. 2012; Duarte et al. 2013; Chen et al., 2015), to sink cultured macroalgae into the deep sea, or to use marine algae for biochar (Roberts et al., 2015). Naturally growing sargassum has also been considered for these purposes (Bach et al., 2021). Froehlich et al. (2019) found a substantial area of the ocean (ca. 48 million km^2) suitable for farming seaweed. N'Yeurt et al. (2012) suggested that converting 9% of the oceans to macroalgal aquaculture could take up 19 GtCO_2 in biomass, generate 12 Gt per annum of biogas, and the CO_2 produced by burning the biogas could be captured and sequestered. Productivity of farmed macroalgae in the open ocean could potentially be enhanced through fertilizing via artificial upwelling (Fan et al., 2020) or through cultivation platforms that dive at night to access nutrient-rich waters below the, often nutrient-limited, surface ocean. If the biomass were sunk, it is unknown how long the carbon would remain in the deep ocean and what the additional impacts would be. Research and development on macroalgae cultivation and use is currently underway in multiple parts of the world, though not necessarily directly focused on CDR.

Extraction of CO_2 from seawater (with storage) CO_2 can be extracted by applying a vacuum, or by purging with a gas low in CO_2 (Koweek et al., 2016). CO_2 stripping can also be accomplished by acidifying seawater with a mineral acid, or through electrodialysis and electrolysis, to convert bicarbonate ions (HCO_3^-) to CO_2 (Eisaman et al., 2018; Eisaman 2020; Willauer et al., 2017, Digdaya et al., 2020) Sharifian et al., 2021). The removal of CO_2 from the ocean surface leads to undersaturation in the water, thus forcing CO_2 to move from the atmosphere into the ocean to restore equilibrium. Electrochemical seawater CO_2 extraction has been modeled, prototyped, and analyzed from a techno-economic perspective (Eisaman et al., 2012; Willauer et al., 2017; de Lannoy et al., 2018; Eisaman et al., 2018a; Eisaman et al., 2018b).

Status, costs, potentials, risk and impacts, co-benefits, trade-offs and spill-over effects and the role in mitigation pathways of ocean-based approaches are summarised in Table 12.6.

12.3.1.4 Feasibility assessment

Following the framework presented in Section 6.4 and Annex II.11, a multi-dimensional feasibility assessment on the CDR methods covered here is provided in Figure 12.4, taking into account the assessment presented in this section. Both DACCS and EW perform positively on the geophysical and technological dimensions while for ocean-based approaches performance is mixed. There is limited evidence to assess social-cultural, environmental/ecological, and institutional dimensions as the literature is still nascent for DACCS and EW, while these aspects are positive for blue carbon and mixed or negative for ocean fertilization. On the economic dimension, the cost is assessed negatively for all CDR methods.

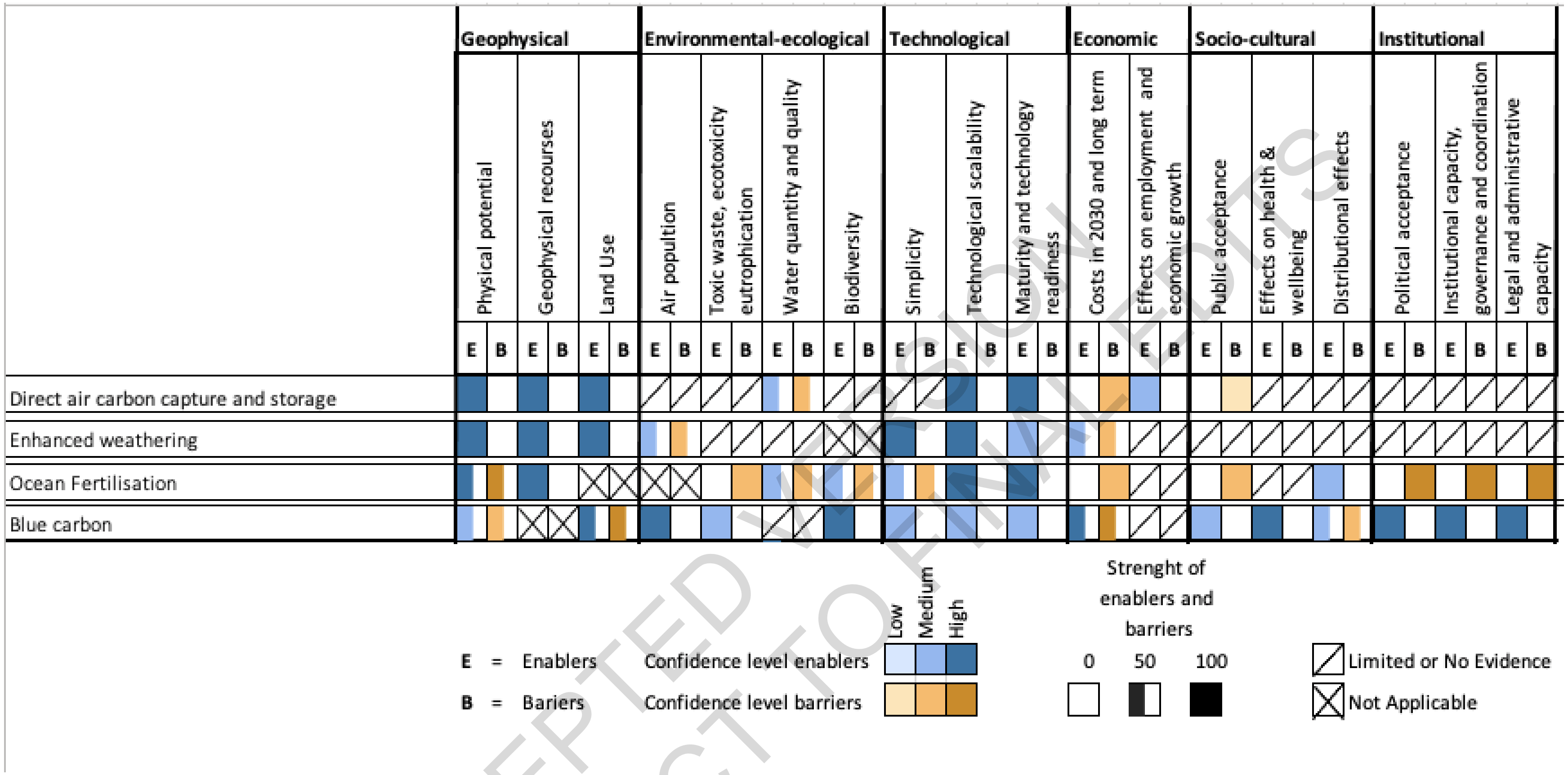


Figure 12.4 Summary of the extent to which different factors would enable or inhibit the deployment of the carbon dioxide methods DACCS, EW, ocean fertilisation and blue carbon management.

Blue bars indicate the extent to which the indicator enables the implementation of the CDR method (E) and orange bars indicate the extent to which an indicator is a barrier (B) to the deployment of the method, relative to the maximum possible barriers and enablers assessed. An 'X' signifies the indicator is not applicable or does not affect the feasibility of the method, while a forward slash indicates that there is no or limited evidence whether the indicator affects the feasibility of the method. The shading indicates the level of confidence, with darker shading signifying higher levels of confidence. Supplementary Material 12.B provides an overview of the factors affecting the feasibility of CDR methods and how they differ across context (e.g., region), time (e.g., 2030 versus 2050), and scale (e.g., small versus large), and includes a line of sight on which the assessment is based. The assessment methodology is explained in Annex II, Part II, Section 11.

12.3.2 Consideration of methods assessed in sectoral chapters; A/R, biochar, BECCS, soil carbon sequestration

Status: BECCS, A/R, soil carbon sequestration (SCS) and biochar are land-based biological CDR methods (Smith et al. 2016). BECCS combines biomass use for energy with CCS to capture and store the biogenic carbon geologically (Section 6.4.2.6); A/R and SCS involve fixing atmospheric carbon in biomass and soils, and biochar involves converting biomass to biochar and using it as a soil amendment. These CDR methods can be associated with both co-benefits and adverse side-effects, see Section 7.4, 12.5 and (Schleicher et al. 2019; Smith et al. 2019b; Hurlbert et al. 2019; Mbow et al. 2019; Olsson et al. 2019; Smith et al. 2016; Babin et al. 2021; Dooley et al. 2021).

Among CDR methods, BECCS and A/R are most commonly selected by IAMs to meet the requirements of likely limiting warming to 2°C or lower. This is partially because of the long lead time required to refine IAMs to include additional methods and update technoeconomic parameters. Currently, few IAMs represent SCS or biochar (Frank et al. 2017). Given the removal potential of SCS and biochar and some potential co-benefits, more efforts should be made to include these methods within IAMs, so that their mitigation potential can be compared to other CDR methods, along with possible co-benefits and adverse side effects (Smith et al. 2016; Rogelj et al. 2018) (Section 12.5).

Potential: The technical potential for BECCS by 2050 is estimated at 0.5–11.3 $GtCO_2$-eq yr^{-1} (Chapter 7, Table 7.3). These potentials do not include avoided emissions resulting from the use of heat, electricity and/or fuels provided by the BECCS system, which depends on substitution patterns, conversion efficiencies, and supply chain emissions for the BECCS and substituted energy systems (see Box 7.7 in Chapter 7). The mitigation effect of BECCS also depends on how deployment affects land carbon stocks and sink strength (see section 7.4.4).

As detailed in Chapter 7, the technical potential for gross removals realised through A/R in 2050 is 0.5–10.1 $GtCO_2$-eq yr^{-1} , and for improved forest management the potential is 1–2.1 $GtCO_2$-eq yr^{-1} (including both CDR and emissions reduction). Technical potential for SCS in 2050 is estimated to be 0.6–9.4 $GtCO_2$-eq yr^{-1}, for agroforestry it is 0.3–9.4 $GtCO_2$-eq yr^{-1}, and for biochar it is 0.2–6.6 $GtCO_2$-eq yr^{-1}. Peatland and coastal wetland restoration have a technical potential of 0.5–2.1 $GtCO_2$-eq yr^{-1} in 2050, with an estimated 80% of the potential being CDR. Note that these potentials reflect only biophysical and technological conditions and become reduced when factoring in economic, environmental, socio-cultural and institutional constraints (Table 12.6).

Costs: Costs across technologies vary substantially (Smith et al. 2016) and were estimated to be 15–400 USD tCO_2^{-1} for BECSS, 0–240 USD tCO_2^{-1} for A/R, -45–100 USD tCO_2^{-1} for SCS and10–345 USD tCO_2^{-1} for biochar. Fuss et al. (2018), estimated abatement cost ranges for BECCS, A/R, SCS and biochar to be 100–200, 5–50, 0–100, and 30–120 tCO_2-eq^{-1} respectively, corresponding to 2100 potentials. Ranges for economic potential (<100 USD tCO_2^{-1}) reported in Chapter 7 are 0.5–3.0 $GtCO_2$ yr^{-1} (A/R); 0.6–1.9 $GtCO_2$ yr^{-1} (improved forest management); 0.7–2.5 $GtCO_2$ yr^{-1} (SCS); 0.4–1.1 $GtCO_2$ yr^{-1} (agroforestry); 0.3–1.8 $GtCO_2$ yr^{-1} (biochar); 0.2–0.8 $GtCO_2$ yr^{-1} (peatland and coastal wetland restoration).

Risks, impacts, and co-benefits: a brief summary of risks, impacts and co-benefits is provided here and more detail is provided in chapter 7 and Section 12.5. A/R and biomass production for BECCS and biochar potentially compete for land, water and other resources, implying possible adverse outcomes for ecosystem health, biodiversity, livelihoods and food security (medium evidence, high agreement) Smith et al. 2016; Heck et al. 2018; Hurlbert et al. 2019; Mbow et al. 2019) (Chapter 7). SCS requires addition of nitrogen and phosphorus to maintain stoichiometry of soil organic matter, leading to a potential risk of eutrophication (Fuss et al. 2018). Apart from possible negative effects associated with biomass supply, adverse side-effects from biochar are relatively low if the biomass is uncontaminated (Tisserant and Cherubini 2019).

Possible climate risks relate to direct and/or indirect land carbon losses (A/R, BECCS, biochar), increased N_2O emissions (BECCS, SCS), saturation and non-permanence of carbon storage (A/R, SCS) (Jia et al. 2019; Smith et al. 2019b) (Chapter 7), and potential CO_2 leakage from deep geological reservoirs (BECCS) (Chapter 6). Land cover change associated with A/R and biomass supply for BECCS and biochar may cause albedo changes that reduce mitigation effectiveness (Jia et al. 2019; Fuss et al. 2018). Potentially unfavourable albedo change resulting from biochar use can be minimised by incorporating biochar into the soil (Fuss et al. 2018)(Chapter 7)

Concerning co-benefits, A/R and biomass production for BECCS or biochar could improve soil carbon, nutrient and water cycling (robust evidence, high agreement), and contribute to market opportunities, employment and local livelihoods, economic diversification, energy security, and technology development and transfer (medium evidence, high agreement) (Chapter 7)(Fuss et al. 2018). It may contribute to reduction of other air pollutants, health benefits, and reduced dependency on imported fossil fuels. A/R can improve biodiversity if native and diverse species are used, and (Fuss et al. 2018). For biochar, additional co-benefits include increased crop yields and reduced drought impacts, reduced CH_4 and N_2O emissions from soils (Section 7.4.5.2) (Joseph et al., 2021). SCS can improve soil quality and resilience and improve agricultural productivity and food security (Frank et al. 2017; Smith et al. 2019c).

Role in Mitigation Pathways: Biomass use for BECCS in 2050 is 61 EJ yr^{-1} (13–208 EJ yr^{-1}, 5-95 percentile range) in scenarios limiting warming to 1.5˚C with no or limited overshoot (C1, excluding traditional energy). This corresponds to 5.3 $GtCO_2$ yr^{-1} (1.1-18 $GtCO_2$ yr^{-1}) CDR, if assuming 28 kg C GJ^{-1} biomass carbon content and 85% capture rate in BECCS systems. In scenarios likely to limit warming to 2˚C (C3), biomass use for BECCS in 2050 is 28 EJ yr^{-1} (0–96 EJ yr-1, 5-95 percentile range), corresponding to 2.4 $GtCO_2$ yr^{-1} (0-8.3 $GtCO_2$ yr^{-1}) CDR. Cumulative net CO_2 removals on managed land (CDR through A/R minus land C losses due to deforestation) in the period 2020-2100 is 262 $GtCO_2$ (17–397 $GtCO_2$) and 209 $GtCO_2$ (20–415 $GtCO_2$) in C1 and C3 scenarios, respectively (5-95 percentile range).

Uncertainties remain in two main areas: the availability of land and biomass, which is affected by many factors (see Chapter 7) (Anandarajah et al. 2018), and the role of other mitigation measures including CDR methods other than A/R and BECCS. Strong near-term climate change mitigation to limit overshoot, and deployment of other CDR methods than A/R and BECCS, may significantly reduce the contribution of these CDR methods in scenarios limiting warming to 1.5˚C or 2˚C (Köberle 2019; Hasegawa et al. 2021).

Trade-offs and spill-overs: Some land-based biological CDR methods, such as BECCS and A/R, demand land. Combining mitigation strategies has the potential to increase overall carbon sequestration rates (Humpenöder et al. 2014). However, these CDR methods may also compete for resources (Frank et al. 2017). Land-based mitigation approaches currently propose the use of forests (i) as a source of woody biomass for bioenergy and various biomaterials, and (ii) for carbon sequestration in vegetation, soils, and forest products. Forests are therefore required to provide both provisioning (biomass feedstock) and regulating (carbon sequestration) ecosystem services. This multifaceted strategy has the potential to result in trade-offs (Makkonen et al. 2015). Some land-based mitigation options could conflict with biodiversity goals, e.g., A/R using monoculture plantations can reduce species richness when introduced into (semi-)natural grasslands (Smith et al. 2019a; Dooley et al. 2021). When trade-offs exist between biodiversity protection and mitigationobjectives, biodiversity is typically given a lower priority, especially if the mitigation option is considered risk-free and economically feasible (Pörtner et al. 2021). Approaches that promote synergies, such as sustainable forest management (SFM), reducing deforestation rates, cultivation of perennial crops for bioenergy in sustainable farming practices, and mixed-species forests in A/R, can mitigate biodiversity impacts and even improve ecosystem capacity to support biodiversity while mitigating climate change (Pörtner et al. 2021) (Section 12.5). Systematic land-use planning could help to deliver land-based mitigation options that also limit trade-offs with biodiversity (Longva et al. 2017) (Cross-Working Group Box 3: Mitigation and Adaptation via the Bioeconomy).

Status, costs, potentials, risk and impacts, co-benefits, trade-offs and spill-over effects and the role in mitigation pathways of A/R, biochar, SCS, peatland and coastal wetland restoration, agroforestry and forest management are summarised in Table 12.6. See also 12.5.

Table 12.6 Summary of status, costs, potentials, risk and impacts, co-benefits, trade-offs and spill over effects and the role in mitigation pathways for CDR methods. TRL = Technology Readiness Level. Author judgement ranges (assessed by authors in the literature) are shown, with full literature ranges shown in brackets

CDR option	**Status (TRL)**	**Cost (USD tCO_2^{-1})**	**Mitigation Potential ($GtCO_2$ yr^{-1})**	**Risk & Impacts**	**Co-benefits**	**Trade-offs and spill over effects**	**Role in modelled mitigation pathways**	**Section**
DACCS	6	100–300 (84–386)	5–40	Increased energy and water use.	Water produced (solid sorbent DAC designs only).	Potentially increased emissions from water supply and energy generation.	In a few IAMs; DACCS complements other CDR methods.	{12.3.1.1}
Enhanced weathering	3–4	50–200 (24–578)	2–4 (<1–95)	Mining impacts; air quality impacts of rock dust when spreading on soil.	Enhanced plant growth, reduced erosion, enhanced soil carbon, reduced pH, soil water retention.	Potentially increased emissions from water supply and energy generation.	In a few IAMs; EW complements other CDR methods.	{12.3.1.2}
Ocean alkalinity enhancement	1–2	40–260	1–100	Increased seawater pH and saturation states and may impact marine biota. Possible release of nutritive or toxic elements and compounds. Mining impacts.	Limiting ocean acidification.	Potentially increased emissions of CO_2 and dust from mining, transport and deployment operations.	No data.	{12.3.1.3}
Ocean fertilisation	1–2	50–500	1–3	Nutrient redistribution, restructuring of the ecosystem, enhanced oxygen consumption and acidification in deeper waters, potential for decadal-to-millennial-scale return to the atmosphere of nearly all the extra carbon	Increased productivity and fisheries, reduced upper ocean acidification.	Subsurface ocean acidification, deoxygenation; altered meridional supply of macro-nutrients as they are utilized in the iron-fertilized region and become unavailable for transport to, and	No data.	{12.3.1.3}

				removed, risks of unintended side effects.		utilization in other regions, fundamental alteration of food webs, biodiversity		
Blue carbon management in coastal wetlands	2–3	Insufficient data, estimates range from ~ 100 to ~ 10000	<1	If degraded or lost, coastal blue carbon ecosystems are likely to release most of their carbon back to the atmosphere; potential for sediment contaminants, toxicity, bioaccumulation and biomagnification in organisms; issues related to altering degradability of coastal plants; use of subtidal areas for tidal wetland carbon removal; effect of shoreline modifications on sediment redeposition and natural marsh accretion; abusive use of coastal blue carbon as means to reclaim land for purposes that degrade capacity for carbon removal.	Provide many non-climatic benefits and can contribute to ecosystem-based adaptation, coastal protection, increased biodiversity, reduced upper ocean acidification; could potentially benefit human nutrition or produce fertiliser for terrestrial agriculture, anti-methanogenic feed additive, or as an industrial or materials feedstock.	If degraded or lost, coastal blue carbon ecosystems are likely to release most of their carbon back to the atmosphere. The full delivery of the benefits at their maximum global capacity will require years to decades to be achieved	Not incorporated in IAMs, but in some bottom-up studies: small contribution.	{12.3.1.3}, Chapter 7, Section 7.4
BECCS	5–6	15–400	0.5–11	Competition for land and water resources, to grow biomass feedstock. Biodiversity and carbon stock loss if from unsustainable biomass harvest.	Reduction of air pollutants; fuel security, optimal use of residues, additional income, health benefits and if implemented well can enhance biodiversity, soil health and land carbon	Competition for land with biodiversity conservation and food production	Substantial contribution in IAMs and bottom -up sectoral studies	Chapter 7, Section 7.4

Afforestation/Reforestation	8–9	0–240	0.5–10	Reversal of carbon removal through wildfire, disease, pests may occur. Reduced catchment water yield and lower groundwater level if species and biome are inappropriate.	Enhanced employment and local livelihoods, improved biodiversity, improved renewable wood products provision, soil carbon and nutrient cycling. Possibly less pressure on primary forest.	Inappropriate deployment at large scale can lead to competition for land with biodiversity conservation and food production.	Substantial contribution in IAMs and also in bottom-up sectoral studies.	Chapter 7, Section 7.4
Biochar	6–7	10–345	0.3–6.6	Particulate and GHG emissions from production; biodiversity and carbon stock loss from unsustainable biomass harvest.	Increased crop yields and reduced non-CO_2 emissions from soil; and resilience to drought.	Environmental impacts associated particulate matter; competition for biomass resource.	In development - not yet in global mitigation pathways simulated by IAMs.	Chapter 7, Section 7.4
Soil Carbon Sequestration in croplands and grasslands	8–9	45–100	0.6–9.3	Risk of increased nitrous oxide emissions due to higher levels of organic nitrogen in the soil; risk of reversal of carbon sequestration.	Improved soil quality, resilience and agricultural productivity.	Attempts to increase carbon sequestration potential at the expense of production. Net addition per hectare is very small; hard to monitor.	In development - not yet in global mitigation pathways simulated by IAMs; in bottom-up studies: with medium contribution.	Chapter 7, Section 7.4
Peatland and coastal wetland restoration	8–9	Insufficient data	0.5–2.1	Reversal of carbon removal in drought or future disturbance. Risk of increased methane emissions.	Enhanced employment and local livelihoods, increased productivity of fisheries, improved biodiversity, soil carbon and nutrient cycling.	Competition for land for food production on some peatlands used for food production.	Not in IAMs but some bottom-up studies with medium contribution.	Chapter 7, Section 7.4

Agroforestry	8–9	Insufficient data	0.3–9.4	Risk that some land area lost from food production; requires high skills.	Enhanced employment and local livelihoods, variety of products improved soil quality, more resilient systems.	Some trade-off with agricultural crop production, but enhanced biodiversity, and resilience of system.	No data from IAMs, but in bottom-up sectoral studies. with medium contribution.	Chapter 7, Section 7.4
Improved Forest management	8–9	Insufficient data	0.1–2.1	If improved management is understood as merely intensification involving increased fertiliser use and introduced species, then it could reduce biodiversity and increase eutrophication.	In case of sustainable forest management, it leads to enhanced employment and local livelihoods, enhanced biodiversity, improved productivity.	If it involves increased fertiliser use and introduced species it could reduce biodiversity and increase eutrophication and upstream GHG emissions.	No data from IAMs, but in bottom-up sectoral studies with medium contribution.	Chapter 7, Section 7.4

12.3.3 CDR governance and policies

As shown in Cross-Chapter Box 8 in this Chapter, CDR fulfils multiple functions in different phases of ambitious mitigation: (1) further reducing net CO_2 or GHG emission levels in the near-term; (2) counterbalancing residual emissions (from hard-to-transition sectors like transport, industry, or agriculture) to help reach net zero CO_2 or GHG emissions in the mid-term; (3) achieving and sustaining net-negative CO_2 or GHG emissions in the long-term. While inclusion of emissions and removals on managed land (LULUCF) is mandatory for developed countries under UNFCCC inventory rules (Grassi et al. 2021), not all Annex I countries have included land-based biological removals when setting domestic mitigation targets in the past, but updated NDCs for 2030 indicate a shift, most notably in the European Union (Gheuens and Oberthür 2021; Schenuit et al. 2021). The early literature on CDR governance and policy has been mainly conceptual rather than empirical, focusing on high-level principles (see the concerns listed in introduction of Section 12.3) and the representation of CDR in global mitigation scenarios (see Section 3.2.2). However, with the widespread adoption of net zero targets and the recognition that CDR is a necessary element of mitigation portfolios to achieve net zero CO_2 or GHG emissions, countries with national net zero emissions targets have begun to integrate CDR into modelled national mitigation pathways, increase research, development & demonstration (RD&D) efforts on CDR methods, and consider CDR-specific incentives and policies (Honegger et al. 2021b; Schenuit et al. 2021), (Box 12.1). Nevertheless, this increasing consideration of CDR has not yet extended to net-negative targets and policies to achieve these. While the use of CDR at levels that would lead to net negative CO_2 or GHG emissions in the long-term has been assumed in most global mitigation scenarios that limit warming to 1.5°C, net-negative emissions trajectories and BECCS as the main CDR method modelled to achieve these have not been mirrored by corresponding UNFCCC decisions so far (Fridahl 2017; Mohan et al. 2021). Likewise, only a few national long-term mitigation plans or legal acts already entail a vision for net-negative GHG emissions (Buylova et al. 2021), for example Finland, Sweden, Germany and Fiji).

For countries with emissions targets aiming for net zero or lower, the core governance question is not whether CDR should be mobilised or not, but which CDR methods governments want to see deployed by whom, by when, at which volumes and in which ways (Bellamy and Geden 2019; Minx et al. 2018). The choice of CDR methods and the scale and timing of their deployment will depend on the respective ambitions for gross emission reductions, how sustainability and feasibility constraints are managed, and how political preferences and social acceptability evolve (Bellamy 2018; Forster et al. 2020; Fuss et al. 2020; Waller et al. 2020; Clery et al. 2021; Iyer et al. 2021; Rogelj et al. 2021). As examples of emerging CDR policymaking at (sub-)national levels show, policymakers are beginning to incorporate CDR methods beyond those currently dominating global mitigation scenarios, i.e. BECCS and afforestation/reforestation (Box 12.1) (Bellamy and Geden 2019; Buylova et al. 2021; Schenuit et al. 2021; Uden et al. 2021). CDR policymaking is faced with the need to consider method-specific timescales of CO_2 storage, as well as challenges in MRV and accounting, potential co-benefits, adverse side effects, interactions with adaptation and trade-offs with SDGs (Table 12.6) (Dooley and Kartha 2018; McLaren et al. 2019; Buck et al. 2020; Honegger et al. 2020; Brander et al. 2021; Dooley et al. 2021; Mace et al. 2021). Therefore, CDR governance and policymaking is expected to focus on responsibly incentivising RD&D and targeted deployment, building on both technical and governance experience with already widely practiced CDR methods like afforestation/reforestation (Lomax et al. 2015; Field and Mach 2017; Bellamy 2018; Carton et al. 2020; VonHedemann et al. 2020), as well as learning from two decades of slow-moving CCS deployment (Buck 2021; Martin-Roberts et al. 2021; Wang et al. 2021). For some less well understood methods and implementation options, such as ocean alkalinisation or enhanced weathering, investment in RD&D can help in understanding the risks, rewards, and uncertainties of deployment (Nemet et al. 2018; Fajardy et al. 2019; Burns and Corbett 2020; Goll et al. 2021).

START BOX 12.1 HERE

Box 12.1 Case Study: Emerging CDR policy, research and development in the United Kingdom

Climate change mitigation policies in the UK have been motivated since 2008 by a domestic, legally-binding framework. This framework includes a 2050 target for net greenhouse gas emissions, interim targets and an independent advisory body called the Climate Change Committee (Muinzer 2019). It has led successive UK governments to publish mitigation plans to 2050, causing policy to be more forward-looking (Averchenkova et al. 2021).

The UK's targets include emissions and removals from LULUCF. In 2008 the target for 2050 was an economy-wide net emissions reduction of at least 80% below 1990 levels. Even the first government plans to achieve this target proposed deployment of removal methods, specifically afforestation and wood in construction, increased soil carbon and BECCS (HM Government 2011).

Adoption of the Paris Agreement in 2015 caused the government to change the legislated 2050 target to a reduction of at least 100% (i.e. net zero). Since then, removal of CO_2 and other greenhouse gases has received greater prominence as a distinct topic. The most recent national plan (published October 2021) proposes deployment not only of the methods mentioned above, but also DACCS, biochar and enhanced weathering. The government has committed to amend accounting of UK targets to include a wider range of removal methods beyond LULUCF, and set a target of 5 $MtCO_2$ yr^{-1} from methods such as BECCS, DACCS and enhanced weathering by 2030. It is consulting on markets and incentives for deployment, and exploring new requirements for MRV (HM Government 2021).

In parallel to these policy developments, the UK funds research into technical, environmental and social aspects of removal (Lezaun et al. 2021). Research on some elements (e.g., forestry, CCS, soils, bioenergy) have been funded for well over a decade, but the first programme dedicated to greenhouse gas removal ran during 2017-2021. This has been followed by two new programmes with greater focus on demonstration, totalling £100m over four years (HM Government 2021). A wide variety of methods is supported in these programmes, covering approaches such as CO_2 capture from seawater and capture of methane from cattle, in addition to those included already in national mitigation scenarios.

Deployment of removal methods has lagged expectations, as national targets for tree planting are not being met and infrastructure for CO_2 transport and storage is not yet in place (Climate Change Committee 2021). While public awareness around carbon removal is low, studies indicate support in general, provided it is perceived as enhancing rather than impeding action to reduce emissions (Cox et al. 2020a).

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Since the enhancement of carbon sinks is a form of climate change mitigation (Honegger et al. 2021a), CDR governance challenges will in many respects be similar to those around emissions reduction measures, as will policy instruments like RD&D funding, carbon pricing, tax or investment credits, certification schemes, and public procurement (see Sections 13.4, 13.6, 14.4, 14.5). Effectively integrating CDR into mitigation portfolios can build on already existing rules, procedures and instruments for emissions abatement (Torvanger 2019; Fridahl et al. 2020; Zakkour et al. 2020; Honegger et al. 2021b; Mace et al. 2021; Rickels et al. 2021). Additionally, to accelerate RD&D and to incentivise CDR deployment a political commitment to formal integration into existing climate policy frameworks is required (*robust evidence, high agreement*) (Lomax et al. 2015; Geden et al. 2018; Honegger and Reiner 2018; VonHedemann et al. 2020; Schenuit et al. 2021) To avoid that CDR is misperceived as a substitute for deep emissions reductions, the prioritisation of emissions cuts can be signalled and achieved with differentiated target setting for reductions and removals (Geden et al. 2019; McLaren et al. 2019). Similarly, sub-targets are conceivable for different types of CDR, to prioritise preferred methods according to characteristics such as removal processes or timescales of storage (Smith 2021).

IPCC guidance on quantifying removals is available for land-based biological CDR methods (IPCC 2006, 2019), but has yet to be developed for other CDR methods (Royal Society and Royal Academy of Engineering 2018). Challenges with development of estimation algorithms, data collection, and attribution between sectors and countries will need to be overcome (Luisetti et al. 2020; Wedding et al. 2021). Trusted methodologies for MRV, required to enable private sector participation will need to address the permanence, leakage, and saturation challenges with land and ocean-based biological methods (Mace et al. 2021). Protocols that also capture social and ecological co-benefits, could encourage the adoption of biological CDR methods such as SCS, biochar, A/R and blue carbon management *(robust evidence, high agreement)* (VonHedemann et al. 2020; Macreadie et al. 2021).

Private capital and companies, impact investors, and philanthropy will play a role in technical demonstrations and bringing down costs, as well as creating demand for carbon removal products on voluntary markets, which companies may purchase to fulfil corporate social responsibility-driven targets (Friedmann 2019; Fuss et al. 2020; Joppa et al. 2021). Niche markets can provide entry points for limited deployment of novel CDR methods (Cox and Edwards 2019), but targeting currently existing revenue streams by using CO_2 captured from the atmosphere in Enhanced Oil Recovery and other utilisation routes (Mackler et al. 2021; Meckling and Biber 2021) is contested, and highlights the importance of choosing appropriate system boundaries when assessing supply chains (Tanzer and Ramírez 2019; Brander et al. 2021). While the private sector will play a distinct role in scaling CDR, governments will need to commit to developing infrastructure for the transport and storage of CO_2, including financing, permitting, and regulating liabilities (Sanchez et al. 2018; Mace et al. 2021; Mackler et al. 2021).

International governance considerations include global technology transfer around CDR implementation options (Batres et al. 2021); land use change that could affect food production and land condition, and cause conflict around land tenure and access (Dooley and Kartha 2018; Hurlbert et al.

2019; Milne et al. 2019); and efforts to create sustainable and just supply chains for CDR (Fajardy and Mac Dowell 2020; Tan et al. 2021), such as resources used for BECCS, enhanced weathering, or ocean alkalinisation. International governance would be particularly important for methods posing transboundary risks, especially for ocean-based methods. Specific regulations have so far only been developed in the context of the London Protocol, an international treaty that explicitly regulates ocean fertilisation and allows parties to govern other marine CDR methods like ocean alkalinity enhancement (GESAMP 2019; Burns and Corbett 2020; Boettcher et al. 2021)(see Section 14.4.5).

Engagement of civil society organisations and publics will be important for shaping CDR policy and deployment (*medium evidence, high agreement*). Public awareness of CDR and its role in national net zero emissions strategies is generally very low (Cox et al. 2020a), and perceptions differ across countries and between methods (Bertram and Merk 2020; Spence et al. 2021; Sweet et al. 2021; Wenger et al. 2021). When awareness increases, social processes will shape political attitudes on CDR (Shrum et al. 2020), as will efforts to frame particular CDR methods as 'natural' or 'technological' (Osaka et al. 2021), and the policy instruments chosen to support CDR (Bellamy et al. 2019). Lack of confidence in CDR implementation options from both publics and investors, and lack of trust in project developers (Cox et al. 2020b) have hampered support for CCS (Thomas et al. 2018) and is expected to affect deployment of CDR methods with geological storage (Gough and Mander 2019). On local and regional scales, CDR projects will need to consider air and water quality, impacts to human health, energy needs, land use and ecological integrity, and local community engagement and procedural justice. Bottom-up and community driven strategies are important for deploying equitable carbon removal projects (Hansson et al. 2021; Batres et al. 2021).

12.4 Food systems

12.4.1 Introduction

This section complements Chapter 7 by reviewing recent estimates of food system emissions and assessing options beyond the agriculture, forestry and land use sectors to mitigate food systems GHG emissions. A food system approach enables identification of cross-sectoral mitigation opportunities including both technological and behavioural options. Further, a system approach permits evaluation of policies that do not necessarily directly target primary producers or consumers, but other food system actors with possibly higher mitigation efficiency. A food system approach was introduced in the IPCC Special Report on Climate Change and Land (SRCCL) (Mbow et al. 2019). Besides major knowledge gaps in the quantification of food system GHG emissions (Section 12.4.2), the SRCCL authors identified as major knowledge gaps the understanding of the dynamics of dietary change (including behavioural patterns, the adoption of plant-based dietary patterns, and interaction with human health and nutrition of sustainable healthy diets and associated feedbacks); and instruments and mechanisms to accelerate transitions towards sustainable and healthy food systems.

Sufficient food and adequate nutrition are fundamental human needs (HLPE 2020; Ingram 2020). Food needs to be grown and processed, transported and distributed, and finally prepared and consumed. Food systems range from traditional, involving only few people and short supply chains, to modern food systems, comprising complex webs involving large numbers of stakeholders and processes that grow and transform food commodities into food products and distribute them globally (HLPE 2017; Gómez and Ricketts 2013). A 'food system' includes all food chain activities (production, processing, distribution, preparation, consumption of food) and the management of food loss and wastes. It also includes institutions and infrastructures influencing any of these activities, as well as people and systems impacted (HLPE 2017; FAO 2018a). Food choices are determined by the food environment consisting of the "physical, economic, political and socio-cultural context in which consumers engage with the food system to acquire, prepare and consume food" (HLPE 2017). Food system outcomes encompass food and nutrition, productivity, profit and livelihood of food producers and other actors in food value chains, but also social outcomes and the impact on the environment (Zurek et al. 2018). 'Sustainable healthy diets' have been defined by FAO and WHO (FAO and WHO 2019) as "dietary patterns that promote all dimensions of individuals' health and wellbeing; have low environmental pressure and impact; are accessible, affordable, safe and equitable; and are culturally acceptable."

The SRCCL estimated overall global anthropogenic emissions from food systems to range between 10.8 and 19.1 $GtCO_2$-eq yr^{-1}, equivalent to 21-37% of total anthropogenic emissions (Rosenzweig et al. 2020a; Mbow et al. 2019). The authors identified major knowledge gaps for the GHG emission inventories of food systems, particularly in providing disaggregated emissions from the food industry and transportation. The food system approach taken in the SRCCL (Mbow et al. 2019) evaluates the synergies and trade-offs of food system response options and its implications for food security, climate change adaptation and mitigation. This integrated framework allows the identification of fundamental attributes of responses to maximise co-benefits, while avoiding maladaptation measures and adverse side effects. A food system approach supports the design of interconnected climate policy responses to tackle climate change, incorporating perspectives of producers and consumers. The SRCCL (Mbow et al. 2019) found that the technical mitigation potential by 2050 of demand-side responses at 0.7–8.0 $GtCO_2$-eq yr^{-1} is comparable to supply-side options at 2.3–9.6 $GtCO_2$-eq yr^{-1}. This shows that mitigation actions need to go beyond food producers and suppliers to incorporate dietary changes and consumers' behavioural patterns and reveals that producers and consumers need to work together to reduce GHG emissions.

Though total production of calories is sufficient for the world population (Wood et al. 2018; Benton et al. 2019), availability and access to food is unequally distributed, and there is a lack of nutrient-dense foods, fruit and vegetables (Berners-Lee et al. 2018; Kc et al. 2018). In 2019, close to 750 million people were food insecure. An estimated 2 billion people lacked adequate access to safe and nutritious food in both quality and quantity (FAO et al. 2020). Two billion adults are overweight or obese through inadequate nutrition, with an upward trend globally (FAO et al. 2019). Low intake of fruit and vegetables is further aggravated by high intake rates of refined grains, sugar and sodium together leading to a high risk of non-communicable diseases such as cardiovascular disease and type 2 diabetes (Springmann et al. 2016; Clark et al. 2018, 2019; GBD 2017 Diet Collaborators et al. 2019; Willett et al. 2019) *(robust evidence, high agreement)*. At least 340 million children under 5 years of age experience lack of vitamins or other essential bio-available nutrients, including almost 200 million suffering from stunting, wasting or overweight (UNICEF 2019).

Bodirsky et al. (Bodirsky et al. 2020) find that global prevalence of overweight will increase to 39–52% of world population in 2050 (from 29% in 2010; range across the Socioeconomic

Pathways studied), and 13–20% obese people (9% in 2010). The prevalence of underweight people was predicted to approximately halve, with absolute numbers stagnating at 0.4–0.7 billion. Although many studies represent future pathways of diets and food systems, there are few holistic and consistent narratives and quantification of the future pathways of diets and food systems (Mora et al. 2020; Mitter et al. 2020). Alternative pathways for improved diets and food systems have been developed, emphasising climate, environmental and health co-benefits (Bajželj et al. 2014; Hedenus et al. 2014; Damerau et al. 2016; Weindl et al. 2017a,b; Springmann et al. 2018a; Bodirsky et al. 2020; Prudhomme et al. 2020; Hamilton et al. 2021), reduced food waste and closing yield gaps (Pradhan et al. 2014; Bajželj et al. 2014), nitrogen management (Bodirsky et al. 2014), urban and peri-urban agriculture (Kriewald et al. 2019) and different sustainability targets (Henry et al. 2018b). The FAO has examined three alternative food system scenarios: "business as usual", "towards sustainability", and "stratified societies" (FAO 2018b). Others have identified research priorities or changes in legislation needed to support adoption of improved food systems (Mylona et al. 2018).

Malnutrition aggravates susceptibility of children to various infectious diseases (Farhadi and Ovchinnikov 2018; França et al. 2009), and infectious diseases can also decrease nutrient uptake, thereby promoting malnutrition (Farhadi and Ovchinnikov 2018). Contamination of food with bacteria, viruses, parasites and microbial toxins can cause foodborne illnesses (Abebe et al. 2020; Ricci et al. 2017; Gallo et al. 2020), foodborne substances such as food additives and specific proteins can cause adverse reactions, and contamination with toxic chemical substances used in agriculture and food processing, can lead to poisoning or chronic diseases (Gallo et al. 2020). Further, health risks from food systems may originate from the use of antibiotics in livestock production and the occurrence of anti-microbial resistance in pathogens (ECDC et al. 2015; Bennani et al. 2020), or zoonotic diseases such as COVID-19 (Vågsholm et al. 2020; Gan et al. 2020; Patterson et al. 2020).

Modern food systems are highly consolidated, through vertical and horizontal integration (Swinnen and Maertens 2007; Folke et al. 2019). This consolidation has led to uneven distribution of power across the food value chain, with influence concentrated among a few actors in the post-farm gate food supply chain (e.g., large food processors and retailers), and has contributed to a loss of indigenous agriculture and food systems, for example on Pacific Islands (Vogliano et al. 2020). While agricultural producers contribute a higher proportion of GHG emissions compared with other actors in the supply chain, they have relatively little power to change the system (Leip et al. 2021; Clapp 2019; Group of Chief Scientific Advisors 2020).

In 2016, the agriculture, fisheries, and forestry sectors employed 29% of working people; employment within these sectors was 4% in developed countries, down from 9% in 1995, and 57% in least developed countries, down from 71% in 1995 (World Bank 2021). Employment in other (non-agriculture) food system sectors, such as the food processing industry and service sectors, differs between food systems. The share of total non-farm food system employment ranges from 10% in traditional food systems (e.g., Sub-Saharan Africa), to over 50% in food systems in transition (e.g., Brazil), to high shares (80%) in modern food systems (e.g., U.S.) (Townsend et al. 2017). The share of the food expenditures that farmers receive is decreasing; at the global level, this share has been estimated at 27% in 2015 (Yi et al. 2021).

12.4.2 GHG emissions from food systems

12.4.2.1 Sectoral contribution of GHG emissions from food systems

New calculations using EDGAR.v6 (Crippa et al. 2021a) and FAOSTAT (FAO 2021) databases provide territorial-based food system GHG emissions by country globally for the time period 1990 to 2018 (Crippa et al. 2021b). The data are calculated based on a combination of country-specific data and aggregated information as described by Crippa et al. (2021b) and Tubiello et al. (2021). The data show that, in 2018, 17 $GtCO_2$-eq yr^{-1} (95% confidence range 13–23 $GtCO_2$-eq yr^{-1}, calculated according to Solazzo et al. (2020) were associated with the production, processing, distribution, consumption of food and management of food system residues. This corresponded to 31% (range 23-42%) of total anthropogenic GHG emissions of 54 $GtCO_2$-eq yr^{-1}. Based on the IPCC sectoral classification (Table 12.7 and Figure 12.5), the largest contribution of food systems GHG emissions in 2018 was from agriculture, i.e. livestock and crop production systems (6.3 $GtCO_2$-eq yr^{-1}, range 2.6–11.9) and land use, land use change and forestry (LULUCF) (4.0 $GtCO_2$-eq yr^{-1}, range 2.1–5.9) (Figure 12.5). Emissions from energy use were 3.9 $GtCO_2$-eq yr^{-1} (3.6–4.4**)**, waste management 1.7 $GtCO_2$-eq yr^{-1} (0.9–2.6), and industrial processes and product use 0.9 $GtCO_2$-eq yr^{-1} (0.6–1.1). The share of GHG emissions from food systems generated outside the AFOLU (agriculture and LULUCF) sectors has increased over recent decades, from 28% in 1990 to 39% in 2018.

Energy. Emissions from energy use occur throughout the food supply chain. In 2018, the main contributions came from energy industries supplying electricity and heat (970 $MtCO_2$-eq yr^{-1}), manufacturing and construction (920 $MtCO_2$-eq yr^{-1}, of which 29% was attributable to the food, beverage, and tobacco industry), and transport (760 $MtCO_2$-eq yr^{-1}). These emissions were almost entirely as CO_2. Energy emissions from forestry and fisheries amounted to 480 $MtCO_2$-eq yr^{-1}, with 91% of emissions as CO_2. Emissions from residential and commercial fuel combustion contributed 250 $MtCO_2$-eq yr^{-1} (79% of emissions as CO_2, and with emissions of 1.7 $MtCH_4$ yr^{-1}) and 130 $MtCO_2$-eq yr^{-1} (with 98% of emissions as CO_2), respectively.

Refrigeration uses an estimated 43% of energy in the retail sector (Behfar et al. 2018) and significantly increases fuel consumption during distribution. Besides being energy intensive, supermarket refrigeration also contributes to GHG emissions through leakage of refrigerants (F-gases), although their contribution to food system GHG emissions is estimated to be minor (Crippa et al. 2021b). The cold chain accounts for approximately 1% of global GHG emissions, but as the number of refrigerators per capita in developing countries is reported to be one order of magnitude lower than the number in developed countries (19 m^3 versus 200 m^3 refrigerated storage capacity per 1000 inhabitants), the importance of refrigeration to total GHG emissions is expected to increase (James and James 2010). Although refrigeration gives rise to GHG emissions, both household refrigeration and effective cold chains could contribute to a substantial reduction in losses of perishable food and thus in emissions associated with food provision (University of Birmingham 2018; James and James 2010). A trade-off exists between reducing food waste and increased refrigeration emissions, with the benefits depending on type of produce, location and technologies used (Wu et al. 2019; Sustainable Cooling for All 2018).

Transport has overall a minor importance for food system GHG emissions, with a share of 5% to 6% (Poore and Nemecek 2018a; Crippa et al. 2021b). The largest contributor to food system transport GHG emissions was road transport (92%), followed by marine shipping (4%), rail (3%), and aviation (1%). Only looking at energy needs, air or road transport consumes one order of magnitude higher energy (road: 70–80 MJ t^{-1} km^{-1}; aviation: 100–200 MJ t^{-1} km^{-1}) than marine shipping (10–20 MJ t^{-1} km^{-1}) or rail (8–10 MJ t^{-1} km^{-1}) (FAO 2011). For specific food products with high water content, relatively low agricultural emissions and high average transport distances, the share of transport in total GHG emissions can be over 40% (e.g., bananas, with total global average GHG emissions of 0.7 $kgCO_2$-eq kg^{-1}) (Poore and Nemecek 2018a), but transport is a minor source of GHG emissions for most food products (Poore and Nemecek 2018a).

Industry. Direct industrial emissions associated with food systems are generated by the refrigerants industry (580 $MtCO_2$-eq yr^{-1} as F-gases) and the fertiliser industry for ammonia production (280 $MtCO_2$-eq yr^{-1} as CO_2) and nitric acid (60 $MtCO_2$-eq yr^{-1} as N_2O). The industry sector data account for CO_2 stored in urea (-50 $MtCO_2$-eq yr^{-1}). Packaging contributed about 6% of total food system emissions (0.98 $GtCO_2$-eq yr^{-1}, 91% as CO_2, with CH_4 emissions of 2.8 Mt CH_4 yr^{-1}). Major emissions sources are pulp and paper (60 $MtCO_2$-eq yr^{-1}) and aluminium (30 $MtCO_2$-eq yr^{-1}), with ferrous metals, glass, and plastics making a smaller contribution. High shares of emissions from packaging are found for beverages and some fruit and vegetables (Poore and Nemecek 2018a).

Waste. Management of waste generated in the food system (including food waste, wastewater, packaging waste etc.) leads to biogenic GHG emissions, and contributed 1.7 $GtCO_2$-eq yr^{-1} to food systems' GHG emissions in 2018. Of these emissions, 55% were from domestic and commercial wastewater (30 $MtCH_4$ yr^{-1} and 310 ktN_2O yr^{-1}), 36% from solid waste management (20 $MtCH_4$ yr^{-1} and 310 ktN_2O yr^{-1}), and 8% from industrial wastewater (4 $MtCH_4$ yr^{-1} and 80 ktN_2O yr^{-1}). Emissions from waste incineration and other waste management systems contributed 1%.

Table 12.7: **GHG emissions from food systems by sector according to IPCC classification in Mt gas yr^{-1} and food systems' share of total anthropogenic GHG emissions in 1990 and 2015.**

Sector	CO_2	CH_4	N_2O	F-gases	GHG	CO_2	CH_4	N_2O	F-gases	GHG
	Emissions (Mt gas yr^{-1})					Share of total sectoral emissions (%)				
					1990					
1 Energy	2212	10	0	-	2583	10.5	10.2	26.7	-	10.7
2 Industrial Processes	190	0	0	0	263	14.5	0	38	4.8	16.2
3 Solv + Product Use	0	-	-	-	0	0.2	-	-	-	0.2
4 Agriculture	102	142	5	-	5370	100	100	99.2	-	99.8
5 LULUCF	4946	-	0	-	5080	181	-	194	-	182
6 Waste	3	40	0	-	1155	29	72.4	99.1	-	73.2
Total	**7453**	**192**	**6**	**0**	**14452**	**29.3**	**65.2**	**84.5**	**4.8**	**40.3**
Total [$MtCO_2$-eq yr^{-1}]	**7453**	**5243**	**1755**	**0**	**14452**	**29.3**	**63.9**	**84.5**	**0.3**	**40.3**
					2018					
1 Energy	3449	13	0	-	3927	10.1	9.5	24.1	-	10.2
2 Industrial Processes	242	0	0	0	881	7.9	0	28.6	58	20.1

3 Solv + Product Use	7	-	-	-	7	4.1	-	-	-	3.6
4 Agriculture	140	161	7	-	6326	100	100	99.1	-	99.7
5 LULUCF	3823	-	1	-	3982	190	-	229	-	191
6 Waste	5	58	0	-	1699	30.6	71.8	99.1	-	72.9
Total	**7666**	**231**	**8**	**0**	**16821**	**19.3**	**61.6**	**83.7**	**58**	**31.1**
Total [MtCO₂-eq yr⁻¹]	**7666**	**6317**	**2256**	**581**	**16821**	**19.3**	**60.2**	**83.7**	**53.6**	**31.1**

Notes: Agricultural emissions include the emissions from the whole sector; biomass production for non-food use currently not differentiated. Non-food system AFOLU emissions are a carbon sink, therefore the share of AFOLU food system emissions is > 100%. Source: EDGARv5 (Crippa et al. 2019, 2021b), and FAOSTAT (FAO 2021). Solv+Produc Use = Solvent and Other Product Use; LULUCF: Land Use, Land-Use Change & Forestry.

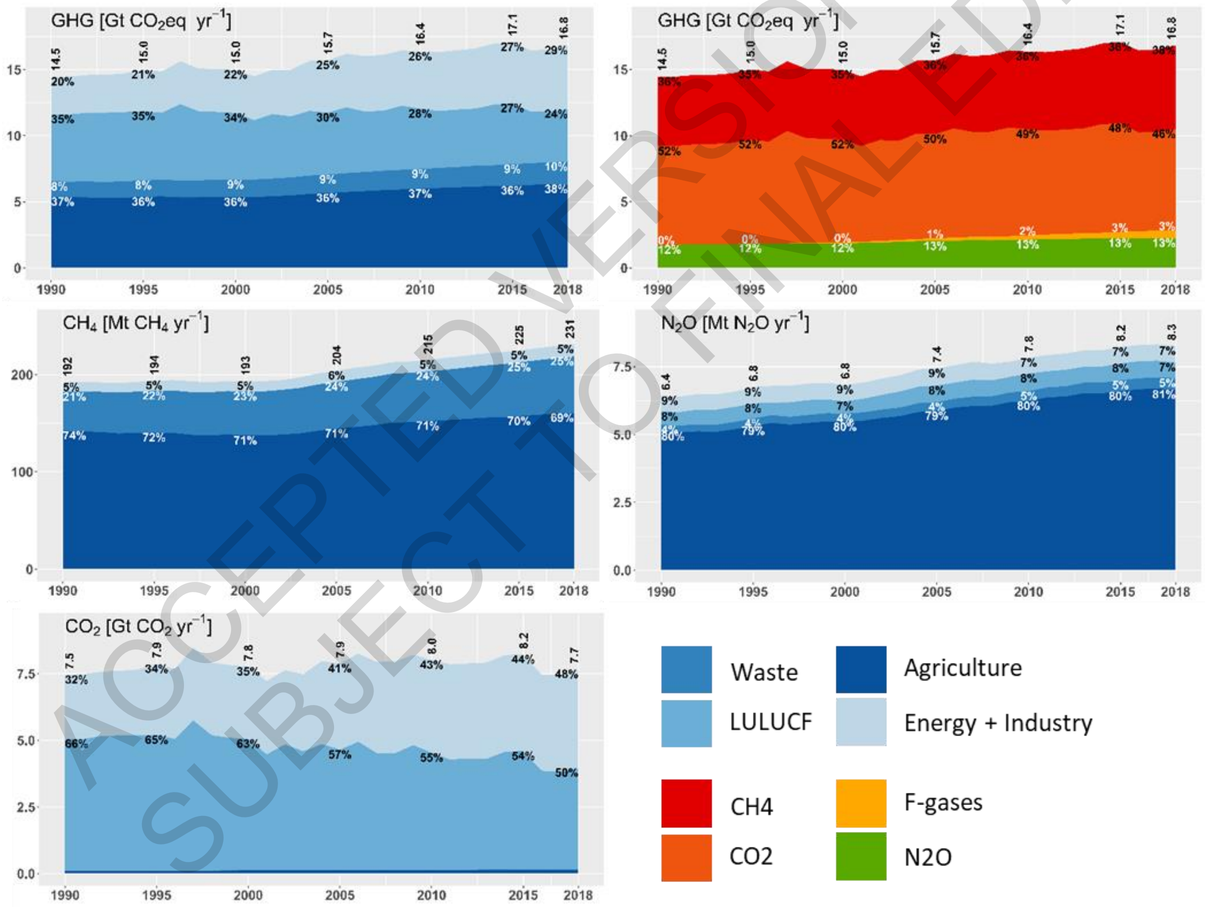


Figure 12.5: Food system GHG emissions from the agriculture, LULUCF, waste, and energy & industry sectors. Source: Crippa et al. (2021b).

12.4.2.2 GHG intensities of food commodities

There is high variability in the GHG emissions of different food products and production systems (Figure 12.6). GHG emissions intensities – measured using attributional Life Cycle Assessment, considering the full supply-chain, expressed as CO_2-eq per kg of product or per kg of protein – are generally highest for ruminant meat, cheese, and certain crustacean species (e.g., farmed shrimp and prawns, trawled lobster) (Nijdam et al. 2012; Clark and Tilman 2017; Clune et al. 2017; Hilborn et al. 2018; Poore and Nemecek 2018) *(robust evidence, high agreement).* Generally, beef from dairy systems has a lower footprint (8–23 kgCO_2-eq (100g protein)$^{-1}$ than beef from beef herds (17–94 kgCO_2-eq (100g protein)$^{-1}$ (Figure 12.6, re-calculated from Poore and Nemecek (2018) using AR6 GWPs based on a 100 year horizon) *(medium evidence, high agreement)*. The wide variation in beef emissions reflects differences in production systems, which range from intensive feedlots with stock raised largely on grains through to rangeland and transhumance production systems. Dairy systems are generally more intensive production systems, with higher digestibility feed than beef systems. Further, emissions from dairy systems are shared between milk and meat, which brings GHG footprints of beef from dairy herds beef closer to those of meat from monogastric animals with emissions intensities of pork (4.4–13 kgCO_2-eq per 100g protein) and poultry meat (2.3–11 kgCO_2-eq per 100g protein) (Poore and Nemecek 2018a).

Emission intensities for farmed fish ranged from 2.4–11 kgCO_2-eq per 100g protein (Poore and Nemecek 2018a). For Norwegian seafood, large differences have been found ranging from 1.1 kgCO_2-eq per kg edible product for herring to more than 8 kgCO_2-eq per kg edible product for salmon shipped by road and ferry from Oslo to Paris (Winther et al. 2020). For capture fish, large differences in emissions have been found, ranging from 0.2–7.9 kgCO_2-eq per kg landed fish (Parker et al. 2018), although an environmental comparison of capture fish to farmed foods should include other indicators such as overfishing. Plant-based foods generally have lower GHG emissions (-2.2–4.5 kgCO_2-eq per 100g protein) than farmed animal based foods (Clune et al. 2017; Hilborn et al. 2018; Clark and Tilman 2017; Nijdam et al. 2012; Poore and Nemecek 2018a) *(robust evidence, high agreement)*. Several plant-based foods are associated with emissions from land use change, for example, palm oil, soy and coffee (Poore and Nemecek 2018a), although emissions intensities are context-specific (Meijaard et al. 2020) and for plant-based proteins, GHG footprints per serving remain lower than those of animal source proteins (Kim et al. 2019).

In traditional production systems, especially in developing countries, livestock serve multiple functions, providing draught power, fertiliser, investment and social status, besides constituting an important source of nutrients (Weiler et al. 2014). In landscapes dominated by forests or cropland, semi-natural pastures grazed by ruminants provide heterogeneity that supports biodiversity (Röös et al. 2016). Grazing on marginal land and the use of crop residues and food waste can provide human-edible food with lower demands for cropland (Röös et al. 2016; van Zanten et al. 2018; Van Hal et al. 2019). Animal protein requires more land than vegetable protein, so switching consumption from animal to vegetable proteins could reduce the pressure on land resources and potentially enable additional mitigation through expansion of natural ecosystems, storing carbon while supporting biodiversity, or reforestation to sequester carbon and enhance wood supply capacity for the production of biobased products substituting fossil fuels, plastics, cement, etc. (Searchinger et al. 2018; Schmidinger and Stehfest 2012; Hayek et al. 2021). At the same time, alternatives to animal-based meat and other livestock products are being developed (Figure 12.6). Their increasing visibility in supermarkets and catering services, as well as falling production prices, could make meat substitutes competitive in one to two decades (Gerhardt et al. 2019). However, uncertainty around their uptake creates uncertainty around their effect on future GHG emissions.

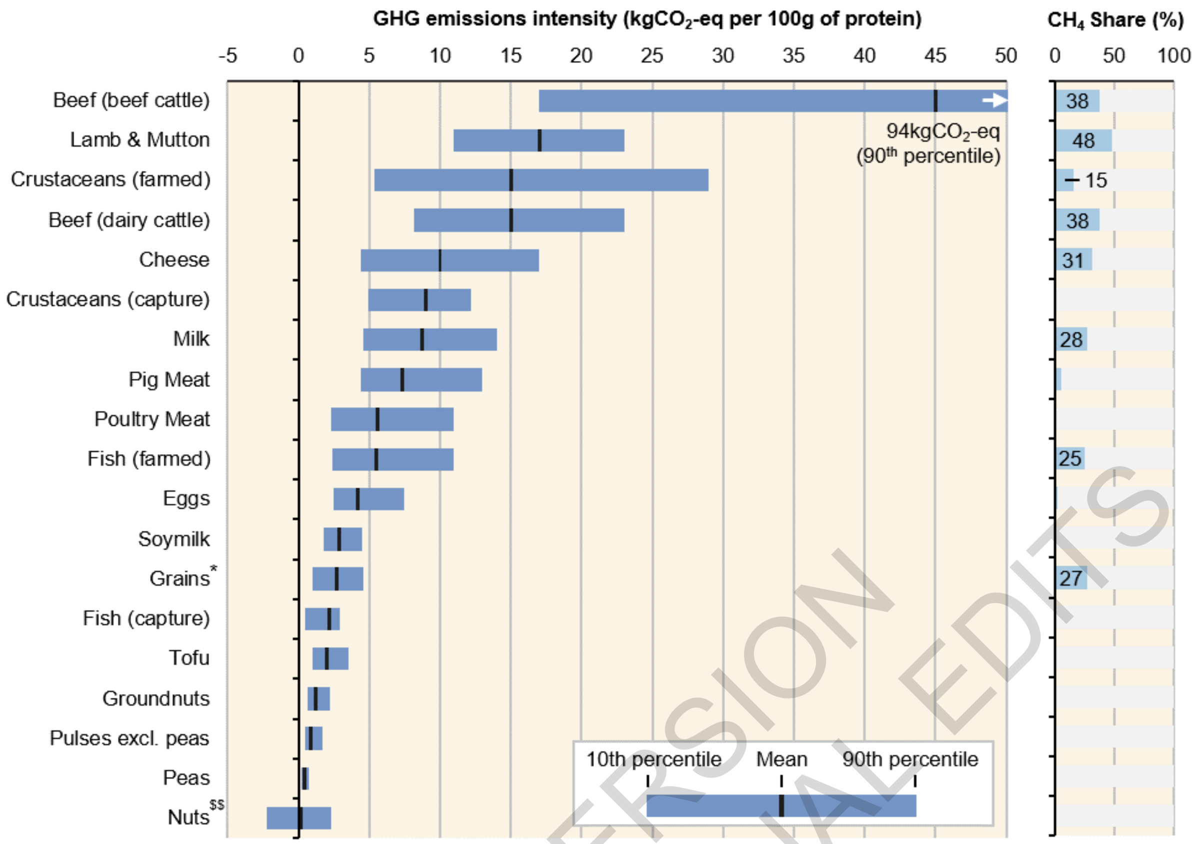


Figure 12.6: Ranges of GHG intensities [kgCO$_2$-eq per 100 g of protein, 10th-90th percentile] in protein-rich foods, quantified via a meta-analysis of attributional Life Cycle Assessment studies using economic allocation

Aggregation of CO$_2$, CH$_4$, and N$_2$O emissions in Poore and Nemecek, (2018) updated to use IPCC-AR6 100-year GWP. Data for capture fish, crustaceans, and cephalopods from Parker et al. (2018), with post-farm data from (Poore and Nemecek 2018a), where the ranges represent differences across species groups. CH$_4$ emissions include emissions from manure management, enteric fermentation, and flooded rice only.

***Grains are not generally classed as protein-rich, but they provide ~41% of global protein intake. Here grains are a weighted average of wheat, maize, oats, and rice by global protein intake (FAO Food Balance Sheets).**

$$Conversion of annual to perennial crops can lead to carbon sequestration in woody biomass and soil, shown as negative emissions intensity.

Source: Poore and Nemecek, 2018; Parker et al., 2018

12.4.2.3 Territorial national per capita GHG emissions from food systems

Food systems are connected to other societal systems, such as the energy system, financial system, and transport system (Leip et al. 2021). Also, food systems are dynamic and continuously changing and adapting to existing and anticipated future conditions. Food production systems are very diverse and vary by farm size, intensity level, farm specialisation, technological level, production methods (e.g., organic, conventional, etc.), with environmental and social consequences (Herrero et al. 2017; Fanzo 2017; Václavík et al. 2013; Herrero et al. 2021).

Various frameworks have been proposed to assess sustainability of food systems, including metrics and indicators on environmental, health, economic and equity issues, pointing to the importance of recognizing the multi-dimensionality of food system outcomes (Béné et al. 2020; Chaudhary et al. 2018; Gustafson et al. 2016; Eme et al. 2019; Hallström et al. 2018; Hebinck et al. 2021; Zurek et al. 2018). Data platforms are being developed, but so far comprehensive data for evidence-based food system policy are lacking (Fanzo et al. 2020).

To visualise several food systems dimensions in a GHG context, Figure 12.7 shows GHG emissions per capita and year for regional country aggregates (Crippa et al. 2021a,b), indicated by the size of the bubbles. The GHG emissions presented here are based on territorial accounting similar to the UNFCCC GHG inventories: emissions are assigned to the country where they occur, not where food is consumed (Section 12.4.2.1 and Crippa et al., 2021a, b). The colours of the bubbles indicate the relative contribution of one of the following risk factors to deaths, according to the classification used in the Global Burden of Disease Study: Child and maternal malnutrition (red, deficiencies of iron, zinc or Vitamin A, or low birth weight or child growth failure), Dietary risks (yellow, for example diets low in vegetables, legumes, whole grains or diets high in red and processed meat and sugar-sweetened beverages) or High body-mass index (blue). The combined contribution of these three risk factors to total deaths varies strongly and is between 28% and 88% of total deaths. Figure 12.7 shows that dietary risk factors are prevalent throughout all regions. Though not a complete measure of the health impact of food, these were selected as a proxy for nutritional adequacy and balance of diets, avoidance of food insecurity, over- or mal-nutrition and associated non communicable diseases (GBD 2017 Diet Collaborators 2018; GBD 2017 Diet Collaborators et al. 2019).

The data are plotted in a matrix with share of GHG emissions from energy use (Crippa et al. 2021b) on the y-axis and the wholesale cost of food (Springmann et al. 2021) on the x-axis. The share of GHG emissions from energy use is taken as a proxy for the structure of food supply in a region (Section 12.4.1), and the cost for food as a proxy for the structure of the demand side and the access to (healthy) food (Chen et al. 2016; Hirvonen et al. 2019; Finaret and Masters 2019; HLPE 2020; Springmann et al. 2021), though acknowledging the limitations of such a simplification.

While total food system emissions in 2018 range between 0.9 and 8.5 tCO_2-eq cap^{-1} yr^{-1} between regions, the share of energy emissions relative to energy and land-based (agriculture and food system land use change) emissions ranges between 3% and 78%. Regional expenditures for food range from 3.0–8.8 USD cap^{-1} day^{-1} (Figure 12.7), though there is high variability within countries and the costs of nutrient-adequate diets often exceeds those of diets delivering adequate energy (Bai et al. 2020; Hirvonen et al. 2019; FAO et al. 2020). Thus, low-income households in industrialised countries can also be affected by food insecurity (Penne and Goedemé 2020).

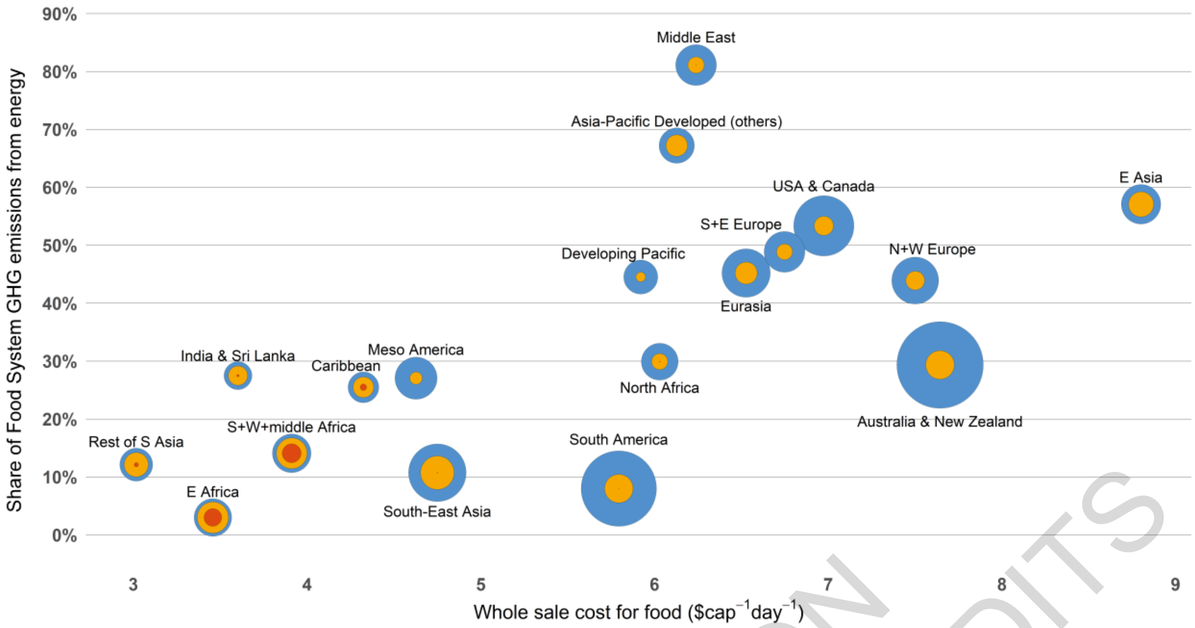


Figure 12.7: Regional differences in health outcome, territorial per capita GHG emissions from national food systems, and share of food system GHG emission from energy use.

GHG emissions are calculated according to the IPCC Tier 1 approach and are assigned to the country where they occur, not necessarily where the food is consumed. Health outcome is expressed as relative contribution of each of the following risk factors to their combined risk for deaths: Child and maternal malnutrition (red), Dietary risks (yellow) or High body-mass index (blue).

Source: cost for food (whole sale price) per capita (Springmann et al. 2021); Territorial food system GHG emissions: EDGAR v.6 (Crippa et al. 2021a), recalculated according to Crippa et al. (2021) using AR6-GWPs; Deaths attributed to dietary factors: (IHME 2018; GBD 2017 Diet Collaborators et al. 2019).

12.4.3 Mitigation opportunities

GHG emissions from food systems can be reduced by targeting direct or indirect GHG emissions in the supply chain including enhanced carbon sequestration, by introducing sustainable production methods such as agro-ecological approaches which can reduce system-level GHG emissions of conventional food production and also enhance resilience (HLPE 2019), substituting food products with high GHG intensities with others of lower GHG intensities, by reducing food over-consumption or by reducing food loss and waste. The substitution of food products with others that are more sustainable and/or healthier is often called ‘dietary shift’.

Clark et al. (2020) showed that even if fossil fuel emissions were eliminated immediately, food system emissions alone would jeopardize the achievement of the 1.5ºC target and threaten the 2ºC target. They concluded that both demand-side and supply-side strategies are needed, including a shift to a diet with lower GHG intensity and rich in plant-based ‘conventional’ foods (e.g., pulses, nuts), or new food products that could support dietary shift. Such dietary shift needs to overcome socio-cultural, knowledge, and economic barriers to significantly achieve GHG mitigation (Section 12.4.5).

Food losses occur at the farm, post-harvest and food processing/wholesale stages of a food supply chain, while in the final retail and consumption stages the term food waste is used (HLPE 2014). Typically, food losses are linked to technical issues such as lack of infrastructure and storage while food waste is often caused by socio-economic and behavioural factors. Mitigation opportunities through reducing food waste and loss exist in all food supply chain stages and are described in the sub-sections below.

Food system mitigation opportunities are divided into five categories as given in Table 12.8:

- Food production from agriculture, aquaculture, and fisheries (Chapter 7.4 and Section 12.4.3.1)
- Controlled environment agriculture (Section 12.4.3.2)
- Emerging food production technologies (Section 12.4.3.3)
- Food processing industries (Section 12.4.3.4)
- Storage and distribution (Section 12.4.3.5)

Food system mitigation opportunities can be either incremental or transformative (Kugelberg et al. 2021). Incremental options are based on mature technologies, for which processes and causalities are understood, and their implementation is generally accepted by society. They do not require a substantial change in the way food is produced, processed, or consumed and might lead to a (slight) shift in production systems or preferences. Transformative mitigation opportunities have wider food system implications and usually coincide with a significant change in food choices. They are based on technologies that are not yet mature and are expected to require further innovation (Klerkx and Rose 2020), and/or mature technologies that might already be part of some food systems but are not yet widely accepted and have transformative potential if applied at large scale, e.g. consumption of insects (Raheem et al. 2019a). Many emerging technologies might be seen as a further step in agronomic development where land-intensive production methods relying on the availability of naturally available nutrients and water are successively replaced with crop variants and cultivation practices reducing these dependencies at the cost of larger energy input (Winiwarter et al. 2014). Others suggest a shift to agro-ecological approaches combining new scientific insights with local knowledge and cultural values (HLPE 2019). Food system transformation can lead to regime shifts or (fast) disruptions (Pereira et al. 2020) if driven by events that are out of control of private or public measures and have a 'crisis' character (e.g., BSE, Skuce et al. 2013).

Table 12.8 summarises the main characteristics of food system mitigation opportunities, their effect on GHG emissions, and associated co-benefits and adverse effects.

Table 12.8: Food system mitigation opportunities

$ Direct and indirect GHG effects: D – Direct emissions except emissions from energy use, E – Energy demand, M – Material demand, FL – food losses, FW – food waste; direction of effect on GHG mitigation: (+) increased mitigation, (0) neutral, (-) decreased mitigation.
& Co-benefits/Adverse effects: H - health aspects, A - Animal welfare, R - resource use, L - Land demand, E – Ecosystem services; (+) co-benefits, (-) adverse effects.

Food system mitigation options (I: incremental; T: transformative)		**Direct and indirect effect on GHG mitigation (+/0/-) $**	**Co-benefits / Adverse effects &**	**Source**
Food from agricultural, aquaculture and fisheries	(I) Dietary shift, in particular increased share of plant-based protein sources	D+ ↓ GHG footprint	A+ Animal welfare L+ Land sparing H+ Good nutritional properties, potentially ↓ risk from zoonotic diseases, pesticides and antibiotics	1-5
	(I/T) Digital agriculture	D+ ↑ logistics	L+ Land sparing R+ ↑ resource use efficiencies	6-7
	(T) Gene technology	D+ ↑ productivity or efficiency	H+ ↑ nutritional quality E0 ↓ use of agrochemicals; ↑ probability of off-target impacts	7-11
	(I) Sustainable intensific. land use optimisation	D+ ↓ GHG footprint E0 Mixed effects	L+ Land sparing R- Might ↑ pollution/biodiversity loss	7, 12
	(I) Agroecology	D+ ↓ GHG/area, positive micro-climatic effects E+ ↓ energy, possibly ↓ transport FL+ Circular approaches	E+ Focus on co-benefits/ecosystem services R+ Circular, ↑ nutrient and water use efficiencies	13-17
Controlled environment agriculture	(T) Soilless agriculture	D+ ↑ productivity, weather independent FL+ Harvest on demand E- Currently ↑ energy demand, but ↓ transport, building spaces can be used for renewable energy	R+ Controlled loops ↑ nutrient and water use efficiency L+ Land sparing H+ Crop breeding can be optimised for taste and/or nutritional quality	18-24

Food system mitigation options (I: incremental; T: transformative)		**Direct and indirect effect on GHG mitigation (+/0/-)** [$]	**Co-benefits / Adverse effects** [&]	**Source**
Emerging Food Production technologies	(T) Insects	D0 Good feed conversion efficiency FW+ Can be fed on food waste	H0 Good nutritional qualities but attention to allergies and food safety issues required	25-28
	(I/T) Algae and bivalves	D+ ↓ GHG footprints	A+ Animal welfare L+ Land sparing H+ Good nutritional qualities; risk of heavy metal and pathogen contamination R+ Biofiltration of nutrient-polluted waters	29-32
	(I/T) Plant-based alternatives to animal-based food products	D+ No emissions from animals, ↓ inputs for feed	A+ Animal welfare L+ Land sparing H+ Potentially ↓ risk from zoonotic diseases, pesticides and antibiotics; but ↑ processing demand	31-33
	(T) Cellular agriculture (including cultured meat, microbial protein)	D+ No emissions from animals, high protein conversion efficiency E- ↑ energy need FLW+ ↓ food loss & waste	A+ Animal welfare R+ ↓ emissions of reactive nitrogen or other pollutants H0 Potentially ↓ risk from zoonotic diseases, pesticides and antibiotics; ↑ research on safety aspects needed	3, 24, 34-42
Food processing and packaging	(I) Valorisation of by-products, FLW logistics and management	M+ Substitution of bio-based materials FL+ ↓ of food losses		43-44
	(I) Food conservation	FW+ ↓ of food waste E0 ↑ energy demand but also energy savings possible (e.g., refrigeration, transport)		45-46

Food system mitigation options (I: incremental; T: transformative)		Direct and indirect effect on GHG mitigation (+/0/-) $	Co-benefits / Adverse effects &	Source
	(I) Smart packaging and other technologies	FW+ ↓ of food waste M0 ↑ material demand and ↑ material-efficiency E0 ↑ energy demand; energy savings possible	H+ Possibly ↑ freshness/reduced food safety risks	46-49
	(I) Energy efficiency	E+ ↓ energy		50
Storage and distribution	(I) Improved logistics	D+ ↓ transport emissions FL+ ↓ losses in transport FW- Easier access to food could ↑ food waste		46-47 51-53
	(I) Specific measures to reduce food waste in retail and food catering	FW+↓ of food waste E+ ↓ downstream energy demand M+ ↓ downstream material demand		54-56
	(I) Alternative fuels/transport modes	D+ ↓ emissions from transport		
	(I) Energy efficiency	E+ ↓ energy in refrigeration, lightening, climatisation		57-58
	(I) Replacing refrigerants	D+ ↓ emissions from the cold chain		50, 59-60

[1] (McDermott and Wyatt 2017); [2] (Foyer et al. 2016); [3] (Semba et al. 2021); [4] (Weindl et al. 2020); [5] (Hertzler et al. 2020); [6] (Finger et al. 2019); [7] (Herrero et al. 2020); [8] Steinwand and Ronald (2020); [9] Zhang et al. (2020a); [10] (Ansari et al. 2020); [11] (Eckerstorfer et al. 2021); [12] (Folberth et al. 2020); [13] (HLPE 2019); [14] (Wezel et al. 2009); [15] (Van Zanten et al. 2018); [16] (van Zanten et al. 2019); [17] (van Hal et al. 2019); [18] (Beacham et al. 2019); [19] (Benke and Tomkins 2017); [20] (Gómez and Gennaro Izzo 2018); [21] (Maucieri et al. 2018); [22] (Rufí-Salís et al. 2020); [23] (Shamshiri et al. 2018); [24] (Graamans et al. 2018); [25] (Fasolin et al. 2019); [26] (Garofalo et al. 2019); [27] (Parodi et al. 2018); [28] (Varelas 2019); [29] (Gentry et al. 2020); [30] (Peñalver et al. 2020); [31] (Torres-Tiji et al. 2020); [32] (Willer and Aldridge 2020); [33] (Fresán et al. 2019); [34] (Mejia et al. 2019); [35] (Tuomisto 2019); [36] (Thorrez and Vandenburgh 2019); [37] (Tuomisto and Teixeira de Mattos 2011);

[38] (Mattick et al. 2015); [39] (Mattick 2018); [40] (Souza Filho et al. 2019); [41] Chriki and Hocquette (Chriki and Hocquette 2020); [42] Hadi and Brightwell (Hadi and Brightwell 2021); [43] (Göbel et al. 2015); [44] (Caldeira et al. 2020); [45] (Silva and Sanjuán 2019); [46] (FAO 2019a); [47] (Molina-Besch et al. 2019); [48] (Poyatos-Racionero et al. 2018); [49] (Müller and Schmid 2019); [50] (Niles et al. 2018); [51] (Lindh et al. 2016); [52] (Wohner et al. 2019); [53] (Bajželj et al. 2020); [54]. (Buisman et al. 2019); [55] (Albizzati et al. 2019); [56] (Liu et al. 2016); [57] (Chaomuang et al. 2017); [58] (Lemma et al. 2014); [59] (McLinden et al. 2017); [60] (Gullo et al. 2017).

12.4.3.1 Food from agriculture, aquaculture, and fisheries

Agricultural food production systems range from smallholder subsistence farms to large animal production factories, in open spaces, greenhouses, rural areas or urban settings.

Dietary shift. Studies demonstrate that a shift to diets rich in plant-based foods, particularly pulses, nuts, fruits & vegetables, such as vegetarian, pescatarian or vegan diets, could lead to substantial reduction of greenhouse gas emissions as compared to current dietary patterns in most industrialized countries, while also providing health benefits and reducing mortality from diet-related non-communicable diseases (Ernstoff et al. 2020; Semba et al. 2020; Theurl et al. 2020; Costa Leite et al. 2020; Chen et al. 2019; Jarmul et al. 2020; Willett et al. 2019; Bodirsky et al. 2020; Hamilton et al. 2021; Springmann et al. 2018a).

Pulses such as beans, chickpeas, or lentils, have a protein composition complementary to cereals, providing together all essential amino acids (McDermott and Wyatt 2017; Foyer et al. 2016). Bio-availability of proteins in foods is influenced by several factors, including amino-acid composition, presence of anti-nutritional factors, and preparation method (Hertzler et al. 2020; Weindl et al. 2020; Semba et al. 2021). Soy beans, in particular, have a well-balanced amino acid profile with high bio-availability (Leinonen et al. 2019). Pulses are part of most traditional diets (Semba et al. 2021) and supply up to 10-35% of protein in low-income countries, but consumption decreases with increasing income and they are globally only a minor share of the diet (McDermott and Wyatt 2017). Pulses play a key role in crop rotations, fixing nitrogen and breaking disease cycles, but yields of pulses are relatively low and have seen small yield increases relative to those of cereals (Barbieri et al. 2021; McDermott and Wyatt 2017; Foyer et al. 2016; Semba et al. 2021).

Technological innovations have made food production more efficient since the onset of agriculture (Winiwarter et al. 2014; Herrero et al. 2020). Emerging technologies include digital agriculture (using advanced sensors, big data), gene technology (crop bio-fortification, genome editing, crop innovations), sustainable intensification (automation of processes, improved inputs, precision agriculture) (Herrero et al. 2020), or multi-trophic aquaculture approaches (Sanz-Lazaro and Sanchez-Jerez 2020; Knowler et al. 2020), though literature on aquaculture and fisheries in the context of GHG mitigation is limited.

Such technologies may contribute to a reduction of GHG emission at the food system level enhanced provision of food, better consideration of ecosystem services, or contribute to nutrition sensitive agriculture, for example, by increasing the nutritional quality of staple crops, increasing the palatability of leguminous crops such as lupines, or the agronomic efficiency or resilience of crops with good nutritional characteristics.

For details on agricultural mitigation opportunities refer to Chapter 7.4.

12.4.3.2 Controlled-environment agriculture

Controlled-environment agriculture is mainly based on hydroponic or aquaponic cultivation systems that do not require soil. Aquaponics combine hydroponics with a re-circulating aquaculture compartment for integrated production of plants and fish (Junge et al. 2017; Maucieri et al. 2018), while aeroponics is a further development of hydroponics that replaces water as a growing medium with a mist of nutrient solution (Al-Kodmany 2018). Aquaponics could potentially produce proteins in urban farms, but the technology is not yet mature and its economic and environmental performance is unclear (O'Sullivan et al. 2019; Love et al. 2015).

Controlled-environmental agriculture is often undertaken in urban environments to take advantage of short supply chains (O'Sullivan et al. 2019), and might use abandoned buildings or be integrated in supermarkets, producing for example herbs 'on demand'.

Optimising growing conditions, hydroponic systems achieve higher yields than un-conditioned agriculture (O'Sullivan et al. 2019); and yields can be further enhanced in CO_2-enriched atmospheres (Armanda et al. 2019; Shamshiri et al. 2018). By using existing spaces or modular systems that can be vertically stacked, this technology minimises land demand, however it is energy intensive and requires large financial investments. So far, only a few crops are commercially produced in vertical farms, including lettuce and other leafy greens, herbs and some vegetables due to their short growth period and high value (Benke and Tomkins 2017; Beacham et al. 2019; O'Sullivan et al. 2019; Armanda et al. 2019). Through breeding, other crops could reach commercial feasibility, or crops with improved taste or nutritional characteristics can be grown (O'Sullivan et al. 2019).

In controlled-environment agriculture, photosynthesis is fuelled by artificial light through LEDs or a combination of natural light with LEDs. Control of the wave band and light cycle of the LEDs and micro-climate can be used to optimise photosynthetic activity, yield and crop quality (Gómez and Gennaro Izzo 2018; Shamshiri et al. 2018).

Co-benefits of controlled-environment agriculture include minimising water and nutrient losses as well as agro-chemical use (Farfan et al. 2019; Shamshiri et al. 2018; O'Sullivan et al. 2019; Armanda et al. 2019; Al-Kodmany 2018; Rufí-Salís et al. 2020) *(robust evidence, high agreement)*. Water is recycled in a closed system and additionally some plants generate fresh water by evaporation from grey or black water, and high nutrient use efficiencies are possible. Food production from controlled-environment agriculture is independent of weather conditions and able to satisfy some consumer demand for locally-produced fresh and diverse produce throughout the year (O'Sullivan et al. 2019; Al-Kodmany 2018; Benke and Tomkins 2017).

Controlled-environment agriculture is a very energy intensive technology (mainly for cooling) and its GHG intensity depends therefore crucially on the source of the energy. Options for reducing GHG intensity include reducing energy use through improved lighting and cooling efficiency or by employing low-carbon energy sources, potentially integrated into the building structure (Benke and Tomkins 2017).

Comprehensive studies assessing the GHG balance of controlled-environment agriculture are lacking. The overall GHG emissions from controlled-environment agriculture is therefore uncertain and depends on the balance of reduced GHG emissions from production and distribution and reduced land requirements, versus increased external energy needs.

12.4.3.3 Emerging foods and production technologies

A diverse range of novel food products and production systems are emerging, that are proposed to reduce GHG emissions from food production, mainly by replacing conventional animal-source food with alternative protein sources. Assessments of the potential of dietary changes are given in Chapter 5.3 and Chapter 7.4. Here, we assess the GHG intensities of emerging food production technologies. This includes products such as insects, algae, mussels and products from bio-refineries, some of which have been consumed in certain societies and/or in smaller quantities (Pikaar et al. 2018; Jönsson et al. 2019; Govorushko 2019; Raheem et al. 2019a; Souza Filho et al. 2019). The novel aspect considered here is the scale at which they are proposed to replace conventional food with the aim to reduce both negative health and environmental impact. To fully realize the health benefits, dietary shifts should also encompass a reduction in consumption of added sugars, salt, and saturated fats, and potentially harmful additives (Curtain and Grafenauer 2019; Fardet and Rock 2019; Petersen et al. 2021).

Meat analogues have attracted substantial venture capital, and production costs have dropped considerably in the last decade, with some reaching market maturity (Mouat and Prince 2018; Santo et al. 2020), but there is uncertainty whether they will 'disrupt' the food market or remain niche products. According to Kumar et al. (2017), the demand for plant-based meat analogues is expected to increase as their production is relatively cheap and they satisfy consumer demands with regard to health and environmental concerns as well as ethical and religious requirements. Consumer acceptance is still low for some options, especially insects (Aiking and de Boer 2019) and cultured meat (Siegrist and Hartmann 2020; Chriki and Hocquette 2020).

Insects. Farmed edible insects have a higher feed conversion ratio than other animals farmed for food, and have short reproduction periods with high biomass production rates (Halloran et al. 2016). Insects have good nutritional qualities (Parodi et al. 2018). They are suited as a protein source for both humans and livestock, with high protein contents and favourable fatty acid composition (Raheem et al. 2019b; Fasolin et al. 2019). If used as feed, they can grow on food waste and manure; if used as food, food safety concerns/regulations can restrict the use of manure (Raheem et al. 2019b) or food waste (Varelas 2019) as growing substrates, and the dangers of pathogenic or toxigenic microorganisms and incidences of anti-microbial resistance need to be managed (Garofalo et al. 2019).

Algae and bivalves have a high protein content and a favourable nutrient profile and can play a role in providing sustainable food. Bivalves are high in omega-3 fatty acids and vitamin B12 and therefore well-suited as replacement of conventional meats, and have a lower GHG footprint (Willer and Aldridge 2020; Parodi et al. 2018). Micro- and macro algae are rich in omega-3 and omega-6 fatty acids, anti-oxidants and vitamins (Peñalver et al. 2020; Parodi et al. 2018; Torres-Tiji et al. 2020). Kim et al. (2019) show that diets with modest amounts of low-food chain animals such as forage fish, bivalves, or insects have similar GHG intensities to vegan diets. Algae and bi-valves can be used to filter nutrients from waters, though care is required to avoid accumulation of hazardous substances (Willer and Aldridge 2020; Gentry et al. 2020).

Plant-based meat, milk and egg analogues. Demand for plant-based proteins is increasing and incentivising the development of protein crop varieties with improved agronomic performance and/or nutritional quality (Santo et al. 2020). There is also an emerging market for meat replacements based on plant proteins, such as pulses, cereals, soya, algae and other ingredients mainly used to imitate the taste, texture and nutritional profiles of animal-source food (Boukid 2021; Kumar et al. 2017). Currently, the majority of plant-based meat analogues is based on soy (Semba et al. 2021). While other products still serve a 'niche' market, their share is growing rapidly and some studies project a sizeable share within a decade (Kumar et al. 2017; Jönsson et al. 2019). In particular, plant-based milk alternatives have seen large increases in the market share (Jönsson et al. 2019). A LCA of 56 plant-based meat analogues showed mean GHG intensities (farm to factory) of 0.21–0.23 kgCO_2-eq per 100 g of product or 20 g of protein for all assessed protein sources (Fresán et al. 2019). Higher footprints were found in the meta-review by Santo et al. (2020). Including preparation, Meija et al. (2019) found higher emissions for burgers and sausages as compared to minced products.

Cellular agriculture. The use of fungi, algae and bacteria is an old process (beer, bread, yoghurt) and serves, among others, for the preservation of products. The concept of cellular agriculture (Mattick 2018) covers bio-technological processes that use micro-organisms to produce acellular (fermentation based cellular agriculture) or cellular products. Yeasts, fungi or bacteria can synthesise acellular products such as haem, milk and egg proteins, or protein-rich animal feed, other food ingredients, and pharmaceutical and material products (Rischer et al. 2020; Mendly-Zambo et al. 2021). Cellular products include cell tissues such as muscle cells to grow cultured meat, fish or other cells (Post 2012; Rischer et al. 2020) and products where the micro-organisms will be eaten themselves (Pikaar et al. 2018; Sillman et al. 2019; Schade et al. 2020). Single cell proteins, combined with photovoltaic electricity generation and direct air capture of carbon dioxide are proposed as highly land- and energy-efficient alternatives to plant-based protein (Leger et al. 2021). Some microbial proteins are produced in a 'bioreactor' and use Haber-Bosch nitrogen and vegetable sugars or atmospheric CO_2 as source of N and C (Simsa et al. 2019; Pikaar et al. 2018). Cultured meat is currently in the research stage and some challenges remain, such as the need for animal-based ingredients to ensure fast/effective growth of muscle cells, tissue engineering to create different meat products, the production at scale and at competitive costs, and regulatory barriers (Rubio et al. 2019; Stephens et al. 2018; Post et al. 2020; Post 2012; Tuomisto 2019). Only a few studies to date have quantified the GHG emissions of microbial proteins or cultured meat, suggesting GHG emissions at the level of poultry meat (Tuomisto and Teixeira de Mattos 2011; Mattick et al. 2015; Souza Filho et al. 2019; Tuomisto 2019).

A review of LCA studies on different plant-based, animal source and nine 'future food' protein sources (Parodi et al. 2018) concluded that insects, macro-algae, mussels, myco-proteins and cultured meat show similar GHG intensities per unit of protein (mean values ranging 0.3–3.1 kgCO_2-eq per 100 g of protein), comparable to milk, eggs, and tuna (mean values ranging 1.2–5.4 kgCO_2-eq per 100 g of protein); while *chlorella* and *spirulina* consume more energy per unit of protein and were associated with higher GHG emissions (mean values ranging 11–13 kgCO_2-eq per 100 g of protein). As the main source of GHG emissions from insects and cellular agriculture foods is energy consumption, their GHG intensity improves with increased use of low-carbon energy (Smetana et al. 2015; Pikaar et al. 2018; Parodi et al. 2018).

Future foods offer other benefits such as lower land requirements, controlled systems with reduced losses of water and nutrients, increased resilience, and possibly reduced hazards from pesticide and antibiotics use and zoonotic diseases, although more research is needed including allergenic and other safety aspects, and possibly reduced protein bioavailability (Tzachor et al. 2021; Alexander et al. 2017; Stephens et al. 2018; Parodi et al. 2018; Santo et al. 2020; Fasolin et al. 2019; Chriki and Hocquette 2020; Hadi and Brightwell 2021) *(medium evidence, high agreement).* Research is needed also on the effect of processing (Wickramasinghe et al. 2021), though a randomized crossover trial comparing appetizing plant foods with meat alternatives found several beneficial and no adverse effects from the consumption of the plant-based meats (Crimarco et al. 2020).

12.4.3.4 Food processing and packaging

Food processing includes preparation and preservation of fresh commodities (fruit and vegetables, meat, seafood and dairy products), grain milling, production of baked goods, and manufacture of pre-prepared foods and meals. Food processors range from small local operations to large multi-national food producers, producing food for local to global markets. The importance of food processing and preservation is particularly evident in developing countries lacking cold chains for the preservation and distribution of fresh perishable products such as fresh fish (Adeyeye 2017; Adeyeye and Oyewole 2016).

Mitigation in food processing largely focuses on reducing food waste and fossil energy usage during the processing itself, as well as in the transport, packaging and storage of food products for distribution and sale (Silva and Sanjuán 2019). Reducing food waste provides emissions savings by reducing wastage of primary inputs required for food production. Another mitigation route, contributing to the circular economy (Sections 12.6.1.2 and Cross-Working Group Box 3 in this Chapter), is by valorisation of food processing by-products through recovery of nutrients and/or energy. No global analyses of the emissions savings potential from the processing step in the value chain could be found.

Reduced food waste during food processing can be achieved by seeking alternative processing routes (Atuonwu et al. 2018), improved communication along the food value chain (Göbel et al. 2015), optimisation of food processing facilities, reducing contamination, and limiting damages and spillage (HLPE 2014). Optimisation of food packaging also plays an important role in reducing food waste, in that it can extend product shelf life; protect against damage during transport and handling; prevent spoilage; facilitate easy opening and emptying; and communicate storage and preparation information to consumers (Molina-Besch et al. 2019).

Developments in smart packaging are increasingly contributing to reducing food waste along the food value chain. Strategies for reducing the environmental impact of packaging include using less, and more sustainable, materials and a shift to re-usable packaging (Coelho et al. 2020). Active packaging increases shelf life through regulating the environment inside the packaging, including levels of oxygen, moisture and chemicals released as the food ages (Emanuel and Sandhu 2019). Intelligent packaging communicates information on the freshness of the food through indicator labels (Poyatos-Racionero et al. 2018), and data carriers can store information on conditions such as temperature along the entire food chain (Müller and Schmid 2019).

LCA can be used to evaluate the benefits and trade-offs associated with different processing or packaging types (Silva and Sanjuán 2019). Some options, such as aluminium, steel and glass, require high energy investment in manufacture when produced from primary materials, with significant savings in energy through recycling being possible (Camaratta et al. 2020). However, these materials are inert in landfill. Other packaging options, such as paper and biodegradable packaging, may require a lower energy investment during manufacture, but may require larger land area and can release methane when consigned to anaerobic landfill where there is no methane recovery. Nevertheless, packaging accounts for only 1-12% (typically around 5%) of the GHG emissions in the life cycle of a food system (Wohner et al. 2019; Crippa et al. 2021b), suggesting that its benefits can often outweigh the emissions associated with the packaging itself.

The second component of mitigation in food processing relates to reduction in fossil energy use. Opportunities include energy efficiency in processes (also discussed in Chapter 11.3), the use of heat and electricity from low-carbon energy sources in processing (Chapter 6), through off-grid thermal processing (sun drying, food smoking) and improving logistics efficiencies. Energy intensive processes with energy saving potential include milling and refining (oil seeds, corn, sugar), drying, and food safety practices such as sterilisation and pasteurisation (Niles et al. 2018). Packaging also plays a role: reduced transport energy can be achieved through reducing the mass of goods transported and improving packing densities in transport vehicles (Lindh et al. 2016; Molina-Besch et al. 2019; Wohner et al. 2019). Choice of packaging also influences refrigeration energy requirements during transport and storage.

12.4.3.5 Storage and distribution

Transport mitigation options along the supply chain include improved logistics, the use of alternative fuels and transport modes, and reduced transport distances. Logistics and alternative fuels and transport modes are discussed in Chapter 10. Transport emissions might increase with increasing demand for a diversity of foods as developing countries become more affluent. New technologies that enable food on demand or online food shopping systems might further increase emissions from food transport; however, the consequences are uncertain and might also entail a shift from individual traffic to bulk transport. The impact on food waste is also uncertain as more targeted delivery options could reduce food waste, but easier access to a wider range of food could also foster over-supply and increase food waste. Mitigation opportunities in food transport are inherently linked to decarbonisation of the transport sector (Chapter 10).

Retail and the food service industry are the main factors shaping the external food environment or 'food entry points'; they are the "physical spaces where food is obtained; the built environment that allows consumers to access these spaces" (HLPE 2017). These industries have significant influence on consumers' choices and can play a role in reducing GHG emissions from food systems. Opportunities are available for optimisation of inventories in response to consumer demands through advanced IT systems (Niles et al. 2018), and for discounting foods close to sell-by dates, which can both serve to reduce food spoilage and wastage (Buisman et al. 2019).

As one of the highest contributors to energy demand at this stage in the food value chain, refrigeration has received a strong focus in mitigation. Efficient refrigeration options include advanced refrigeration temperature control systems, and installation of more efficient refrigerators, air curtains and closed display fridges (Chaomuang et al. 2017). Also related to reducing emissions from cooling and refrigeration is the replacement of hydrofluorocarbons which have very high GWPs with lower GWP alternatives (Niles et al. 2018). The use of propane, isobutane, ammonia, hydrofluoroolefins and CO_2 (refrigerant R744) are among those that are being explored, with varying success (McLinden et al. 2017). In recent years, due to restrictions on high GWP-refrigerants, a considerable growth in the market availability of appliances and systems with non-fluorinated refrigerants has been seen (Eckert et al. 2021)

Energy efficiency alternatives generic to buildings more broadly are also relevant here, including efficient lighting, HVAC systems and building management, with ventilation being a particularly high energy user in retail, that warrants attention (Kolokotroni et al. 2015).

In developing countries particularly, better infrastructure for transportation and expansion of processing and manufacturing industries can significantly reduce food losses, particularly of highly perishable food (Niles et al. 2018; FAO 2019a).

12.4.4 Enabling food system transformation

Food system mitigation potentials in AFOLU are assessed in Chapter 7.4, and food system mitigation potentials linked to demand side measures are assessed in Chapter 5. Studies suggest that using supply and demand-side policies are implemented in combination makes ambitious mitigation targets easier to achieve (Latka et al. 2021a; Temme et al. 2020; Global Panel on Agriculture and Food Systems for Nutrition 2020; Clark et al. 2020) *(high agreement; limited evidence).*

The trends in the global and national food systems towards a globalisation of food supply chains and increasing dominance of supermarkets and large corporate food processors (Dries et al. 2004; Neven and Reardon 2004; Baker and Friel 2016; Andam et al. 2018; Popkin and Reardon 2018; Reardon et al. 2019; Pereira et al. 2020) has led to environmental, food insecurity and malnutrition problems. Studies therefore call for a transformation of current global and national food systems to solve these problems (Schösler and Boer 2018; McBey et al. 2019; Kugelberg et al. 2021). This has not yet been successful, including due to insufficient coordination between relevant food system policies (Weber et al. 2020) *(medium evidence, high agreement)*.

Different elements of food systems are currently governed by separate policy areas that in most countries scarcely interact or cooperate (iPES Food 2019; Termeer et al. 2018). This compartmentalisation makes the identification of synergetic and antagonistic effects difficult and faces the possibility of failure due to unintended and unanticipated negative impacts on other policy areas and consequently lack of agreement and social acceptance (Mylona et al. 2018; Brouwer et al. 2020; Mausch et al. 2020; Hebinck et al. 2021) (Section 12.4.5). This could be overcome through cooperation across several policy areas (Sections 12.6.2; 13.7), in particular agriculture, nutrition, health, trade, climate, environment policies, and an inclusive and transparent governance structure (Bhunnoo 2019; Diercks et al. 2019; Herrero et al. 2021; iPES Food 2019; Termeer et al. 2018; Mausch et al. 2020; Kugelberg et al. 2021), making use of potential spill-over effects (Kanter et al. 2020; OECD 2021).

Transformation of food systems may come from technological, social or institutional innovations that start as niches but can potentially lead to rapid changes, including changes in social conventions (Centola et al. 2018; Benton et al. 2019).

Where calories and ruminant animal-source food are consumed in excess of health guidelines, reduction of excess meat (and dairy) consumption is amongst the most effective measures to mitigate GHG emissions, with a high potential for environment, health, food security, biodiversity, and animal welfare co-benefits (Stylianou et al. 2021; Chai et al. 2019; Semba et al. 2020; Willett et al. 2019; Chen et al. 2019; Hamilton et al. 2021; Hedenus et al. 2014; Kim et al. 2019; Theurl et al. 2020; Springmann et al. 2018a) *(robust evidence, high agreement)*. Dietary changes are relevant for several SDGs, apart from SDG 13 (climate action), including SDG 2 (zero hunger), SDG 3 (good health and well-being), SDG 6 (clean water and sanitation), SDG 12 (responsible consumption and production), SDG 14 (life below water) and SDG 15 (life on land) (Bruce M et al. 2018; Vanham et al. 2019; Mbow et al. 2019; Herrero et al. 2021) (Section 12.6.1). However, behavioural change towards diets of lower environmental impact and higher nutritional qualities faces barriers both from agricultural producers and consumers (Apostolidis and McLeay 2016; Aiking and de Boer 2018; de Boer et al. 2018; Milford et al. 2019), and requires policy packages that combine informative instruments with behavioural, administrative and/or market-based instruments, and are attentive to the needs of, and engage, all food system stakeholders including civil society networks, and change the food environment (see Section 12.4.1) (Stoll-Kleemann and Schmidt 2017; Kraak et al. 2017; El Bilali 2019; Cornelsen et al. 2015; iPES Food 2019; Milford et al. 2019; Temme et al. 2020) *(robust evidence, high agreement)*.

Table 12.9 summarizes the implications of a range of policy instruments discussed in more detail in the following sub-sections and highlights the benefits of integrated policy packages. Furthermore, Table 12.9 assesses transformative potential, environmental effectiveness, feasibility, distributional effect, cost, and cost-benefits and trade-offs of individual policy instruments, as well as their potential role as part of coherent policy packages. Table 12.9 shows that information and behavioural policy instruments can have significant but small effects in changing diets *(robust evidence, medium agreement)*, but are mutually enforcing and might be essential to lower barriers and increase acceptance of market-based and administrative instruments *(medium evidence, high agreement)*.

The policy instruments are assessed in relation to shifting food consumption and production towards increased sustainability and health. This includes lowering GHG emissions, although not in all cases is this the primary focus of the instrument, and in some cases lowering GHG emission may not even be explicitly mentioned.

Table 12.9: Assessment of food system policies targeting (post-farm gate) food chain actors and consumers

	Level	Transformative potential	Environ. effective.	Feasibility	Distributional effects	Cost	Co-benefits[$] and adverse side-effect	Implications for coordination, coherence and consistency in policy package [&]
Integrated food policy packages	**NL**				**can be controlled**	**Cost efficient**	**+ balanced, addresses multiple sustainability goals**	Reduces cost of uncoordinated interventions; increases acceptance across stakeholders and civil society *(robust evidence, high agreement)*
Taxes on food products	GN				regressive	low[#1]	- unintended substitution effects	High enforcing effect on other food policies; higher acceptance if compensation or hypothecated taxes *(medium evidence, high agreement)*
GHG taxes on food	GN				regressive	low[#2]	-unintended substitution effects +high spillover effect	Supportive, enabling effect on other food policies, agricultural/fishery policies; requires changes in power distribution and trade agreements *(medium evidence, medium agreement)*
Trade policies	G				impacts global distribution	complex effects	+ counters leakage effects +/- effects on market structure and jobs	Requires changes in existing trade agreements *(medium evidence, high agreement)*
Investment into research & innovation	GN				none	medium	+ high spillover effect + converging with digital society	Can fill targeted gaps for coordinated policy packages (e.g. monitoring methods) *(robust evidence, high agreement)*
Food and marketing regulations	N					low		Can be supportive; might be supportive to realise innovation; voluntary standards might be less effective *(medium evidence, medium agreement)*

Organisational level procurement policies	NL					low	+ can address multiple sustainability goals	Enabling effect on other food policies; reaches large share of population *(medium evidence, high agreement)*
Sustainable food-based dietary guidelines	GN L				none	low	+ can address multiple sustainability goals	Little attention so far on environmental aspects; can serve as benchmark for other policies (labels, food formulation standards, etc.) *(medium evidence, medium agreement).*
Food labels/ information	GN L				education level relevant	low	+ empowers citizens + increases awareness + multiple objectives	Effective mainly as part of a policy package; incorporation of other objectives (e.g. animal welfare, fair trade...); higher effect if mandatory *(medium evidence, medium agreement).*
Nudges	NL				none	low	+ possibly counteracting information deficits in population subgroups	High enabling effect on other food policies, *(medium evidence, high agreement)*

Colour code: **Effect of measures:** negative , none/unclear , slightly positive , positive ; **Level:** G: global/multinational, N: national, L: local; **#1** Minimum level to be effective 20% price increase; **#2** Minimum level to be effective 50-80USD per tCO2eq. **$** In addition, all interventions are assumed to address health and climate change mitigation. **&** Requires coordination between policy areas, participation of stakeholders, transparent methods and indicators to manage trade-offs and prioritisation between possibly conflicting objectives; and suitable indicators for monitoring and evaluation against objectives.

12.4.4.1 Market based instruments

Taxes and subsidies: Food-based taxes have largely been implemented to reduce non-communicable diseases and sugar intake, particularly those targeting sugar-sweetened beverages (WHO 2019). Many health-related organisations recommend the introduction of such taxes to improve the nutritional quality of marketed products and consumers' diets (Park and Yu 2019; Wright et al. 2017; WHO 2019), even though the impacts of food taxes are complex due to cross-price and substitution effects and supplier reactions (Blakely et al. 2020; Gren et al. 2019; Cornelsen et al. 2015) and their regressive effect (WHO 2019). Subsidies and taxes are found to be effective in changing dietary behaviour at levels above 20% price increase (Niebylski et al. 2015; Mozaffarian et al. 2018; Nakhimovsky et al. 2016; Hagenaars et al. 2017; Cornelsen et al. 2015), even though longer term effects are scarcely studied (Cornelsen et al. 2015) and effects of sugar tax with tax rates lower than 20% have been observed for low-income groups (Temme et al. 2020).

Modelling results show only small consumption shifts with moderate meat price increases; and high price increases are required to reach mitigation targets, even though model predictions become highly uncertain due to lack of observational data (Zech and Schneider 2019; Fellmann et al. 2018; Bonnet et al. 2018; Mazzocchi 2017; Latka et al. 2021b). Taxes applied at the consumer level are found to be more effective than levying the taxes at the production side (Springmann et al. 2017).

Unilateral taxes on food with high GHG intensities have been shown to induce increases in net export flows, which could reduce global prices and increase global demand. Indirect effects on GHG mitigation therefore could be reduced by up to 70–90% of national results (Fellmann et al. 2018; Zech and Schneider 2019) *(limited evidence, high agreement)*. The global mitigation potential for GHG taxation of food products at 52 USD kgCO_2-eq^{-1} has been estimated at 1 GtCO_2-eq yr^{-1} (Springmann et al. 2017).

Studies have shown that taxes can improve the nutritional quality of diets and reduce GHG emissions from the food system, particularly if accompanied by other policies that increase acceptance and elasticity, and reduce regressive and distributional problems (Niebylski et al. 2015; Hagenaars et al. 2017; Mazzocchi 2017; Springmann et al. 2017; Wright et al. 2017; Henderson et al. 2018; Säll 2018; FAO et al. 2020; Penne and Goedemé 2020) *(robust evidence, high agreement)*.

Trade: Since the middle of the last century, global trade of agricultural products has contributed to boosting productivity and reducing commodity prices, while also incentivising national subsidies for farmers to remain competitive in the global market (Benton et al. 2019). Trade liberalisation has been coined as an essential element of sustainable food systems, and as one element required to achieve sustainable development, that can shift pressure to regions where the resources are less scarce (Traverso and Schiavo 2020; Wood et al. 2018). However, Clapp (2017) argues that the main economic benefit of trade liberalisation flows to large transnational firms. Benton and Bailey (2019) argue that low food prices in the second half of last century contributed to both yield and food waste increases, and to a focus on staple crops to the disadvantage of nutrient dense foods. However, global trade can also contribute to economic benefits such as jobs and income, reduce food insecurity and facilitate access to nutrients (Wood et al. 2018; Hoff et al. 2019; Traverso and Schiavo 2020; Geyik et al. 2021) and has contributed to increased food supply diversity (Kummu et al. 2020). The relevance of trade for food security, and adaptation and mitigation of agricultural production, has also been discussed in Mbow et al. (2019).

Trade policies can be used to protect national food system measures, by requiring front-of-package labels, or to impose border taxes on unhealthy products (Thow and Nisbett 2019). For example, in the frame of the Pacific Obesity Prevention in Communities (OPIC), the Fijian government implemented three measures (out of seven proposed) that eliminated import duties on fruits and vegetables, and imposed 15% import duties on unhealthy oils (Latu et al. 2018). Trade agreements, however, have the potential to undermine national efforts to improve public health (Unar-Munguía et al. 2019). GHG mitigation efforts in food supply chains can be counteracted by GHG leakage, with a general increase of environmental and social impact in developing countries exporting food products, and a decrease in the developed countries importing food products (Wiedmann and Lenzen 2018; Sandström et al. 2018; Fellmann et al. 2018). The demand for agricultural commodities has also been associated with tropical deforestation, though a robust estimate on the extent of embodied deforestation in food commodities is not available (Pendrill et al. 2019).

Investment into research & innovation: El Bilali (2019) assessed research gaps in the food system transition literature and found a need to develop comparative studies that enable the assessment of spatial variability and scalability of food system transitions. The author found also that the role of private industry and corporate business is scarcely researched, although they could play a major role in food system transitions.

The InterAcademy Partnership assessed how research can contribute to providing the required evidence and opportunities for food system transitions, with a focus on climate change impacts and mitigation (IAP 2018). The project builds on four regional assessments of opportunities and challenges on food and nutrition security in Africa (NASAC 2018), the Americas (IANAS 2018), Asia (AASSA 2018), and Europe (EASAC 2017). The Partnership concludes with a set of research questions around food systems, that need to be better understood: (i) how are sustainable food systems constituted in different contexts and at different scales, (ii) how can transition towards sustainable food systems be achieved, and (iii) how can success and failure be measured along sustainability dimensions including climate mitigation?

12.4.4.2 Regulatory and administrative instruments

Marketing regulations: Currently, 16 countries regulate marketing of unhealthy food to children, mainly on television and in schools (Taillie et al. 2019), and many other efforts are ongoing across the globe (European Commission 2019). The aim to counter the increase in obesity in children and target products high in saturated fats, trans-fatty acids, free sugars and/or salt (WHO 2010) was endorsed by 192 countries (Kovic et al. 2018). Nutrition and health claims for products are used by industry to increase sales, for example in the sport sector or for breakfast cereals. They can be informative, but can also be misleading if misused for promoting unhealthy food (Ghosh and Sen 2019; Sussman et al. 2019; Whalen et al. 2018).

Strong statutory marketing regulations can significantly reduce the exposure of children to, and sales of, unhealthy food compared with voluntary restrictions (Kovic et al. 2018; Temme et al. 2020). Data on effectiveness of marketing regulations with a broader food sustainability scope are not available. On the other hand, regulations that mobilise private investment into emerging food production technologies can be instrumental in curbing the cost and making them competitive (Bianchi et al. 2018a).

Voluntary sustainability standards: Voluntary sustainability standards are developed either by a public entity or by private organisations to respond to consumers' demands for social and environmental standards (Fiorini et al. 2019). For example, the Dutch "Green Protein Alliance", an alliance of government, industry, NGOs and academia, formulated a goal to shift the ratio of protein consumption from 60% animal source proteins currently to 40% by 2050 (Aiking and de Boer 2020), and Cool Food Pledge signatories (organisations that serve food, such as restaurants, hospitals and universities) committed to a 25% reduction in GHG emissions by 2030, compared with 2015 (Cool Food 2020). For firms, obtaining certification under such schemes can be costly, and costs are generally borne by the producers and/or supply chain stakeholders (Fiorini et al. 2019). The effectiveness of private voluntary sustainability standards is uncertain. Cazzolla Gatti et al. (2019) have investigated the effectiveness of the Roundtable on Sustainable Palm Oil on halting forest loss and habitat degradation in Southeast Asia and concluded that production of certified palm oil continued to lead to deforestation.

Organisational procurement: Green public procurement is a policy that aims to create additional demand for sustainable products (Bergmann Madsen 2018; Mazzocchi and Marino 2019) or decrease demand for less sustainable products (e.g., the introduction of "Meatless Monday" by the Norwegian Armed Forces (Milford and Kildal 2019; Cheng et al. 2018; Wilts et al. 2019; Gava et al. 2018)). To improve dietary choices, organisations can increase the price of unsustainable options while decreasing the price of sustainable ones, or employ information or choice architecture measures (Goggins and Rau 2016; Goggins 2018). Procurement guidelines exist at global, national, organisational or local levels (Neto and Gama Caldas 2018; Noonan et al. 2013). Procurement rules in schools or public canteens increase the accessibility of healthy food and can improve dietary behaviour and decrease purchases of unhealthy food (Cheng et al. 2018; Temme et al. 2020).

Food regulations: Novel foods based on insects, microbial proteins or cellular agriculture must go through authorisation processes to ensure compliance with food safety standards before they can be sold to consumers. Several countries have 'novel food' regulations governing the approval of foods for human consumption. For example, the European Commission, in its update of the Novel Food Regulation in 2015, expanded its definition of novel food to include food from cell cultures, or that produced from animals by non-traditional breeding techniques (EU 2015).

For animal product analogues, regulatory pathways and procedures (Stephens et al. 2018) and terminology issues (defining equivalence questions) (Carrenõ and Dolle 2018; Pisanello and Ferraris 2018) need clarification, as does their relation to religious rules (Chriki and Hocquette 2020).

Examples of legislation targeting food waste include the French ban on wasting food approaching best-before dates, requiring its donation to charity organisations (Global Alliance for the Future of Food 2020). In Japan, the Food Waste Recycling Law set targets for food waste recycling for industries in the food sector for 2020, ranging between 50% for restaurants and 95% for food manufacturers (Liu et al. 2016).

12.4.4.3 Informative instruments.

Sustainable Food-Based Dietary Guidelines: National food based dietary guidelines (FBDGs) provide science-based recommendations on food group consumption quantities. They are available for 94, mostly upper- and middle-income countries globally (Wijesinha-Bettoni et al. 2021), adapted to national cultural and socio-economic context, and can be used as a benchmark for food formulation standards or public and private food procurement, or to inform citizens (Bechthold et al. 2018; Temme et al. 2020). Most FBDGs are based on health considerations and only a few mention environmental sustainability aspects (Bechthold et al. 2018; Ritchie et al. 2018; Ahmed et al. 2019; Springmann et al. 2020). Implementation of FBDGs so far focuses largely in the education and health sectors, with few countries also using their potential for guiding food system policies in other sectors (Wijesinha-Bettoni et al. 2021).

Despite the fact that 1.5 billion people follow a vegetarian diet from choice or necessity and the position statements of various nutrition societies point out that vegetarian diets are adequate if well planned, few FBDGs give recommendations for vegetarian diets (Costa Leite et al. 2020). An increase in consumption of plant-based food is a recurring recommendation in FBDGs, though an explicit reduction or limit of animal source proteins is not often included, with the exception of red or processed meat (Temme et al. 2020). To account for changing dietary trends, however, FBDGs need to incorporate sustainability aspects (Herforth et al. 2019). A healthy diet respecting planetary boundaries has been proposed by Willett et al. (2019), though some authors have questioned the validity of the nutritional (Zagmutt et al. 2019) or environmental implications, such as water use (Vanham et al. 2020). In October 2019, 14 global cities pledged to adhere to this 'planetary health diet' (C40 Cities 2019).

Education on food/nutrition and environment: Some consumers are reluctant to adopt sustainable healthy dietary patterns because of a lack of awareness of the environmental and health consequences of what they eat, but also out of suspicion towards alternatives that are perceived as not 'natural' and that seem to be difficult to integrate into their daily dietary habits (Hartmann and Siegrist 2017; Stephens et al. 2018; McBey et al. 2019; Siegrist and Hartmann 2020) or simply lack of knowledge on how to prepare or eat unfamiliar foods (Aiking and de Boer 2020; El Bilali 2019; Temme et al. 2020). Misconceptions may contribute, for example, the belief that packaging or 'food miles' dominate the climate impact of food (Macdiarmid et al. 2016). However, spill-over effects can induce sustainable behaviour from 'entry points' such as concerns about food waste (El Bilali 2019). Early-life experiences are crucial determinants for adopting healthy and sustainable lifestyles (Bascopé et al. 2019; McBey et al. 2019), so improved understanding of sustainability aspects in the education of public health practitioners and in university education is proposed (Wegener et al. 2018). Investment in education, particularly of women (Vermeulen et al. 2020), might lower the barrier for stronger policies to be accepted and effective (McBey et al. 2019; Temme et al. 2020) *(medium evidence, high agreement).*

Food labels: Instruments to improve transparency and information on food sustainability aspects are based on the assumption of the 'rational' consumer. Information gives the necessary freedom of choice, but also the responsibility to make the 'right choice' (Kersh 2015; Bucher et al. 2016). Studies find a lack of consumer awareness about the link between own food choices and environmental effect (Grebitus et al. 2016; Leach et al. 2016; de Boer et al. 2018; Hartmann and Siegrist 2017) and so effective messaging is required to raise awareness and acceptance of potentially stricter food system policies.

Back-of-package labels usually provide detailed nutritional information (Temple 2019). Front-of-package labels simplify and interpret the information: for example, the traffic light system or the Nutri-Score label used in France (Kanter et al. 2018b) and the health star rating used in Australia and New Zealand (Shahid et al. 2020) provide an aggregate rating based on product attributes such as energy, sugar, saturated fat and fibre content; other labels warn against frequent consumption (e.g., in the 1990s Finland introduced a mandatory warning for products high in salt; the keyhole label was introduced in Sweden in 1989 (Storcksdieck genannt Bonsmann et al. 2020); and 'high in' (energy/ saturated fat/ sugar) labels were introduced in Chile in 2016 to reduce obesity (Corvalán et al. 2019)). Front-of-package labels serve also as an incentive to industry to produce healthier or more sustainable products, or can serve as a marketing strategy (Van Loo et al. 2014; Kanter et al. 2018b; Apostolidis and McLeay 2016). Carbon footprint labels can be difficult for consumers to understand (Hyland et al. 2017), and simple, interpretative summary indicators used in front-of-package labels (e.g., traffic lights) are more effective than more complex ones (Tørris and Mobekk 2019; Ikonen et al. 2019; Bauer and Reisch 2019; Temple 2019) (*robust evidence, high agreement)*. Reviews find mixed results but overall a positive effect of food labels in improving direct purchasing decisions (Sarink et al. 2016; Anastasiou et al. 2019; Shangguan et al. 2019; Hieke and Harris 2016; Temple 2019), and in raising level of awareness, thus possibly increasing success of other policy instruments (Al-Khudairy et al. 2019; Samant and Seo 2016; Miller et al. 2019; Temple 2019; Apostolidis and McLeay 2016) *(medium evidence, high agreement)*.

12.4.4.4 Behavioural instruments.

Choice architecture: Information is more effective if accompanied by reinforcement through structural changes or by changing the food environment, such as through product placement in supermarkets, to overcome the intention-behaviour gap (Bucher et al. 2016; Broers et al. 2017; Tørris and Mobekk 2019). Behavioural change strategies have also been shown to improve efficiencies of school food programs (Marcano-Olivier et al. 2020).

Environmental considerations rank behind financial, health, or sensory factors for determining citizens' food choices (Leach et al. 2016; Hartmann and Siegrist 2017; Rose 2018; Neff et al. 2018; Gustafson et al. 2019). There is evidence that choice architecture ("nudging") can be effective in influencing purchase decisions, but regulators do not normally explore this option (Broers et al. 2017). Examples of green nudging include making the sustainable option the default option, enhancing visibility, accessibility of, or exposure to, sustainable products and reducing visibility and accessibility of un-sustainable products, or increasing the salience of healthy sustainable choices through social norms or food labels (Bucher et al. 2016; Wilson et al. 2016; Broers et al. 2017; Al-Khudairy et al. 2019; Bauer and Reisch 2019; Ferrari et al. 2019; Weinrich and Elshiewy 2019; Cialdini and Jacobson 2021). Available evidence suggests that choice architecture measures are relatively inexpensive and easy to implement (Ferrari et al. 2019; Tørris and Mobekk 2019), they are a preferred solution if a restriction of choices is to be avoided (Wilson et al. 2016; Kraak et al. 2017; Vecchio and Cavallo 2019), and can be effective (Arno and Thomas 2016; Bianchi et al. 2018b; Cadario and Chandon 2018; Bucher et al. 2016) if embedded in policy packages (Wilson et al. 2016; Tørris and Mobekk 2019) *(medium evidence, high agreement)*.

Choice architecture measures are also facilitated by growing market shares of animal-free protein sources taken up by discount chains and fast food companies, that enhance visibility of new products and ease integration into daily life for consumers, particularly if sustainable products are similar to the products they substitute (Slade 2018). This effect can be further increased by media and role models (Elgaaied-Gambier et al. 2018).

12.4.5 Food Systems Governance

To support the policies outlined in Section 12.4.4, food system governance depends on the cooperation of actors across traditional sectors in several policy areas, in particular agriculture, nutrition, health, trade, climate, and environment (Termeer et al. 2018; Bhunnoo 2019; Diercks et al. 2019; iPES Food 2019; Rosenzweig et al. 2020b). Top-down integration, mandatory mainstreaming, or boundary-spanning structures like public-private partnerships may be introduced to promote coordination (Termeer et al. 2018). "Flow-centric" rather than territory-centric governance combined with private governance mechanisms has enabled codes of conduct and certification schemes (Eakin et al. 2017), for example the *Roundtable for Sustainable Palm Oil* (RSPO), as well as commodity chain transparency initiatives and platforms like *Trase* (Pirard et al. 2020; Meijaard et al. 2020). Trade agreements are an emerging arena of governance in which improving GHG performance may be an objective, and trade agreements can involve sustainability assessments.

Research on food system governance is mostly non-empirical or case study based, which means that there is limited understanding of which governance arrangements work in specific social and ecological contexts to produce particular food system outcomes (Delaney et al. 2018). Research has identified a number of desirable attributes in food systems governance, including adaptive governance (Termeer et al. 2018), a systems perspective (Whitfield et al. 2018), governance that considers food system resilience (Moragues-Faus et al. 2017; Ericksen 2008; Meyer 2020), transparency, participation of civil society (Duncan 2015; Candel 2014), and cross-scale governance (Moragues-Faus et al. 2017).

Food systems governance has multiple targets and objectives, not least contributing the achievement of the SDGs. GHG emissions from food systems can be impacted by both interventions targeted at different parts of the food system and interventions in other systems, such as reducing deforestation or promoting reforestation (Lee et al. 2019). For example, policies targeting health can contribute to diet shifts away from red meat, while also influencing GHG emissions (Springmann et al. 2018b; Semba et al. 2020); national and local food self-sufficiency policies may also have GHG impacts (Loon et al. 2019; Kriewald et al. 2019). Cross-sectoral governance could enhance synergies between reduced GHG emissions from food systems and other goals; however, integrative paradigms for cross-sectoral governance between food and other sectors have faced implementation challenges (Delaney et al. 2018). For example, in the late 2000s, the water-energy-food nexus emerged as a framework for cross-sectoral governance, but has not been well-integrated into policy (Urbinatti et al. 2020), perhaps because of perceptions that it is an academic concept, or that it takes a technical-administrative view of governance; simply adopting the paradigm is not sufficient to develop effective nexus governance (Cairns and Krzywoszynska 2016; Weitz et al. 2017; Pahl-Wostl et al. 2018). Other policy paradigms and theoretical frameworks that aim to integrate food systems governance include system transition, agroecology, multifunctionality in agriculture (Andrée et al. 2018), climate-smart agriculture (Taylor 2018) and the circular economy (Box 12.2). Cross-sectoral coordination on food systems and climate governance could be aided by internal recognition and ownership by agencies, dedicated budgets for cross-sectoral projects, and consistency in budgets (Pardoe et al. 2018); see also Box 12.1 and Box 12.2.

Food systems governance is still fragmented at national levels, which means that there may be a proliferation of efforts that cannot be scaled and are ineffective (Candel 2014). National policies can be complemented or possibly pioneered by initiatives at the local level (de Boer et al. 2018; Rose 2018). The city-region has been proposed as a useful focus for food system governance (Vermeulen et al. 2020); for example, the Milan Urban Food Policy Pact involves 180 global cities committed to integrative food system strategies (Candel 2019; Moragues-Faus 2021). Local food policy groups and councils that assemble stakeholders from government, civil society, and the private sector have formed trans-local networks of place-based local food policy groups, with over two hundred food policy councils worldwide (Andrée et al. 2018). However, the fluidity and lack of clear agendas and membership structures may hinder their ability to confront fundamental structural issues like unsustainable diets or inequities in food access (Santo and Moragues-Faus 2019).

Early characterisations of food systems governance featured a binary distinction between global and local scales, but this has been replaced by a relational approach where the local governance is seen a process that relies on the interconnections between scales (Lever et al. 2019). Cross-scalar governance is not simply an aggregation of local groups, but involves the telecoupling of distant systems; for example, transnational NGO networks have been able to link coffee retailers in the global North with producers in the global South via international NGOs concerned about deforestation and social justice (Eakin et al. 2017). Global governance institutions like the *Committee on World Food Security* can promote policy coherence globally and reinforce accountability at all levels (McKeon 2015), as can norm-setting efforts like the 'Voluntary Guidelines for the Responsible Governance of Tenure of Land, Fisheries and Forests' (FAO 2012). Global multi-stakeholder processes like the *UN Food Systems Summit* can foster the development of principles for guiding further actions based on sound scientific evidence. The European Commission's *Farm to Fork* strategy aims to promote policy coherence in food policy at EU and national levels, and could be the exemplar of a genuinely integrated food policy (Schebesta and Candel 2020).

START BOX 12.2 HERE

Box 12.2: Case Study: The Finnish Food2030 Strategy

Until 2016, the strategic goals of Finnish food policy were split between different programs and Ministries, resulting in fragmented national oversight of the Finnish food system. To enable policy coordination, a national food strategy was adopted in 2017 called Food2030 (Government of Finland 2017). Food2030 embodies a holistic food system approach and addresses multiple outcomes of the food system, including the competitiveness of the food supply chain and the development of local, organic and climate-friendly food production, as well as responsible and sustainable consumption.

The specific policy mix covers a range of policy instruments to enable changes in agro-food supply, processing and societal norms (Kugelberg et al. 2021). The government provides targeted funding and knowledge support to drive technological innovations on climate solutions to reduce emissions from food and in the agriculture, forestry and land-use sectors. In addition, the Finnish government applies administrative means, such as legislation, advice, guidance on public procurement and support schemes to diversify and increase organic food production to 20% of arable land, which in turn improve the opportunities of small-scale food production and steer public bodies to purchase local and organic food. The Finnish government applies educational and informative instruments to enable a shift to healthy and sustainable dietary behaviours. The policy objective is to reduce consumption of meat and replace it with other sources of protein, aligned with nutrition recommendations and avoiding food waste. The Ministry of Agriculture and Forestry, in collaboration with the Finnish Farmer's unions (MTK) and the Union of Swedish-speaking Farmers and Forest Owners in Finland (SLC), ran a two-year multi-media campaign in 2018 with key messages on sustainability, traceability and safety of the locally-produced food (Ministry of Agriculture and Forestry 2021). A "Food Facts website project" (Luke 2021), funded by the Ministry of Agriculture and Forestry in collaboration with the Natural Resources Institute Finland and the Finnish Food Safety Authority, helps to raise knowledge about food, which could shape responsible individual food behaviour, for example choosing local and sustainable foods and reducing food waste.

A critical enabler for developing a shared food system strategy across sectors and political party boundaries was the implementation of a one-year inclusive, deliberative and consensual stakeholder engagement process. A wide range of stakeholders could exert real influence during the vision-building process, resulting in strong agreement on key policy objectives, and subsequently an important leverage point to policy change (Kugelberg et al. 2021). Moreover, cross-sectoral coordination of Food2030 and the government's wider climate action programs are enabled by a number of institutional mechanisms and collaborative structures, for example the Advisory board for the food chain, formally established during the agenda-setting stage of Food2030, inter-ministerial committees to guide and assess policy implementation, and Our common dining table, a multi-stakeholder partnership that assembles 18 food system actors to engage in reflexive discussions about the Finnish food system.

Critical barriers to strategy and policy formulation include a lack of attention to integrated impact assessments (Kugelberg et al. 2021), which blurs a transparent overview of potential trade-offs and hidden conflicts. There were few policy evaluations from independent organisations to inform policymaking, reducing the opportunities for more progressive policy approaches. Monitoring and food policy evaluation is very close to the ministry in charge, which hampers critical thinking about policy measures (Hildén et al. 2014). In addition, there is a lack of standardised indicators covering the whole food system, which hinders comprehensive oversight of government's progress towards a sustainable food system (Kanter et al. 2018a). Some of the problems related to monitoring, reporting and verification (MRV) are typical for countries in the EU. To improve MRV will probably require structural changes, such as efforts to build up institutional capacity and application of new technology, development of standardised indicators covering the whole food system, regulations on transparency and verification, and mechanisms to enable reflexive discussions between business, farmers, public, NGOs and the government (Meadowcroft and Steurer 2018; Kanter et al. 2020).

END BOX 12.2 HERE

12.5 Land-related impacts, risks and opportunities associated with mitigation options

12.5.1 Introduction

This Section provides a cross-sectoral perspective on land occupation and related impacts, risks and opportunities associated with land-based mitigation options as well as mitigation options that are not designated land-based, yet occupy land. It builds on Chapter 7, that covers mitigation in agriculture, forestry and other land use (AFOLU), including future availability of biomass resources for mitigation in other sectors. It complements Section 12.4, which covers mitigation inherent in the food system, as well as Chapters 6, 9, 10 and 11 that cover mitigation in the energy, transport, building and industry sectors, and Chapters 3 and 4 that cover land and biomass use, primarily in energy applications, in mitigation and development pathways in the near- to mid-term (Chapter 4) and in pathways compatible with long-term goals (Chapter 3).

The deployment of climate change mitigation options often affects land and water conditions, and ecosystem capacity to support biodiversity and a range of ecosystem services (IPCC 2019; IPBES 2019) (r*obust evidence, high agreement*). It can increase or decrease terrestrial carbon stocks and sink strength, hence impacting the mitigation effect positively or negatively. As for any other land uses, impacts, risks and opportunities associated with mitigation options that occupy land depend on deployment strategy and on contextual factors that vary geographically and over time (Doelman et al. 2018; Hurlbert et al. 2019; Smith et al. 2019a; Wu et al. 2020) *(robust evidence, high agreement).*

The SR1.5 found that large areas may be utilised for A/R and energy crops in modelled pathways limiting warming to 1.5 C (Rogelj et al. 2018). The SRCCL investigated the implications of land-based mitigation measures for land degradation, food security and climate change adaptation. It focussed on identification of synergies and trade-offs associated with individual land-based mitigation measures (Smith et al. 2019b). In this section we expand beyond the scope of the SRCCL assessment to include also mitigation measures that occupy land while not considered land-based measures, we discuss ways to minimise potential adverse effects, and we consider the potential for synergies through integrating mitigation measures with other land uses, by applying a systems perspective that seeks to meet multiple objectives from multi-functional landscapes. Mitigation measures with zero land occupation, e.g., offshore wind and kelp farming, are not considered,

12.5.2 Land occupation associated with different mitigation options

As reported in Chapter 3, in scenarios limiting warming to 1.5ºC with no or limited overshoot, median area dedicated for energy crops in 2050 is 1.99 (0.56 to 4.82) Mkm^2 and median forest area increased 3.22 (-0.67 to 8.90) Mkm^2 in the period 2019-2050 (5-95 percentile range, scenario category C1). For comparison, the total global areas of forests, cropland and pasture (year 2015) are in the SRCCL estimated at about 40 Mkm^2, 15.6 Mkm^2, and 27.3 Mkm^2, respectively (additionally, 21 Mkm^2 of savannahs and shrublands are also used for grazing) (IPCC 2019). The SRCCL concluded that conversion of land for A/R and bioenergy crops at the scale commonly found in pathways limiting warming to 1.5°C or 2°C is associated with multiple feasibility and sustainability constraints, including land carbon losses *(high confidence)*. Pathways in which warming exceeds 1.5°C require less land-based mitigation, but the impacts of higher temperatures on regional climate and land, including land degradation, desertification, and food insecurity, become more severe (Smith et al. 2019b).

Depending on emission-reduction target, the portfolio of mitigation options chosen, and the policies developed to support their implementation, different land-use pathways can arise with large differences in resulting agricultural and forest area. Some response options can be more effective when applied together (Smith et al. 2019c); for example, dietary change, efficiency increases, and reduced wastage can reduce emissions as well as the pressure on land resources, potentially enabling additional land-based mitigation such as A/R and cultivation of biomass crops for biochar, bioenergy and other bio-based products. The SRCCL (Smith et al. 2019c) report that dietary change combined with reduction in food loss and waste can reduce the land requirement for food production by up to 5.8 Mkm^2 (0.8–2.4 Mkm^2 for dietary change; about 2 Mkm^2 for reduced post-harvest losses, and 1.4 Mkm^2 for reduced food waste (see also Sections 7.4 and 12.4 and Parodi et al. 2018; Springmann et al. 2018; Clark et al. 2020; Rosenzweig et al. 2020b). Stronger mitigation action in the near term targeting non-CO_2 emissions reduction and deployment of other CDR options (DACCS, enhanced weathering, ocean-based approaches, see 12.3) can reduce the land requirement for land-based mitigation (Obersteiner et al. 2018; van Vuuren et al. 2018).

Global Integrated Assessment Models (IAMs) provide insights about the roles of land-based mitigation in pathways limiting warming to 1.5°C or 2°C; interaction between land-based and other mitigation options such as wind and solar power; influence of land-based mitigation on food markets, land use and land carbon; and the role of BECCS vis- à-vis other CDR options (See Chapter 3). However, IAMs do not capture more subtle changes in land management and in the associated industrial/energy systems due to relatively coarse temporal and spatial resolution, and limited representation of land quality and feedstocks/management practices, interactions between biomass production and conversion systems, and local context, e.g., governance of land use (Daioglou et al. 2019; Rose et al. 2020; Welfle et al. 2020; Calvin et al. 2021). A/R have generally been modelled as forests managed for carbon sequestration alone, rather than forestry providing both carbon sequestration and biomass supply (Calvin et al. 2021). Because IAMs do not include options to integrate new biomass production with existing agricultural and forestry systems (Paré et al. 2016; Mansuy et al. 2018; Cossel et al. 2019; Braghiroli and Passarini 2020; Moreira et al. 2020; Djomo et al. 2020; Strapasson et al. 2020; Rinke Dias de Souza et al. 2021), they may over-estimate the total additional land area required for biomass production. On the other hand, some integrated biomass production systems may prove less attractive to landholders than growing biomass crops in large blocks, from logistic, economic, or other points of view (Ssegane et al. 2016; Busch 2017; Ferrarini et al. 2017).

Land occupation associated with mitigation options other than A/R and bioenergy is rarely quantified in global scenarios. Stressing large uncertainties (e.g., type of biomass used and share of solar PV integrated in buildings), (Luderer et al. 2019) modelled land occupation and land transformation associated with a range of alternative power system decarbonisation pathways in the context of a global 2°C climate stabilisation effort. On a per-MWh basis, bioelectricity with CCS was most land-intensive, followed by hydropower, coal with CCS, and concentrated solar power (CSP), which in turn were around five times as land-intensive as wind and solar photovoltaics (PV). A review of studies of power densities (electricity generation per unit land area) confirmed the relatively larger land occupation associated with biopower, although hydropower overlaps with biopower (van Zalk and Behrens 2018). This study also quantifies the low land occupation of nuclear energy, similar to fossil energy sources.

The land occupation of PV depends on the share of ground-mounted vs. buildings-integrated PV, the latter assumed to reach 75% share by 2050 in (Luderer et al. 2019). van de Ven et al. (2021) assumed a 3% share of urbanized land in 2050 available for rooftop PV, referring to (Capellán-Pérez et al. 2017; Dupont et al. 2020) reporting 2-3% availability of urbanized surface area, when considering factors such as roof slopes and shadows between buildings, and threshold relating to energy return on investment. Referring to (De Castro et al. 2013; MacKay 2013; Ong et al. 2013; Smil; Capellán-Pérez et al. 2017) state that land occupation of solar technologies is underestimated in studies assuming ideal conditions, with real occupation being five to ten times higher.

Production of hydrogen and synthetic hydrocarbon fuels via electrolysis and hydrocarbon synthesis is subject to conversion losses that vary depending on technology, system integration and source of carbon (Wulf et al. 2020; Ince et al. 2021)(cross-ref 6.4.4.1 and 6.4.5.1). Indicative electricity-to-hydrocarbon fuel efficiency loss is estimated at about 60% (Ueckerdt et al. 2021). The advantage of smaller land occupation for solar, wind, hydro and nuclear, compared with biomass-based options, is therefore smaller for hydrocarbon fuels than for electricity. Furthermore, biofuels are often co-produced with other bio-based products, which further reduces their land occupation, although comparisons are complicated by inconsistent approaches to allocating land occupation between co-products (Ahlgren et al. 2015; Czyrnek-Delêtre et al. 2017).

Note that comparisons on a per-MWh basis do not reflect the GHG emissions associated with the power options, or that the different options serve different functions in power systems. Reservoir hydropower and biomass-based dispatchable power can complement other balancing options (e.g., battery storage, grid extensions and demand-side management (Göransson and Johnsson 2018; Chapter 6) to provide power stability and quality needed in power systems with large amounts of variable electricity generation from wind and solar power plants. Furthermore, the requirements of transport in grids, pipelines etc. differ. For example, electricity from buildings-integrated PV can be used in the same location as it is generated.

The character of land occupation, and, consequently, the associated impacts (see 12.5.3), vary considerably among mitigation options and also for the same option depending on geographic location, scale, system design and deployment strategy (Olsson et al. 2019; Ioannidis and Koutsoyiannis 2020; van de Ven et al. 2021). Land occupation associated with different mitigation options can be large uniform areas (e.g., large solar farms, reservoir hydropower dams, or tree plantations), or more distributed occupation, such as wind turbines, solar PV, and patches of biomass cultivation integrated with other land uses in heterogeneous landscapes (Cacho et al. 2018; Jager and Kreig 2018; Correa et al. 2019; Englund et al. 2020a). Studies with broader scope, covering total land use requirement induced by plant infrastructure, provide a more complete picture of land footprints. For example, Wu et al. (2021) quantified a land footprint by the infrastructure of a pilot solar plant being three times the onsite land area. Sonter et al. (2020b) found significant overlap of mining areas (82% targeting materials needed for renewable energy production) and biodiversity conservation sites and priorities, suggesting that strategic planning is critical to address mining threats to biodiversity (See section 12.5.4) along with recycling and exploration of alternative technologies that use that use abundant minerals (See Chapter 11, Box Critical Minerals and The Future of Electro-Mobility and Renewables)

There are also situations where expanding mitigation is more or less decoupled from additional land use. The use of organic consumer waste, harvest residues and processing side-streams in the agriculture and forestry sectors can support significant volumes of bio-based products with relatively lower land-use change risks than dedicated biomass production systems (Hanssen et al. 2019; Spinelli et al. 2019; Mouratiadou et al. 2020). Such uses can provide waste management solutions while increasing the mitigation achieved from the land that is already used for agricultural and forest production. Bioenergy accounts for about 90% of renewable heat used in industrial applications, mainly in industries that can use their own biomass waste and residues, such as the pulp and paper industry, food industry, and ethanol production plants (see Chapters 6 and 11) (IEA 2020c). Heat and electricity produced on-site from side-streams but not needed for the industrial processes can be sold to other users, e.g., district heating systems. Surplus waste and residues can also be used to produce solid and liquid biofuels, or be used as feedstock in other industries such as the petrochemical industry (IRENA 2018; Lock and Whittle 2018; Thunman et al. 2018; IRENA 2019; Haus et al. 2020; Chapters 6 and 11). Electrification and improved process efficiencies can reduce GHG emissions and increase the share of harvested biomass that is used for production of bio-based products (Johnsson et al. 2019; Madeddu et al. 2020; Lipiäinen and Vakkilainen 2021; Rahnama Mobarakeh et al. 2021; Silva et al. 2021; Chapter 11). Besides integrating solar thermal panels and solar PV into buildings and other infrastructure, floating solar PV panels in, e.g., hydropower dams (Ranjbaran et al. 2019; Cagle et al. 2020; Haas et al. 2020; Lee et al. 2020; Gonzalez Sanchez et al. 2021), and over canals (Lee et al. 2020; McKuin et al. 2021) could decouple renewable energy generation from land use while simultaneously reducing evaporation losses and potentially mitigating aquatic weed growth and climate change impacts on water body temperature and stratification (Cagle et al. 2020; Exley et al. 2021; Gadzanku et al. 2021; Solomin et al. 2021).

12.5.3 Consequences of land occupation: biophysical and socioeconomic risks, impacts and opportunities

Land occupation associated with mitigation options can present challenges related to impacts and trade-offs, but can also provide opportunities and in different ways support the achievement of additional societal objectives, including adaptation to climate change. This section focuses on mitigation options that have significant risks, impacts and/or co-benefits with respect to land resources, food security and the environment. Bioenergy (with or without CCS), biochar and bio-based products require biomass feedstocks that can be obtained from purpose-grown crops, residues from conventional agriculture and forestry systems, or from biomass wastes, each with different implications for the land. Here we consider separately (i) "biomass-based systems", including dedicated biomass crops (e.g., perennial grasses, short rotation woody crops) and biomass produced as a co-product of conventional agricultural production (e.g. maize stover), and (ii) "afforestation/reforestation", including forests established for ecological restoration, plantations grown for forest products and agroforestry, where biomass may also be a co-product. We then discuss impacts and opportunities common to both systems, before considering impacts and opportunities associated with non-land-based mitigation options that nevertheless occupy land.

<u>Biomass-based systems</u>

Mitigation options that are based on the use of biomass, that is, bioenergy/BECCS, biochar, wood buildings, and other bio-based products, can have different positive and negative effects depending on the character of the mitigation option, the land use, the biomass conversion process, how the bio-based products are used and what other product they substitute (Leskinen et al. 2018; Howard et al. 2021; Myllyviita et al. 2021). The impacts of the same mitigation option can therefore vary significantly and the outcome in addition depends on previous land/biomass use (Cowie et al. 2021). As biomass-based systems commonly produce multiple food, material and energy products, it is difficult to disentangle impacts associated with individual bio-based products (Ahlgren et al. 2015; Djomo et al. 2017; Obydenkova et al. 2021). As for other mitigation options, governance has a critical influence on outcome, but larger scale and higher expansion rate generally translates into higher risk for negative outcomes such as competition for scarce land, freshwater and phosphorous resources, displacement of natural ecosystems, and diminishing capacity of agro-ecosystems to support biodiversity and essential ecosystem services, especially if produced without sustainable land management and in inappropriate contexts (Popp et al. 2017; Dooley and Kartha 2018; Hasegawa et al. 2018; Heck et al. 2018; Humpenöder et al. 2018; Fujimori et al. 2019; Hurlbert et al. 2019; IPBES 2019; Smith et al. 2019b; Drews et al. 2020; Hasegawa et al. 2020; Schulze et al. 2020; Stenzel et al. 2021) (*medium evidence, high agreement*).

Removal of crop and forestry residues can cause land degradation through soil erosion and decline in nutrients and soil organic matter (Cherubin et al. 2018) (*robust evidence, high agreement*). These risks can be reduced by retaining a proportion of the residues to protect the soil surface from erosion and moisture loss and maintain or increase soil organic matter (See Section 7.4.3.6); incorporating a perennial groundcover into annual cropping systems (Moore et al. 2019); and by replacing nutrients removed, such as by applying ash from bioenergy combustion plants (Kludze et al. 2013; Harris et al. 2015; Warren Raffa et al. 2015; de Jong et al. 2017) while safeguarding against contamination risks (Pettersson et al. 2020) (*medium evidence, high agreement*). Besides topography, soil, and climate conditions, sustainable residue removal rates also depend on the fate of extracted biomass. For example, to maintain the same level of soil organic carbon, the harvest of straw, if used for combustion (which would return no carbon to fields), was estimated to be only 26% of the rate that could be extracted if used for anaerobic digestion involving return of recalcitrant carbon to fields (Hansen et al. 2020). Similarly, biomass pyrolysis produces biochar which can be returned to soils to counteract C losses associated with biomass extraction (Joseph et al. 2021; Lehmann et al. 2021).

Expansion of biomass crops, especially monocultures of exotic species, can pose risks to natural ecosystems and biodiversity through introduction of invasive species and land use change, also impacting the mitigation value (*robust evidence, high agreement*) ((Liu et al. 2014; El Akkari et al. 2018). Cultivation of conventional oil, sugar, and starch crops tends to have larger negative impact than lignocellulosic crops (Núñez-Regueiro et al. 2020). Social and environmental outcomes can be enhanced through integration of suitable plants (such as perennial grasses and short rotation woody crops) into agricultural landscapes (within crop rotations or through strategic localization, e.g., as contour belts, along fencelines and riparian buffers). Such integrated systems can provide shelter for livestock, retention of nutrients and sediment, erosion control, pollination, pest and disease control, and flood regulation (*robust evidence, high agreement*) (See Figure 12.8 below; Box 12.3 and Cross-Working Group Box 3) (Berndes et al. 2008; Christen and Dalgaard 2013; Asbjornsen et al. 2014; Holland et al. 2015; Ssegane et al. 2015; Dauber and Miyake 2016; Milner et al. 2016; Ssegane and Negri 2016; Styles et al. 2016; Crews et al. 2018; Zalesny et al. 2019; Englund et al. 2020b, 2021). (Zheng et al. 2016; Osorio et al. 2019). (Ferrarini et al. 2017; Henry et al. 2018a). Many of the land use practices described above align with agroecology principles [cross ref WGII CCB Nature-Based Solutions, WGII 5.14 box 5.11] and can simultaneously contribute to climate change mitigation, climate change adaptation and reduced risk of land degradation (IPCC 2019) (*robust evidence, high agreement*).

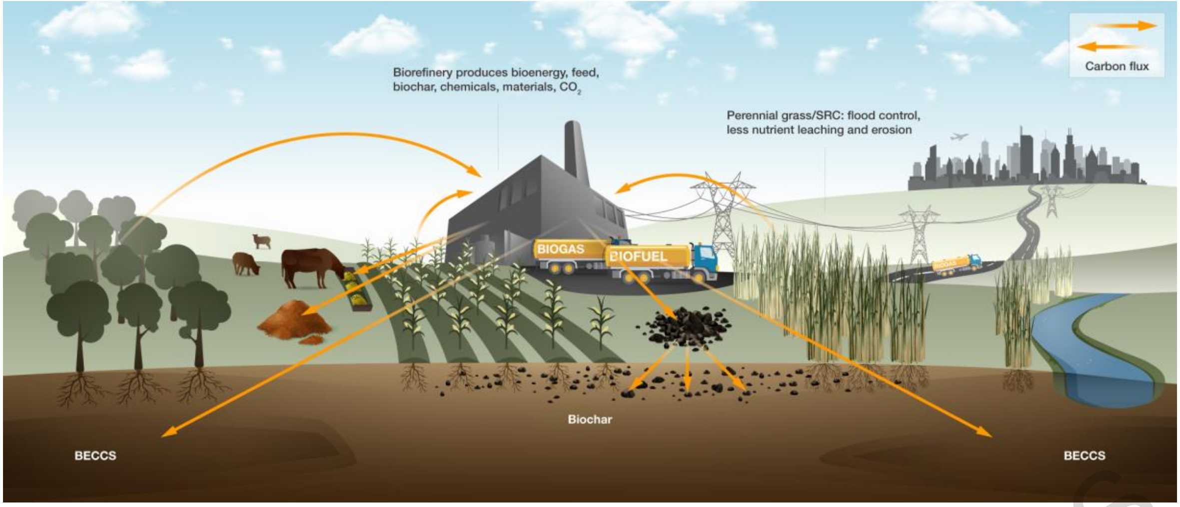


Figure 12.8 Overview of opportunities related to selected land-based climate change mitigation options

<u>Afforestation/Reforestation (A/R)</u>

When A/R activities comprise the establishment of natural forests, the risk to land is primarily associated with potential displacement of previous land use to new locations, which could indirectly cause land use change including deforestation (see Sections 7.4.2 and 7.6.2.4). A/R (including agroforestry) aimed at providing timber, fibre, biomass, non-timber resources and other ecosystem services can provide renewable resources to society and long-term livelihoods for communities. Forest management and harvesting regimes around the world will adjust in different ways as society seeks to meet climate goals. The outcome depends on forest type, climate, forest ownership and the character and product portfolio of the associated forest industry (Lauri et al. 2019; Favero et al. 2020). How forest carbon stocks, biodiversity, hydrology, etc. are affected by changes in forest management and harvesting in turn depends on both management practices and the characteristics of the forest ecosystems (Eales et al. 2018; Griscom et al. 2018; Kondo et al. 2018; Nieminen et al. 2018; Thom et al. 2018; Runting et al. 2019; Tharammal et al. 2019) (*robust evidence*, *medium agreement*). As described above, the GHG savings achieved from producing and using bio-based products will in addition depend on the character of existing societal systems, including technical infrastructure and markets, as this determines the product substitution patterns.

Environmental and socio-economic co-benefits are enhanced when ecological restoration principles are applied (Gann et al. 2019) along with effective planning at landscape level and strong governance (Morgan et al., 2020). For example, restoration of natural vegetation and establishing plantations on degraded land enable organic matter to accumulate in the soil and have potential to deliver significant co-benefits for biodiversity, land resource condition and livelihoods (See Box 12.3 and Cross-Working Group Box 3). Tree planting and agroforestry on cleared land can deliver biodiversity benefits (Seddon et al. 2009; Kavanagh and Stanton 2012; Law et al. 2014), with biodiversity outcomes influenced by block size, configuration and species mix (Cunningham et al. 2015; Paul et al. 2016)(*robust evidence, high agreement)*.

<u>Risks and opportunities common to biomass production and A/R mitigation options</u>

Biomass-based systems and A/R can contribute to addressing land degradation through land rehabilitation or restoration (Box 12.3). Land-based mitigation options that produce biomass for bioenergy/BECCS or biochar through land *rehabilitation* rather than land *restoration* imply a trade-off between production / carbon sequestration and biodiversity outcomes (Hua et al. 2016; Cowie et al.

2018). Restoration, seeking to establish native vegetation with the aim to maximise ecosystem integrity, landscape connectivity, and conservation of on-ground C stock, will have higher biodiversity benefits than rehabilitation measures (Lin et al. 2013). However, sequestration rate declines as forests mature, and the sequestered C is vulnerable to loss through disturbance such as wildfire, so there is a higher risk of reversal of the mitigation benefit compared with use of biomass for substitution of fossil fuels and GHG-intensive building materials (Russell and Kumar 2017; Dugan et al. 2018; Anderegg et al. 2020). Trade-offs between different ecosystem services, and between societal objectives including climate change mitigation and adaptation, can be managed through integrated landscape approaches that aim to create a mosaic of land uses, including conservation, agriculture, forestry and settlements (Freeman et al. 2015; Nielsen 2016; Reed et al. 2016; Sayer et al. 2017) where each is sited with consideration of land potential and socioeconomic objectives and context (Cowie et al. 2018) *(limited evidence, high agreement).*

Impacts of biomass production and A/R on the hydrological cycle and water availability and quality, depend on scale, location, previous land use/cover and type of biomass production system. For example, extraction of logging residues in forests managed for timber production has little effect on hydrological flows, while land use change to establish dedicated biomass production can have a significant effect (Teter et al. 2018; Drews et al. 2020). Deployment of A/R can affect temperature, albedo and precipitation locally and regionally, and can mitigate or enhance the effects of climate change in the affected areas (Stenzel et al. 2021b) and Section 7.2.4). A/R activities can increase evapotranspiration impacting groundwater and downstream water availability, but can also result in increased infiltration to groundwater and improved water quality (Farley et al. 2005; Zhang et al. 2016, 2017; Lu et al. 2018) and can be beneficial where historical clearing has caused soil salinisation and stream salinity (Farrington and Salama 1996; Marcar 2016). There is *limited evidence* that very large-scale land use or vegetation cover changes can alter regional climate and precipitation patterns, e.g., downwind precipitation depends on upwind evapotranspiration from forests and other vegetation (Keys et al. 2016; Ellison et al. 2017; van der Ent and Tuinenburg 2017).

Another example of beneficial effects includes perennial grasses and woody crops planted to intercept runoff and subsurface lateral flow, reducing nitrate entering groundwater and surface waterbodies (e.g Woodbury et al. 2018; Femeena et al. 2018; Griffiths et al. 2019). In India, (Garg et al. 2011) found desirable effects as a result of planting Jatropha on wastelands previously used for grazing (which could continue in the Jatropha plantations): soil evaporation was reduced, as a larger share of the rainfall was channelled to plant transpiration and groundwater recharge, and less runoff resulted in reduced soil erosion and improved downstream water conditions. Thus, adverse effects can be reduced and synergies achieved when plantings are sited carefully, with consideration of potential hydrological impacts (Davis et al. 2013).

Several biomass conversion technologies can generate co-benefits for land and water. Anaerobic digestion of organic wastes (e.g., food waste, manure) produces a nutrient-rich digestate and biogas that can be utilised for heating and cooking or upgraded for use in electricity generation, industrial processes, or as transportation fuel (See Chapter 6) (Parsaee et al. 2019; Hamelin et al. 2021). The digestate is a rich source of nitrogen, phosphorus and other plant nutrients, and its application to farmland returns exported nutrients as well as carbon (Cowie 2020b). Studies have identified potential risks, including Mn toxicity, Cu and Zn contamination, and ammonia emission, compared with application of undigested animal manure (Nkoa 2014). Although the anaerobic digestion process reduces pathogen risk compared with undigested manure feedstocks, it does not destroy all pathogens (Nag et al. 2019). Leakage of methane is a significant risk that needs to be managed, to ensure mitigation potential is achieved (Bruun et al. 2014). Anaerobic digestion of wastewater, such as sugarcane vinasse, reduces methane emissions and pollution loading as well as producing biogas (Parsaee et al. 2019).

Biorefineries can convert biomass to food, feed and biomaterials along with bioenergy (Aristizábal-Marulanda and Cardona Alzate 2019; Schmidt et al. 2019). Biorefinery plants are commonly characterised by high process integration to achieve high resource use efficiency, minimise waste production and energy requirements, and maintain flexibility towards changing markets for raw materials and products (Schmidt et al. 2019). Emerging technologies can convert biomass that is indigestible for monogastric animals or humans (e.g., algae, grass, clover or alfalfa) into food and feed products. For example, Lactic acid bacteria can facilitate the use of green plant biomass such as grasses and clover to produce a protein concentrate suitable for animal feed and other products for material or energy use (Lübeck and Lübeck 2019). Selection of crops suitable for co-production of protein feed along with biofuels and other bio-based products can significantly reduce the land conversion pressure by reducing the need to cultivate other crops (e.g., soybean) for animal feeding (Bentsen and Møller 2017; Solati et al. 2018). Thus, such solutions, using alternatives to high-input, high-emission grain-based feed, can enable sustainable intensification of agricultural systems with reduced environmental impacts (Jørgensen and Lærke 2016). The use of seaweed and algae as biorefinery feedstock can facilitate recirculation of nutrients from waters to agricultural land, thus reducing eutrophication while substituting purpose-grown feed (Thomas et al. 2021).

Pyrolysis can convert organic wastes, including agricultural and forestry residues, food waste, manure, poultry litter and sewage sludge, into combustible gas and biochar, which can be used as a soil amendment (Joseph et al. 2021; Schmidt et al. 2021; Chapter 7). Pyrolysis facilitates nutrient recovery from biomass residues, enabling return to farmland as biochar, noting, however, that a large fraction of nitrogen is lost during pyrolysis (Joseph et al. 2021). Conversion to biochar aids the logistics of transport and land application of materials such as sewage sludge, by reducing mass and volume, improving flow properties, stability and uniformity, and decreasing odour. Pyrolysis is well-suited for materials that may be contaminated with pathogens, microplastics, per- and polyfluoroalkyl substances, such as abattoir and sewage wastes, removing these risks, and reduces availability of heavy metals in feedstock (Joseph et al. 2021). Applying biochar to soil sequesters biochar-carbon for hundreds to thousands of years and can further increase soil carbon by reducing mineralisation of soil organic matter and newly added plant carbon (Singh et al. 2012; Wang et al. 2016a; Weng et al. 2017; Lehmann et al. 2021). Biochars can improve a range of soil properties, but effects vary depending on biochar properties, which are determined by feedstock and production conditions (Singh et al. 2012; Wang et al. 2016a), and on the soil properties where biochar is applied (e.g. Razzaghi et al. 2020). Biochars can increase nutrient availability, reduce leaching losses (Singh et al. 2010; Haider et al. 2017) and enhance crop yields particularly in infertile acidic soils (Jeffery et al. 2017), thus supporting food security under changing climate. Biochars can enhance infiltration and soil water-holding capacity, reducing runoff and leaching, increasing water retention in the landscape and improving drought tolerance and resilience to climate change (Quin et al. 2014; Omondi et al. 2016). (See Chapter 7 for review of biochar's potential contribution to climate change mitigation).

Both A/R and dedicated biomass production could have adverse impacts on food security and cause indirect land use change if deployed in locations used for food production (IPCC 2019). But the degree of impact associated with a certain mitigation option also depends on how deployment takes place and also the rate and total scale of deployment. The highest increases in food insecurity due to deployment of land-based mitigation are expected to occur in Sub-Saharan Africa and Asia (Hasegawa et al. 2018). The land area that could be used for bioenergy or other land-based mitigation options with low to moderate risks to food security depends on patterns of socioeconomic development, reaching limits between 1 and 4 million km^2 (IPCC 2019; Hurlbert et al. 2019; Smith et al. 2019c).

The use of less-productive, degraded/marginal lands has received attention as an option for biomass production and other land-based mitigation that can improve the productive and adaptive capacity of the lands (Liu et al. 2017; Qin et al. 2018; Dias et al. 2021; Kreig et al. 2021) (Section 7.4.4 and Cross-Working Group Box 3). The potential is however uncertain as biomass growth rates may be low, a variety of assessment approaches have been used, and the identification of degraded/marginal land as "available" has been contested, as much low productivity land is used informally by impoverished communities, particularly for grazing, or may be economically infeasible or environmentally undesirable for development of energy crops (Baka 2013, 2014; Haberl et al. 2013; Fritz et al. 2013) (*medium evidence, low agreement*).

As many of the SDGs are closely linked to land use, the identification and promotion of mitigation options that rely on land uses described above can support a growing use of bio-based products while advancing several SDGs, e.g., SDG2 "Zero hunger", SDG6 "Clean water and sanitation", SDG7 "Affordable and Clean Energy" and SDG15 "Life on Land" (Fritsche et al. 2017; IRP 2019; Blair et al. 2021). Policies supporting the target of Land Degradation Neutrality (LDN; SDG 15.3) encourage planning of measures to counteract loss of productive land due to unsustainable agricultural practices and land conversion, through sustainable land management, and strategic restoration and rehabilitation of degraded land (Cowie et al. 2018). LDN can thus be an incentive for land-based mitigation measures that build carbon in vegetation and soil, and can provide impetus for land use planning to achieve multifunctional landscapes that integrate land-based mitigation with other land uses (see Box 12.3). The application of sustainable land management practices that build soil carbon will enhance productivity and resilience of crop and forestry systems, thereby enhancing biomass production (Henry et al. 2018a). Non-bio-based mitigation options can enhance land-based mitigation: enhanced weathering, that is, adding ground silicate rock to soil to take up atmospheric CO_2 through chemical weathering (Section 12.3), could supply nutrients and alleviate soil acidity, thereby boosting productivity of biomass crops and A/R, particularly when combined with biochar application (Haque et al. 2019; De Oliveira Garcia et al. 2020; Buss et al. 2021) Land rehabilitation and enhanced landscape diversity through production of biomass crops could simultaneously contribute to climate change mitigation, climate change adaptation, addressing land degradation, increasing biodiversity and improving food security in the longer term (Mackey et al. 2020; Chapter 7).

<u>Wind power</u>

The land requirement and impacts (including visual and noise impacts) of on-shore wind turbines depend on the size and type of installation, and location (Ioannidis and Koutsoyiannis 2020). Wind power and agriculture can coexist in beneficial ways and wind power production on agriculture land is well established (Fritsche et al. 2017; Miller and Keith 2018a). Spatial planning and local stakeholder engagement can reduce opposition due to visual landscape impacts and noise (Frolova et al. 2019; Hevia-Koch and Ladenburg 2019). Repowering, i.e., replacing with higher capacity wind turbines, can mitigate additional land requirement associated with deployment towards higher share of wind in power systems (Pryor et al. 2020).

Mortality and disturbance risks to birds, bats and insects are major ecological concerns associated with wind farms (Thaxter et al. 2017; Cook et al. 2018; Heuck et al. 2019; Coppes et al. 2020; Choi et al. 2020; Fernández-Bellon 2020; Marques et al. 2020; Voigt 2021). Careful siting is critical (May et al. 2021), while painting blades to increase the visibility can also reduce mortality due to collision (May et al. 2020). Theoretical studies have suggested that wind turbines could lead to warmer night temperatures due to atmospheric mixing (Keith et al. 2004), later confirmed through observation (Zhou et al. 2013), although Vautard et al. (2014) found limited impact at scales consistent with climate policies. More recent studies report mixed results; indications that the warming effect could be substantial with widespread deployment Miller and Keith 2018b and conversely limited impacts on regional climate at 20% of US electricity from wind. (Pryor et al. 2020).

Solar power

As for wind power, land impacts of solar power depend on the location, size and type of installation (Ioannidis and Koutsoyiannis 2020). Establishment of large-scale solar farms could have positive or negative environmental effects at the site of deployment, depending on the location. Solar PV and CSP power installations can lock away land areas, displacing other uses (Mohan 2017). Solar PV can be deployed in ways that enhance agriculture: for example, Hassanpour Adeh et al. (2018) found that biomass production and water use efficiency of pasture increased under elevated solar panels. PV systems under development may achieve significant power generation without diminishing agricultural output (Miskin et al. 2019). Global mapping of solar panel efficiency showed that croplands, grasslands and wetlands are located in regions with the greatest solar PV potential (Adeh et al. 2019). Dual-use agrivoltaic systems are being developed that overcome previously recognised negative impact on crop growth, mainly due to shadows (Armstrong et al. 2016; Marrou et al. 2013b,a), thus facilitating synergistic co-location of solar photovoltaic power and cropping (Miskin et al. 2019; Adeh et al. 2019). Assessment of the potential for optimising deployment of solar PV and energy crops on abandoned cropland areas produced an estimate of the technical potential for optimal combination at 125 EJ per year (Leirpoll et al. 2021).

Deserts can be well-suited for solar PV and CSP farms, especially at low latitudes where global horizontal irradiance is high, as there is lower competition for land and land carbon loss is minimal, although remote locations may pose challenges for power distribution (Xu et al. 2016). Solar arrays can reduce the albedo, particularly in desert landscapes, which can lead to local temperature increases and regional impacts on wind patterns (Millstein and Menon 2011). Modelling studies suggest that large-scale wind and solar farms, for example in the Sahara (Li et al. 2018), could increase rainfall through reduced albedo and increased surface roughness, stimulating vegetation growth and further increasing regional rainfall (Li et al. 2018) (*limited evidence*). Besides impacts at the site of deployment, wind and solar power affect land through mining of critical minerals required by these technologies (Viebahn et al. 2015; McLellan et al. 2016; Carrara et al. 2020).

Nuclear power

Nuclear power has land impacts and risks associated with mining operations (Falck 2015; Winde et al. 2017; Srivastava et al. 2020) and disposal of spent fuel (IAEA 2006a; Ewing et al. 2016; Bruno et al. 2020), but the land occupation is small compared to many other mitigation options. Substantial volumes of water are required for cooling (Liao et al. 2016), as for all thermal power plants, but most of this water is returned to rivers and other water bodies after use (Sesma Martín and Rubio-Varas 2017). Negative impacts on aquatic systems can occur due to chemical and thermal pollution loading (Fricko et al. 2016; Raptis et al. 2016; Bonansea et al. 2020). The major risk to land from nuclear power is that a nuclear accident leads to radioactive contamination. An extreme example, the 1986 Chernobyl accident in Ukraine, resulted in radioactive contamination across Europe. Most of the fallout concentrated near Belarus, Ukraine and Russia, where some 125,000 km^2 of land (more than a third of which was in agricultural use) was contaminated. About 350,000 people were relocated away from these areas (Sovacool 2008; IAEA 2006b). About 116,000 people were permanently evacuated from the 4,200 km Chernobyl exclusion zone (IAEA 2006a). New reactor designs with passive and enhanced safety systems reduce the risk of such accidents significantly (Section 6.4.2.4). An example of alternatives to land reclamation for productive purposes, a national biosphere reserve has been established around Chernobyl to conserve, enhance and manage carbon stocks and biodiversity (Deryabina et al. 2015; Ewing et al. 2016), although invertebrate and plant populations area affected (Mousseau and Møller 2014, 2020).

Hydropower

Reservoir hydropower projects submerge areas as dams are established for water storage. Hydropower can be associated with significant and highly varying land occupation and carbon footprint (Poff and Schmidt 2016; Scherer and Pfister 2016a; Ocko and Hamburg 2019; dos Santos et al. 2017). The flooding of land causes CH_4 emissions due to the anaerobic decomposition of submerged vegetation and there is also a loss of C sequestration due to mortality of submerged vegetation. The size of GHG emissions depends on the amount of vegetation submerged. The carbon in accumulated sediments in reservoirs may be released to the atmosphere as CO_2 and CH_4 upon decommissioning of dams, and while uncertain, estimates indicate that these emissions can make up a significant part of the cumulative GHG emissions of hydroelectric power plants (Almeida et al. 2019; Moran et al. 2018; Ocko and Hamburg 2019). Positive radiative forcing due to lower albedo of hydropower reservoirs compared to surrounding landscapes can reduce mitigation contribution significantly (Wohlfahrt et al. 2021).

Hydropower can have high water usage due to evaporation from dams (Scherer and Pfister 2016b). Hydropower projects may impact aquatic ecology and biodiversity, necessitate the relocation of local communities living within or near the reservoir or construction sites and affect downstream communities (in positive or negative ways) (Barbarossa et al. 2020; Moran et al. 2018). Displacement as well as resettlement schemes can have both socio-economic and environmental consequences including those associated with establishment of new agricultural land (Nguyen et al. 2017; Ahsan and Ahmad 2016). Dam construction may also stimulate migration into the affected region, which can lead to deforestation and other negative impacts (Chen et al. 2015). Impacts can be mitigated through basin-scale dam planning that considers GHG emissions along with social and ecological effects (Almeida et al. 2019). Land occupation is minimal for run-of-river hydropower installations, but without storage they have no resilience to drought and installations inhibit dispersal and migration of organisms (Lange et al. 2018). Reservoir hydropower schemes can regulate water flows and reduce flood damage to agricultural production (Amjath-Babu et al. 2019). On the other hand, severe flooding due to failure of hydropower dams has caused fatalities, damage to infrastructure and loss of productive land (Lu et al. 2018; Zhang et al. 2016, 2017; Farley et al. 2005)(Farrington and Salama 1996; Marcar 2016; Kalinina et al. 2018).

12.5.4 Governance of land-related impacts of mitigation options

The land sector (Chapter 7) contributes to mitigation via emissions reduction and enhancement of land carbon sinks, and by providing biomass for mitigation in other sectors. Key challenges for governance of land-based mitigation include social and environmental safeguards (Larson et al. 2018; Sills et al. 2017; Duchelle et al. 2017); insufficient financing (Turnhout et al. 2017); capturing co-benefits; ensuring additionality, addressing non-permanence of carbon sequestration; monitoring, reporting, and verification (MRV) of emissions reduction and carbon dioxide removals; and avoiding leakage or spill-over effects. Governance approaches to addressing these challenges are discussed in section 7.6, and include MRV systems and integrity criteria for project-level emissions trading; payments for ecosystem services; land use planning and land zoning; certification schemes, standards and codes of practice.

With respect to renewable energy options that occupy land, the focus of governance has been directed to technological adoption and, public acceptance (Sequeira and Santos 2018), rather than land use. Recent work has found that spatial processes shape the emerging energy transition, creating zones of friction between global investors, national and local governments, and civil society (McEwan 2017;

Jepson and Caldas 2017). For example, hydropower and ground-based solar parks in India have involved enclosure of lands designated as degraded, displacing pastoral use by vulnerable communities, constituting forms of spatial injustice (Yenneti et al. 2016). Hydropower leads to dam-induced displacement, and though this can be addressed through compensation mechanisms, governance is complicated by a lack of transparency in resettlement data (Kirchherr et al. 2016, 2019). Renewable energy production is resulting in new land conflict frontiers where degraded land is framed as having mitigation value such as for palm oil production and wind power in Mexico (Backhouse and Lehmann 2020); land use conflict as well as impacts on wildlife from large-scale solar installations have also emerged in the southwestern United States (Mulvaney 2017). The renewable energy transition also involves the extraction of critical minerals used in renewable energy technologies, such as lithium and cobalt. Governance challenges include the lack of transparent greenhouse gas accounting for mining activities (Lee et al. 2020a), and threats to biodiversity from land disturbance, which require strategic planning to address (Sonter et al. 2020a). Strategic spatial planning is needed more generally to address trade-offs between using land for renewable energy and food: for example, agriculture can be co-located with solar photovoltaics (Barron-Gafford et al. 2019) or wind power (Miller and Keith 2018a). Integrative spatial planning can integrate renewable energy with not just agriculture, but mobility and housing (Hurlbert et al. 2019). Integrated planning is needed to avoid scalar pitfalls, and local and regional contextualised governance solutions need to be sited within a planetary frame of reference (Biermann et al. 2016). Greater planning and coordination are also needed to ensure co-benefits from land-based mitigation (see Box 12.3) as well as from CDR and efforts to reduce food systems emissions.

In emerging domains for governance such as land-based mitigation, global institutions, private sector networks and civil society organisations are also playing key roles in terms of norm-setting. The shared languages and theoretical frameworks, or cognitive linkages (Pattberg et al. 2018) that arise with polycentric governance can not only be helpful in creating expectations and establishing benchmarks for (in)appropriate practices where enforceable 'hard law' is missing (Karlsson-Vinkhuyzen et al. 2018; Gajevic Sayegh 2020), but can also form the basis of voluntary guidelines or niche markets (See also the case study in Box 12.3) However, the ability to apply participatory processes for developing voluntary guidelines and other participatory norm-setting endeavours varies from place to place. Social and cultural norms shape the ability of women, youth, and different ethnic groups to participate in governance fora, such as those around agroecological transformation (Anderson et al. 2019). Furthermore, establishing new norms alone does not solve structural challenges such as lack of access to food, confront power imbalances, or provide mechanisms to deal with uncooperative actors (Morrison et al. 2019).

START BOX 12.3 HERE

Box 12.3 Land Degradation Neutrality as a framework to manage trade-offs in land-based mitigation

The UNCCD introduced the concept of Land Degradation Neutrality (LDN), defined as "a state whereby the amount and quality of land resources necessary to support ecosystem functions and services and enhance food security remain stable or increase within specified temporal and spatial scales and ecosystems" (UNCCD 2015), and it has been adopted as a target of Goal 15 of the SDGs, Life on Land. At December 2020, 124 (mostly developing) countries have committed to pursue voluntary LDN targets.

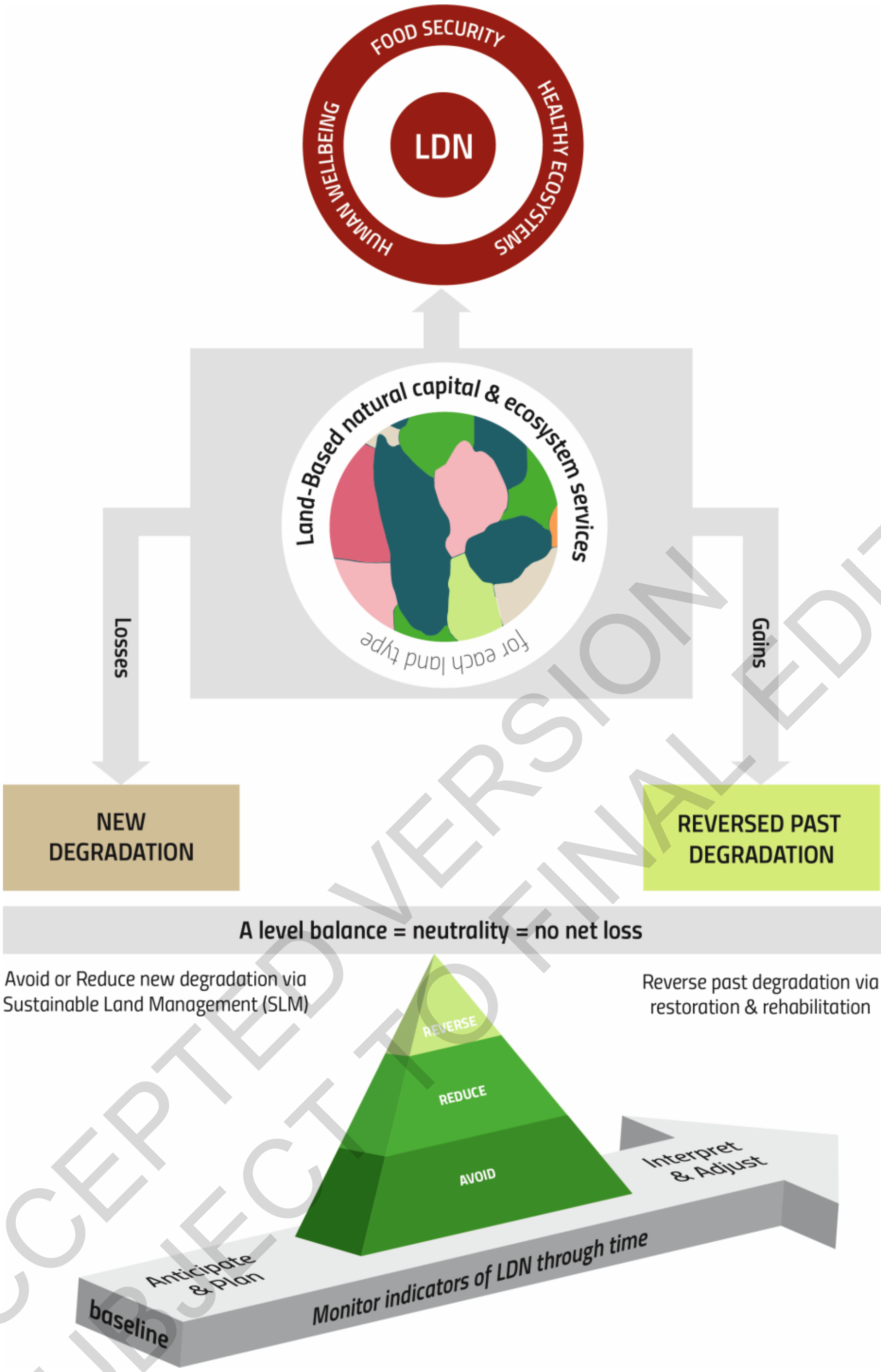
The goal of LDN is to maintain or enhance land-based natural capital, and its associated ecosystem services such as provision of food and regulation of water and climate, while enhancing the resilience of the communities that depend on the land. LDN encourages a dual-pronged approach promoting sustainable land management (SLM) to avoid or reduce land degradation, combined with strategic effort in land restoration and rehabilitation to reverse degradation on degraded lands and thereby deliver the target of "no net loss" of productive land (Orr et al. 2017).

In the context of LDN, land restoration refers to actions undertaken with the aim of reinstating ecosystem functionality, whereas land rehabilitation refers to actions undertaken with a goal of provision of goods and services (Cowie et al. 2018). Restoration interventions can include destocking to encourage regeneration of native vegetation; shelter belts of local species established from seed or seedlings, strategically located to provide wildlife corridors and link habitat; and rewetting drained peatland. "Farmer-managed natural regeneration" is a low-cost restoration approach in which regeneration of tree stumps and roots is encouraged, stabilising soil and enhancing soil nutrients and organic matter levels (Chomba et al. 2020; Lohbeck et al. 2020). Rehabilitation actions include establishment of energy crops, or afforestation with fast-growing exotic trees to sequester carbon or produce timber. Application of biochar can facilitate rehabilitation by enhancing nutrient retention and water holding capacity, and stimulating microbial activity (Cowie 2020a).

SLM, rehabilitation and restoration activities undertaken towards national LDN targets have potential to deliver substantial CDR through carbon sequestration in vegetation and soil. In addition, biomass production, for bioenergy or biochar, could be an economically viable land use option for reversing degradation, through rehabilitation. Alternatively, a focus on ecological restoration (Gann et al. 2019) as the strategy for reversing degradation will deliver greater biodiversity benefits.

Achieving neutrality requires estimating the likely impacts of land-use and land management decisions, to determine the area of land, of each land type, that is likely to be degraded (Orr et al. 2017). This information is used to plan interventions to reverse degradation on an equal area of the same land type. Therefore, pursuit of LDN requires concerted and coordinated efforts to integrate LDN objectives into land-use planning and land management, underpinned by sound understanding of the human-environment system and effective governance mechanisms.

Countries are advised to apply a landscape-scale approach for planning LDN interventions, in which land uses are matched to land potential, and resilience of current and proposed land uses is considered, to ensure that improvement in land condition is likely to be maintained (Cowie 2020a). A participatory approach that enables effective representation of all stakeholders is encouraged, to facilitate equitable outcomes from planning decisions, recognising that decisions on LDN interventions are likely to involve trade-offs between various environmental and socio-economic objectives (Schulze et al. 2021). Planning and implementation of LDN programmes provides a framework in which locally-adapted land-based mitigation options can be integrated with use of land for production, conservation and settlements, in multifunctional landscapes where trade-offs are recognised and managed, and synergistic opportunities are sought. LDN is thus a vehicle to focus collaboration in pursuit of the multiple land-based objectives of the multilateral environmental agreements and the SDGs.



Box 12.3, Figure 1 Schematic illustrating the elements of the Land Degradation Neutrality conceptual framework.
Source: (Cowie et al. 2018)

END BOX 12.3 HERE

Table 12.10 collates risks, impacts and opportunities associated with different mitigation options that occupy land.

Table 12.10 Summary of impacts, risks and co-benefits associated with land occupation by mitigation options considered in section 12.5.

Mitigation option	Impacts and risks	Opportunities for co-benefits
Non-bio-based options that may displace food production		
Solar farms	Land use competition; Loss of soil carbon; heat island effect (scale dependent) {12.5.3, 12.5.4}	Target areas unsuitable for agriculture such as deserts {12.5.3}
Hydropower (dams)	Land use competition, displacement of natural ecosystems, CO_2 and CH_4 emissions {12.5.3, 12.5.4}	Water storage (including for irrigation) and regulation of water flows; Pumped storage can store excess energy from other renewable generation sources. {12.5.3}
Non-bio-based options that can (to a varying degree) be integrated with food production		
Wind turbines	May affect local/regional weather and climate (scale dependent) Impact on wildlife and visual impacts {12.5.3}	Design and siting informed by t visual landscape impacts, relevant habitats, and flight trajectories of migratory birds. {12.5.3}
Solar panels	Land use competition {12.5.3}	Integration with buildings and other infrastructure. integration with food production is being explored {12.5.2}
Enhanced weathering	Disturbance at sites of extraction; Ineffective in low rainfall regions {12.3.1.2}	Increase crop yields and biomass production through nutrient supply and increasing pH of acid soils; synergies with biochar {12.5.3}
Bio-based options that may displace existing food production		
A/R	Land use competition, potentially leading to indirect land use change; reduced water availability; loss of biodiversity {12.5.3}	Strategic siting to minimise adverse impacts on hydrology, land use, biodiversity {12.5.3}
Biomass crops	Land use competition, potentially leading to indirect land use change; reduced water availability; reduced soil fertility; loss of biodiversity {12.5.3}	Strategic siting to minimise adverse impacts / enhance beneficial effects on land use, landscape variability, biodiversity, soil organic matter, hydrology and water quality {12.5.3}
Bio-based options that can (to a varying degree) be combined with food production		

Agroforestry	Competition with adjacent crops and pastures reduces yields {7.4.3.3}	Shelter for stock and crops, diversification, biomass production, increases soil organic matter and soil fertility. Increased biodiversity and perennial vegetation enhance beneficial organisms; can reduce need for pesticides {7.4.3.3, 12.5.3}
Soil carbon management in croplands and grasslands	Increase in nitrous oxide emissions if fertiliser used to enhance crop production; Reduced cereal production through increased crop legumes and pasture phases could lead to indirect land use change {7.4.3.1, 7.4.3.6}	Increasing soil organic matter improves soil health, increases crop and pasture yields, and resilience to drought, can reduce fertiliser requirement, nutrient leaching and need for land use change. {7.4.3.1}
Biochar addition to soil	Land use competition if biochar is produced from purpose-grown biomass. Loss of forest carbon stock and impacts on biodiversity if biomass is harvested unsustainably. {12.5.3}	Facilitate beneficial use of organic residues, to return nutrients to farmland. Increase land productivity to increase C sequestration in vegetation and soil. Increase nutrient-use efficiency, and reduce requirement for chemical fertiliser. {7.4.3.2, 12.5.3}
Harvest residue extraction and use for bioenergy, biochar and other bio-products	Decline in soil organic matter and soil fertility {12.5.3}	Retain portion of stubble; return nutrients e.g. as ash Utilising forest residues for bioenergy reduces fuel load and wildfire risk {7.4.3.2, 12.5.3}
Manure management (i.e., for biogas)	Risk of fugitive emissions Can contain pathogens {7.4.3.7, 12.5.3}	Biogas as renewable energy source. Apply digestate as soil amendment {12.5.3}
	Options that don't occupy land used for food production	
Management of organic waste (food waste, bio-solids, organic component of MSW)	Can contain contaminants (heavy metals, persistent organic pollutants, pathogens) {12.5.3}	Processing using anaerobic digestion or pyrolysis produces renewable gas and soil amendment, enabling return of nutrients to farmland. (note that some feedstock nitrogen is lost in pyrolysis) {12.5.3}
A/R and biomass production on degraded non-forested land (e.g., abandoned agricultural land)	High labour and material inputs can be needed to restore productivity on degraded land. Abandoned land can support informal grazing and have significant biodiversity value. Reduced water availability. {12.5.3}	Application of biochar can re-establish nutrient cycling; bioenergy crops can add organic matter, restoring soil fertility, and can remove heavy metals, enabling food production. {7.4.3.2, 12.5.3}

START CROSS-WORKING GROUP BOX 3 HERE

Cross-Working Group Box in Working Group II, Chapter 5

Cross-Working Group Box 3: Mitigation and Adaptation via the Bioeconomy

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Summary statement

The growing demand for biomass offers both opportunities and challenges to mitigate and adapt to climate change and natural resource constraints (high confidence). Increased technology innovation, stakeholder integration and transparent governance structures and procedures at local to global scales are key to successful bioeconomy deployment maximizing benefits and managing trade-offs (high confidence).

Limited global land and biomass resources accompanied by growing demands for food, feed, fibre, and fuels, together with prospects for a paradigm shift towards phasing out fossil fuels, set the frame for potentially fierce competition for land[2] and biomass to meet burgeoning demands even as climate change increasingly limits natural resource potentials (*high confidence*).

Sustainable agriculture and forestry, technology innovation in bio-based production within a circular economy and international cooperation and governance of global trade in products to reflect and disincentivize their environmental and social externalities, can provide mitigation and adaptation via bioeconomy development that responds to the needs and perspectives of multiple stakeholders to achieve outcomes that maximize synergies while limiting trade-offs *(high confidence)*.

Background

There is *high confidence* that climate change, population growth and changes in per capita consumption will increase pressures on managed as well as natural and semi-natural ecosystems, exacerbating existing risks to livelihoods, biodiversity, human and ecosystem health, infrastructure, and food systems (Conijn et al. 2018; IPCC 2018, 2019; Lade et al. 2020). At the same time, many global mitigation scenarios presented in IPCC assessment reports rely on large GHG emissions reduction in the AFOLU sector and concurrent deployment of reforestation/afforestation and biomass use in a multitude of applications (Rogelj et al. 2018; Hanssen et al. 2020; AR6 WG1 Ch.4 and Ch.5; AR6 WG3 Ch.3 and Ch.7).

Given the finite availability of natural resources, there are invariably trade-offs that complicate land-based mitigation unless land productivity can be enhanced without undermining ecosystem services (e.g., Obersteiner et al. 2016; Campbell et al. 2017; Conijn et al. 2018; Caron et al. 2018; WRI 2018; Heck et al. 2018; Smith et al. 2019). Management intensities can often be adapted to local conditions

FOOTNOTE[2] For lack of space the focus is on land only although the bioeconomy also includes sea-related bioresources.

with consideration of other functions and ecosystem services, but at a global scale the challenge remains to avoid further deforestation and degradation of intact ecosystems, in particular biodiversity-rich systems (AR6 WGII Cross-Chapter Box on NATURAL), while meeting the growing demands. Further, increased land-use competition can affect food prices and impact food security and livelihoods (To and Grafton 2015; Chakravorty et al. 2017), with possible knock-on effects related to civil unrest (Abbott et al. 2017; D'Odorico et al. 2018).

Developing new bio-based solutions while mitigating overall biomass demand growth

Many existing bio-based products have significant mitigation potential. Increased use of wood in buildings can reduce GHG emissions from cement and steel production while providing carbon storage (Churkina et al. 2020). Substitution of fossil fuels with biomass in manufacture of cement and steel can reduce GHG emissions where these materials are difficult to replace. Dispatchable power based on biomass can provide power stability and quality as the contribution from solar and wind power increases (See AR6 WG3 Ch.6), and biofuels can contribute to reducing fossil fuel emissions in the transport and industry sectors (See AR6 WG3 Ch.10 and Ch.11). The use of bio-based plastics, chemicals and packaging could be increased, and biorefineries can achieve high resource-use efficiency in converting biomass into food, feed, fuels and other bio-based products (Aristizábal-Marulanda and Cardona Alzate 2019; Schmidt et al. 2019). There is also scope for substituting existing bio-based products with more benign products. For example, cellulose-based textiles can replace cotton, which requires large amounts of water, chemical fertilizers and pesticides to ensure high yields.

While increasing and diversified use of biomass can reduce the need for fossil fuels and other GHG-intensive products, unfavourable GHG balances may limit the mitigation value. Growth in biomass use may in the longer term also be constrained by the need to protect biodiversity and ecosystems' capacity to support essential ecosystem services. Biomass use may also be constrained by water scarcity and other resource scarcities, and/or challenges related to public perception and acceptance due to impacts caused by biomass production and use. Energy conservation and efficiency measures and deployment of technologies and systems that do not rely on carbon, e.g., carbon-free electricity supporting, inter alia, electrification of transport as well as industry processes and residential heating (IPCC 2018; UNEP 2019), can constrain the growth in biomass demand when countries seek to phase out fossil fuels and other GHG-intensive products while providing an acceptable standard of living. Nevertheless, demand for bio-based products may become high where full decoupling from carbon is difficult to achieve (e.g., aviation, bio-based plastics and chemicals) or where carbon storage is an associated benefit (e.g., wood buildings, BECCS, biochar for soil amendments), leading to challenging trade-offs (e.g., food security, biodiversity) that need to be managed in environmentally sustainable and socially just ways.

Changes on the demand side as well as improvements in resource-use efficiencies within the global food and other bio-based systems can also reduce pressures on the remaining land resources. For example, dietary changes toward more plant-based food (where appropriate) and reduced food waste can provide climate change mitigation along with health benefits (Willett et al. 2019; WG3 Ch 7.4 and Ch 12.4) and other co-benefits with regard to food security, adaptation and land use (Smith et al. 2019a; Mbow et al. 2019; WG2 Ch.5). Advancements in the provision of novel food and feed sources (e.g., cultured meat, insects, grass-based protein feed and cellular agriculture) can also limit the pressures on finite natural resources (Parodi et al. 2018; Zabaniotou 2018; WG3 Ch 12.4).

Circular bioeconomy

Circular economy approaches (AR6 WG3 Ch 12.6) are commonly depicted by two cycles, where the biological cycle focuses on regeneration in the biosphere and the technical cycle focuses on reuse, refurbishment and recycling to maintain value and maximize material recovery (Mayer et al. 2019a). Biogenic carbon flows and resources are part of the biological carbon cycle, but carbon-based products can be included in, and affect, both the biological and the technical carbon cycles (Velenturf et al. 2019; Winans et al. 2017; Kirchherr et al. 2017). The integration of circular economy and bioeconomy principles has been discussed in relation to organic waste management (Teigiserova et al. 2020), societal transition and policy development (Bugge et al. 2019; European Commission 2018) as well as COVID-19 recovery strategies (Palahí et al. 2020). To maintain the natural resource base, circular bioeconomy emphasizes sustainable land use and the return of biomass and nutrients to the biosphere when it leaves the technical cycle.

Biomass scarcity is an argument for adopting circular economy principles for the management of biomass as for non-renewable resources. This includes waste avoidance, product reuse and material recycling, which keep down resource use while maintaining product and material value. However, reuse and recycling is not always feasible, e.g., when biofuels are used for transport and bio-based biodegradable chemicals are used to reduce ecological impacts where losses to the environment are unavoidable. A balanced approach to management of biomass resources could take departure in the carbon cycle from a value-preservation perspective and the possible routes that can be taken for biomass and carbon, considering a carbon budget defined by the Paris Agreement, principles for sustainable land use and natural ecosystem protection.

Land use opportunities and challenges in the bioeconomy

Analyses of synergies and trade-offs between adaptation and mitigation in the agriculture and forestry sectors show that outcomes depend on context, design and implementation, so actions have to be tailored to the specific conditions to minimize adverse effects (Kongsager 2018). This is supported in literature analyzing the nexus between land, water, energy and food in the context of climate change which consistently concludes that addressing these different domains together rather than in isolation would enhance synergies and reduce trade-offs (Obersteiner et al. 2016; D'Odorico et al. 2018; Soto Golcher and Visseren-Hamakers 2018; Momblanch et al. 2019; Froese et al. 2019).

Nature-based solutions addressing climate change can provide opportunities for sustainable livelihoods as well as multiple ecosystem services, such as flood risk management through floodplain restoration, saltmarshes, mangroves or peat renaturation (UNEP 2021; AR6 WGII Cross-Chapter Box on NATURAL). Climate-smart agriculture can increase productivity while enhancing resilience and reducing GHG emissions inherent to production (Lipper et al. 2014; Singh and Chudasama 2021). (Bell et al. 2018; FAO 2019b; Singh and Chudasama 2021) Similarly, climate-smart forestry considers the whole value chain and integrates climate objectives into forest sector management through multiple measures (from strict reserves to more intensively managed forests) providing mitigation and adaptation benefits (Nabuurs et al. 2018; Verkerk et al. 2020) (AR6 WG3 Ch 7.3).

Agroecological approaches can be integrated into a wide range of land management practices to support a sustainable bioeconomy and address equity considerations (HLPE 2019). Relevant land-use practices, such as agroforestry, intercropping, organic amendments, cover crops and rotational grazing, can provide mitigation and support adaption to climate change via food security, livelihoods, biodiversity and health co-benefits (Bezner Kerr et al. 2019; Bharucha et al. 2020; Clark et al. 2019b; D'Annolfo et al. 2017; Garibaldi et al. 2016; Ponisio et al. 2015; Renard and Tilman 2019; HLPE 2019; Sinclair et al. 2019; Córdova et al. 2019; Mbow et al. 2019; Bezner Kerr et al. 2021; and AR6 WGII Chapter 2 Cross-Chapter Box NATURAL). Strategic integration of appropriate biomass production systems into agricultural landscapes can provide biomass for bioenergy and other bio-based products while providing co-benefits such as enhanced landscape diversity, habitat quality, retention of nutrients and sediment, erosion control, climate regulation, flood regulation, pollination and biological pest and disease control (Christen and Dalgaard 2013; Asbjornsen et al. 2014; Englund et al. 2020; Cacho et al. 2018; Dauber and Miyake 2016; Holland et al. 2015; Milner et al. 2016; Ssegane et al. 2015; Ssegane and Negri 2016; Styles et al. 2016; Zalesny et al. 2019; Zumpf et al. 2017; HLPE 2019; Cubins et al. 2019; Alam and Dwivedi 2019; Olsson et al. 2019) (AR6 WGIII Chapter 12 Box 12.3 on UNCCD-LDN). Such approaches can help limit environmental impacts from intensive agriculture while maintaining or increasing land productivity and biomass output.

Cross-Working Group Box 3, Figure 1 Left: High-input intensive agriculture, aiming for high yields of a few crop species, with large fields and no semi-natural habitats. Right: Agroecological agriculture, supplying a range of ecosystem services, relying on biodiversity and crop and animal diversity instead of external inputs, and integrating plant and animal production, with smaller fields and presence of semi-natural habitats.

Credit: Jacques Baudry (left); Valérie Viaud (right), published in (van der Werf et al. 2020)

Transitions from conventional to new biomass production and conversion systems include challenges related to cross-sector integration and limited experience with new crops and land use practices, including needs for specialized equipment (Thornton and Herrero 2015; HLPE 2019; AR6 WG2 Section 5.10). Introduction of agroecological approaches and integrated biomass/food crop production can result in lower food crop yields per hectare, particularly during transition phases, potentially causing indirect land use change, but can also support higher and more stable yields, reduce costs, and increase profitability under climate change (Muller et al. 2017; Seufert and Ramakutty 2017; Barbieri et al. 2019; HLPE 2019; Sinclair et al. 2019; Smith et al. 2019a, 2020). Crop diversification, organic amendments, and biological pest control (HLPE 2019) can reduce input costs and risks of occupational pesticide exposure and food and water contamination (González-Alzaga et al. 2014; EFSA 2017; Mie et al. 2017), reduce farmers' vulnerability to climate change (e.g., droughts and spread of pests and diseases affecting plant and animal health (Delcour et al. 2015; FAO 2020) and enhance provisioning and sustaining ecosystem services, such as pollination (D'Annolfo et al. 2017; Sinclair et al. 2019).

Barriers toward wider implementation include absence of policies that compensate land owners for providing enhanced ecosystem services and other environmental benefits, which can help overcome short term losses during the transition from conventional practices before longer term benefits can accrue. Other barriers include limited access to markets, knowledge gaps, financial, technological or labour constraints, lack of extension support and insecure land tenure (Jacobi et al. 2017; Kongsager 2017; Hernández-Morcillo et al. 2018; Iiyama et al. 2018; HLPE 2019). Regional-level agroecology transitions may be facilitated by co-learning platforms, farmer networks, private sector, civil society groups, regional and local administration and other incentive structures (e.g. price premiums, access to credit, regulation) (Coe et al. 2014; Pérez-Marin et al. 2017; Mier y Terán Giménez Cacho et al. 2018;

HLPE 2019; Valencia et al. 2019; SAEPEA 2020). With the right incentives, improvements can be made with regard to profitability, making alternatives more attractive to land owners.

Governing the solution space

Literature analysing the synergies and trade-offs between competing demands for land suggest that solutions are highly contextualized in terms of their environmental, socioeconomic and governance-related characteristics, making it difficult to devise generic solutions (Haasnoot et al. 2020). Aspects of spatial and temporal scale can further enhance the complexity, for instance where transboundary effects across jurisdictions or upstream-downstream characteristics need to be considered, or where climate change trajectories might alter relevant biogeophysical dynamics (Postigo and Young 2021). Nonetheless, there is broad agreement that taking the needs and perspectives of multiple stakeholders into account in a transparent process during negotiations improves the chances of achieving outcomes that maximize synergies while limiting trade-offs (Ariti et al. 2018; Metternicht 2018; Favretto et al. 2020; Kopáček 2021; Muscat et al. 2021). Yet differences in agency and power between stakeholders or anticipated changes in access to or control of resources can undermine negotiation results even if there is a common understanding of the overarching benefits of more integrated environmental agreements and the need for greater coordination and cooperation to avoid longer-term losses to all (Aarts and Leeuwis 2010; Weitz et al. 2017). There is also the risk that strong local participatory processes can become disconnected from broader national plans, and thus fail to support the achievement of national targets. Thus, connection between levels is needed to ensure that ambition for transformative change is not derailed at local level (Aarts and Leeuwis 2010; Postigo and Young 2021).

Decisions on land uses between biomass production for food, feed, fibre or fuel, as well as nature conservation or restoration and other uses (e.g., mining, urban infrastructure), depend on differences in perspectives and values. Because the availability of land for diverse biomass uses is invariably limited, setting priorities for land-use allocations therefore first depends on making the perspectives underlying what is considered as 'high-value' explicit (Fischer et al. 2007; Garnett et al. 2015; De Boer and Van Ittersum 2018; Muscat et al. 2020). Decisions can then be made transparently based on societal norms, needs and the available resource base. Prioritization of land-use for the common good therefore requires societal consensus-building embedded in the socioeconomic and cultural fabric of regions, societies and communities. Integration of local decision-making with national planning ensures local actions complement national development objectives.

International trade in the global economy today provides important opportunities to connect producers and consumers, effectively buffering price volatilities and potentially offering producers countries access to global markets, which can be seen as an effective adaptation measure (Baldos and Hertel 2015; Costinot et al. 2016; Hertel and Baldos 2016; Gouel and Laborde 2021; AR6 WG2 Ch 5.11). But there is also clear evidence that international trade and the global economy can enhance price volatility, lead to food price spikes and affect food security due to climate and other shocks, as seen recently due to the COVID-19 pandemic (Cottrell et al. 2019; WFP-FSIN 2020; Verschuur et al. 2021; AR6 WG2 Ch 5.12). The continued strong demand for food and other bio-based products, mainly from high- and middle-income countries, therefore requires better cooperation between nations and global governance of trade to more accurately reflect and disincentivize their environmental and social externalities. Trade in agricultural and extractive products driving land-use change in tropical forest and savanna biomes is of major concern because of the biodiversity impacts and GHG emissions incurred in their provision (Hosonuma et al. 2012; Forest Trends 2014; Smith et al. 2014; Henders et al. 2015; Curtis et al. 2018; Pendrill et al. 2019; Seymour and Harris 2019; Kissinger et al. 2021; AR6 WG2 CCP Tropical Forests).

In summary, there is significant scope for optimizing use of land resources to produce more biomass while reducing adverse effects (*high confidence*). Context-specific prioritisation, technology innovation in bio-based production, integrative policies, coordinated institutions and improved governance mechanisms to enhance synergies and minimize trade-offs can mitigate the pressure on managed as well as natural and semi-natural ecosystems (*medium confidence*). Yet, energy conservation and efficiency measures, and deployment of technologies and systems that do not rely on carbon-based energy and materials, are essential for mitigating biomass demand growth as countries pursue ambitious climate goals (*high confidence*).

END CROSS-WORKING BOX 3 HERE

12.6 Other cross-sectoral implications of mitigation

This section presents further cross-sectoral considerations related to GHG mitigation. Firstly, various cross-sectoral perspectives on mitigation actions are presented. Then, sectoral policy interactions are presented. Finally, implications in terms of international trade spill-over effects and competitiveness, and finance flows and related spill-over effects at the sectoral level are addressed.

12.6.1 Cross-sectoral perspectives on mitigation action

Chapters 5 to 11 present mitigation measures applicable in individual sectors, and potential co-benefits and adverse side effects[3] of these individual measures. This section builds on the sectoral analysis of mitigation action from a cross-sectoral perspective. Firstly, Section 12.6.1.1 brings together some of the observations presented in the sectoral chapters to show how different mitigation actions in different sectors can contribute to the same co-benefits and result in the same adverse side effects, thereby demonstrating the potential synergistic effects. The links between these co-benefits and adverse side effects and the SDGs is also demonstrated. In Section 12.6.1.2, the focus turns from sector-specific mitigation measures to mitigation measures which have cross-sectoral implications, including measures that have application in more than one sector and measures where implementation in one sector impacts on implementation in another. Finally, Section 12.6.1.3 notes the cross-sectoral relevance of a selection of General-Purpose Technologies, a topic that is covered further in Chapter 16.

12.6.1.1 A cross-sectoral perspective on co-benefits and adverse side effects of mitigation measures, and links the SDGs

A body of literature has been developed which addresses the *co-benefits* of climate mitigation action, (Karlsson et al. 2020). *Adverse side effects* of mitigation are also well documented. Co-benefits and adverse side-effects in individual sectors and associated with individual mitigation measures are discussed in the individual sector chapters (Sections 5.2, 6.7.7, 7.4, 7.6, 8.2, 8.4, 9.8, 10.1.1, 11.5.3), as well as in previous IPCC General and Special Assessment reports. The term *co-impacts* has been proposed to capture both the co-benefits and adverse side-effects of mitigation. An alternative framing is one of multiple objectives, where climate mitigation is placed alongside other objectives when

FOOTNOTE[3] Here, the term co-benefits is used to refer to the additional benefits to society and the environment that are realised in parallel with emissions reductions, while an understanding of adverse side effects highlights where policy and decision makers are required to make trade-offs between mitigation benefits and other impacts. The choice of language differs to some degree in other chapters.

assessing policy decisions (Ürge-Vorsatz et al. 2014; Mayrhofer and Gupta 2016; Cohen et al. 2017; Bhardwaj et al. 2019).

The identification and assessment of co-benefits has been argued to serve a number of functions (Section 1.4) including using them as a leverage for securing financial support for implementation, providing justification of actions which provide a balance of both short and long-term benefits and obtaining stakeholder buy-in *(robust evidence, low agreement)* (Karlsson et al. 2020). Assessment of adverse side-effects has been suggested to be useful in avoiding unforeseen negative impacts of mitigation and providing policy and decision makers with the information required to make informed trade-offs between climate and other benefits of actions (Ürge-Vorsatz et al. 2014; Bhardwaj et al. 2019; Cohen et al. 2019) *(high evidence, low agreement)*.

Various approaches to identifying and organising co-impacts in specific contexts and across sectors have been proposed towards providing more comparable and standardised analyses. However, consistent quantification of co-impacts, including cost-benefit analysis, and the utilisation of the resulting information, remains a challenge (Ürge-Vorsatz et al. 2014; Floater et al. 2016; Mayrhofer and Gupta 2016; Cohen et al. 2019; Karlsson et al. 2020). This challenge is further exacerbated when considering that co-impacts of a mitigation measure in one sector can either enhance or reduce the co-impacts associated with mitigation in another, or the achievement of co-benefits in one geographic location can lead to adverse side effects in another. For example, the production of lithium for batteries for energy storage has the potential to contribute to protecting water resources and reducing wastes associated with coal fired power in many parts of the world, but mining of lithium has the potential for creating water and waste challenges if not managed properly (Agusdinata et al. 2018; Kaunda 2020).

While earlier literature has suggested that co-impacts assessments can support adoption of climate mitigation action, a more recent body of literature has suggested limitations in such framing (Ryan 2015; Bernauer and McGrath 2016; Walker et al. 2018). Presenting general information on co-impacts as a component of a mitigation analysis does not always lead to increased support for climate mitigation action. Rather, the most effective framing is determined by factors relating to local context, type of mitigation action under consideration and target stakeholder group. More work has been identified to be required to bring context into planning co-impacts assessments and communication thereof (Ryan 2015; Bernauer and McGrath 2016; Walker et al. 2018) *(low evidence, low agreement)*.

An area where the strong link between the cross-sectoral co-impacts of mitigation action and global government policies is being clearly considered is in the achievement of the SDGs (Chapters 1 and 17, individual sectoral chapters) (Obergassel et al. 2017; Doukas et al. 2018; Markkanen and Anger-Kraavi 2019; Smith et al. 2019; van Soest et al. 2019). Figure 12.9 demonstrates these relationships from a cross-sectoral perspective. It shows the links between sectors which give rise to emissions, the mitigation measures that can find application in the sector, co-benefits and adverse side effects of mitigation measures and the SDGs (noting that the figure is not intended to be comprehensive). Such a framing of co-impacts from a cross-sectoral perspective in the context of the SDGs could help to further support climate mitigation action, particularly within the context of the Paris Agreement (Gomez-Echeverri 2018) (*medium evidence, medium agreement*). Literature sources utilised in the compilation of this diagram are presented in Supplementary Material 12.C.

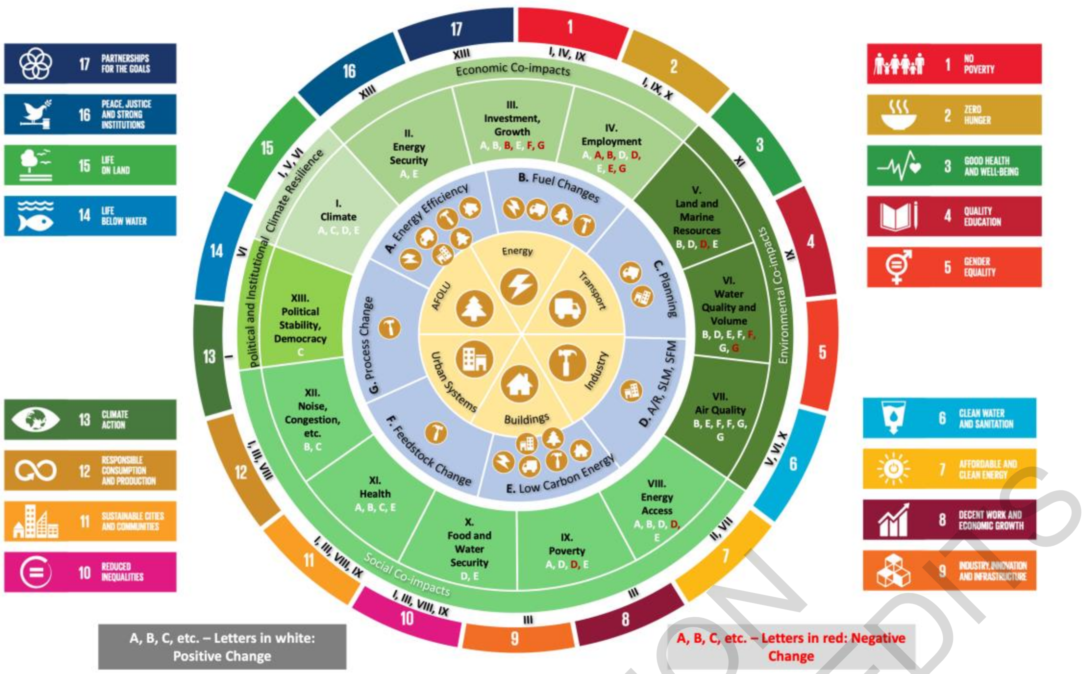


Figure 12.9 Co-benefits and adverse side effects of mitigation actions with links to the SDGs.

The inner circle represents the sectors in which mitigation occurs. The second circle shows different generic types of mitigation actions (A to G), with the symbols showing which sectors they are applicable to. The third circle indicates different types of climate related co-benefits (green letters) and adverse side effects (red letters) that may be observed as a result of implementing each of the mitigation actions (as indicated by the letters A-G). Here I relates to climate resilience, II-IV economic co-impacts, V-VII environmental, VIII-XII social, and XIII political and institutional. The final circle maps co-benefits and adverse side-effects to the SDGs (Cohen et al. 2021).

12.6.1.2 Mitigation measures from a cross-sectoral perspective

Three aspects of mitigation from a cross-sectoral perspective are considered, following (Barker et al. 2007):

- mitigation measures used in more than one sector;
- implications of mitigation measures for interaction and integration between sectors; and
- competition among sectors for scarce resources.

A number of mitigation measures find application in more than one sector. Renewable energy technologies such as solar and wind may be used for grid electricity supply, as embedded generation in the buildings sector and for energy supply in the agriculture sector (Chapters 6, 7 and 8) (Shahsavari and Akbari 2018). Hydrogen and fuel cells, coupled with low carbon energy technologies for producing the hydrogen, is being explored in transport, urban heat, industry and for balancing electricity supply (Chapters 6, 8, 11) (Dodds et al. 2015; Staffell et al. 2019). Electric vehicles are considered an option for balancing variable power (Kempton and Tomić 2005; Liu and Zhong 2019). Carbon Capture and Storage (CCS) and Carbon Capture and Utilisation (CCU) has potential application in a number of industrial processes (cement, iron and steel, petroleum refining and pulp and paper) (Chapters 6 and 11) (Leeson et al. 2017; Garcia and Berghout 2019) and the fossil fuel electricity sector (Chapter 6). When coupled with energy recovery from biomass , CCS can provide a carbon sink (BECCS) (Section 12.5). On the demand side, energy efficiency options find application across the sectors (Chapters 6, 8, 9, 10, and 11), as does reducing demand for goods and services (Chapter 5), and improving material efficiency (Section 11.3.2).

A range of examples of where mitigation measures result in cross-sectoral interactions and integration is identified. The mitigation potential of electric vehicles, including plug-in hybrid hybrids, is linked to the extent of decarbonisation of the electricity grid, as well as to the liquid fuel supply emissions profile (Lutsey 2015). Making buildings energy positive, where excess energy is used to charge vehicles, can increase the potential of electric and hybrid vehicles (Zhou et al. 2019). Advanced process control and process optimisation in industry can reduce energy demand and material inputs (Section 11.3), which in turn can reduce emissions linked to resource extraction and manufacturing. Reductions in coal-fired power generation through replacement with renewables or nuclear power result in a reduction in coal mining and its associated emissions. Increased recycling results in a reduction in emissions from primary resource extraction. CCU can contribute to the transition to more renewable energy systems via power-to-X technologies, which enables the production of CO_2-based fuels/e-fuels and chemicals using carbon dioxide and hydrogen (Breyer et al. 2015; Anwar et al. 2020). Certain reductions in the AFOLU sector are contingent on energy sector decarbonisation. Trees and green roofs planted to counter urban heat islands reduce the demand for energy for air conditioning and simultaneously sequester GHGs (Kim and Coseo 2018; Kuronuma et al. 2018). Recycling of organic waste avoids methane generation if the waste would have been disposed of in landfill sites, can generate renewable energy if treated through anaerobic digestion and can reduce requirements for synthetic fertiliser production if the nutrient value is recovered (Creutzig et al. 2015). Liquid transport biofuels links to the land, energy and transport sectors (Section 12.5.2.2).

Demand-side mitigation measures, discussed in Chapter 5, also have cross-sectoral implications which need to be taken into account when calculating mitigation potentials. Residential electrification has the potential to reduce emissions associated with lighting and heating particularly in developing countries where this is currently met by fossil fuels and using inefficient technologies, but will increase demand for electricity (Chapters 5, 8 and Sections 6.6.2.3, 8.4.3.1). Many industrial processes can also be electrified in the move away from fossil reductants and direct energy carriers (Chapter 11). The impact of electrification on electricity sector emissions will depend on whether electricity generation is based on fossil fuels in the absence of CCS or low carbon energy sources (Chapter 5).

At the same time, saving electricity in all sectors reduces the demand for electricity, thereby reducing mitigation potential of renewables and CCS. Demand side flexibility measures and electrification of vehicle fleets are supportive of more intermittent renewable energy supply options (Sections 6.3.7, 6.4.3.1 and 10.3.4). Production of maize, wheat, rice and fresh produce requires lower energy inputs on a life cycle basis than poultry, pork and ruminant based meats (Section 12.4) (Clark and Tilman 2017). They also require less land and area per kilocalorie or protein output (Clark and Tilman 2017; Poore and Nemecek 2018), and so replacing meat with these products makes land available for sequestration, biodiversity or other societal needs. However, production of co-products of the meat industry, such as leather and wool, is reduced, resulting in a need for substitutes. Further discussion and examples of cross-sectoral implications of mitigation, with respect to cost and potentials, are presented in Section 12.2. One final example on this topic included here is that of Circular Economy (Box 12.4).

Finally, in terms of competition among sectors for scarce resources, this issue is often considered in the assessments of mitigation potentials linked to bioenergy and diets (vegetable vs. animal food products), land use and water (Section 12.5, Cross-Working Group Box 3 in this Chapter) (*robust evidence, high agreement*). It is, however, also relevant elsewhere. Constraints have been identified in the supply of indium, tellurium, silver, lithium, nickel and platinum that are required for implementation of some specific renewable energy technologies (Watari et al. 2018; Moreau et al. 2019). Other studies have shown constraints in supply of cobalt, one of the key elements used in production of lithium-ion batteries, which has been assessed for mitigation potential in energy, transport and buildings sectors (Jaffe 2017; Olivetti et al. 2017) (*medium evidence, high agreement*), although alternatives to cobalt are being developed (Olivettie et al. 2017; Watari et al. 2018).

START BOX 12.4 HERE

Box 12.4: Circular Economy from a Cross-Sectoral Perspective

Circular economy approaches consider the entire life cycle of goods and services, and seek to design out waste and pollution, keep products and materials in use, and regenerate natural systems (The Ellen MacArthur Foundation 2013; CIRAIG 2015). The use of Circular Economy for rethinking how society's needs for goods and services is delivered in such a way as to minimise resource use and environmental impact and maximise societal benefit has been discussed elsewhere in this assessment report (Chapter 5 and Section 5.3.4). A wide range of potential application areas is identified, from food systems to bio-based products to plastics to metals and minerals to manufactured goods. Circular economy approaches are implicitly cross-sectoral, impacting the energy, industrial, AFOLU, waste and other sectors. They will have climate and non-climate co-benefits and trade-offs. The scientific literature mainly investigates incremental measures claiming but not demonstrating mitigation; highest mitigation potential is found in the industry, energy, and transport sector; mid-range potential in the waste and building sector; and lowest mitigation gains in agriculture (Cantzler et al. 2020). Circular economy thinking has been identified to support increased resilience to the physical effects of climate change and contribute to meeting other UN SDGs, notably SDG12 (responsible consumption and production) (The Ellen MacArthur Foundation 2019).

Circular economy approaches to deployment of low-carbon infrastructure have been suggested to be important to optimise resource use and mitigate environmental and societal impacts caused by extraction and manufacturing of composite and critical materials as well as infrastructure decommissioning (Jensen and Skelton 2018; Sica et al. 2018; Salim et al. 2019; Watari et al. 2019; Jensen et al. 2020; Mignacca et al. 2020). The circular carbon economy is an approach inspired by the circular economy principles that rely on a combination of technologies, including CCU, CCS and CDR, to enable transition pathways especially relevant in economies dependent on fossil fuel exports (Lee et al. 2017; Alshammari 2020; Morrow and Thompson 2020; Zakkour et al. 2020). The integration of circular economy and bioeconomy principles (See Cross-Working Group Box 3 in this Chapter on mitigation and adaption via the bioeconomy) is conceptualised in relation to policy development (European Commission 2018) as well as COVID-19 recovery strategies (Palahí et al. 2020) emphasising the use of renewable energy sources and sustainable management of ecosystems with transformation of biological resources into food, feed, energy and biomaterials.
At this stage, however, there is no single globally agreement of how circular economy principles are best to be implemented, and differential government support for circular economy interventions is observed in different jurisdictions.

END BOX 12.4 HERE

12.6.1.3 Cross-sectoral considerations relating to emerging general purpose technologies

General Purpose Technologies (GPTs) include, but are not limited to, additive manufacturing, artificial intelligence, biotechnology, hydrogen, digitalisation, electrification, nanotechnology and robots (de Coninck et al. 2018). Many of the individual sectoral chapters have identified the roles that such technologies can have in supporting mitigation of GHG emissions. Section 16.2.2.3 presents an overview of the individual technologies and specific applications thereof.

In this chapter, which focuses on cross-sectoral implications of mitigation, it is highlighted that certain of these GPTs will find application across the sectors, and there will be synergies and trade-offs when utilising these technologies in more than sector. One example here is the use of hydrogen as an energy carrier, which when coupled with low carbon energy, has potential for driving mitigation in energy, industry, transport, and buildings. The increased uptake of hydrogen across the economy requires establishment of hydrogen production, transport and storage infrastructure which could simultaneously support multiple sectors, although there is the potential to utilise existing infrastructure in some parts of the world (Alanne and Cao 2017).

Box **12.5** provides for further details on hydrogen in the context of cross-sectoral mitigation specifically, while further details on the role of hydrogen in individual sectors are provided in Chapters 6, 8. 9, 10 and 11. In contrast, the benefits of digitalisation, which could potentially give rise to substantial energy savings across multiple sectors, need to be traded off against demand for electricity to operate consumer devices, data centres, and data networks. Measures are required to increase energy efficiency of these technologies (IEA 2017). Section 5.3.4.1 of this report provides further information on energy and emissions benefits and costs of digitalisation.

With respect to co-impacts of GPTs, the other focus of this chapter, it is highlighted that assessment of the environmental, social and economic implications of such technologies is challenging and context specific with multiple potential cross-sectoral linkages (de Coninck et al. 2018). Each GPT would need to be explored in context of what it is being used for, and potentially in the geographical context, in order to understand the co-impacts of its use.

START BOX 12.5 HERE

Box 12.5: Hydrogen in the context of cross-sectoral mitigation options

The interest in hydrogen as an intermediary energy carrier has grown rapidly in the years since the 5th Assessment Report of WGIII (AR5) was published. This is reflected in this WGIII assessment report, where the term ‘hydrogen’ is used more than five times more often than in AR5. In Chapter 6 of this report, it is shown that hydrogen can be produced with low carbon impact from fossil fuels (Section 6.4.2.6), renewable electricity and nuclear energy (Section 6.4.5.1), or biomass (Section 6.4.2.5). In the energy sector, hydrogen is one of the options for storage of energy in low-carbon electricity systems (Sections 6.4.4.1 and 6.6.2.2). But, also importantly, hydrogen can be produced to be used as a fuel for sectors that are hard-to-decarbonise; this is possible directly in the form of hydrogen, but also in the form of ammonia or other energy carriers (Section 6.4.5.1). In the transport sector, fuel cell engines (Section 10.3.3) running on hydrogen can become important, especially for heavy duty vehicles (Section 10.4.3). In the industry sector hydrogen already plays an important role in the chemical sector (for ammonia and methanol production (Box 11.1 in Chapter 11) and in the fuel sector (in oil refinery processes and for biofuel production (IEA 2019b). Beyond the production of ammonia and methanol for both established and novel applications, the largest potential industrial application for low-carbon hydrogen is seen in steelmaking (Section 11.4.1.1). Hydrogen and hydrogen-derivatives can play a further role as substitute energy carriers (Section 11.3.5) and for the production of intermediate chemical products such as methanol, ethanol and ethylene when combined with CCU (Section 11.3.6). For the building sector, the exploration of the usefulness of hydrogen is at an early stage (Box 9.4 in Chapter 9).

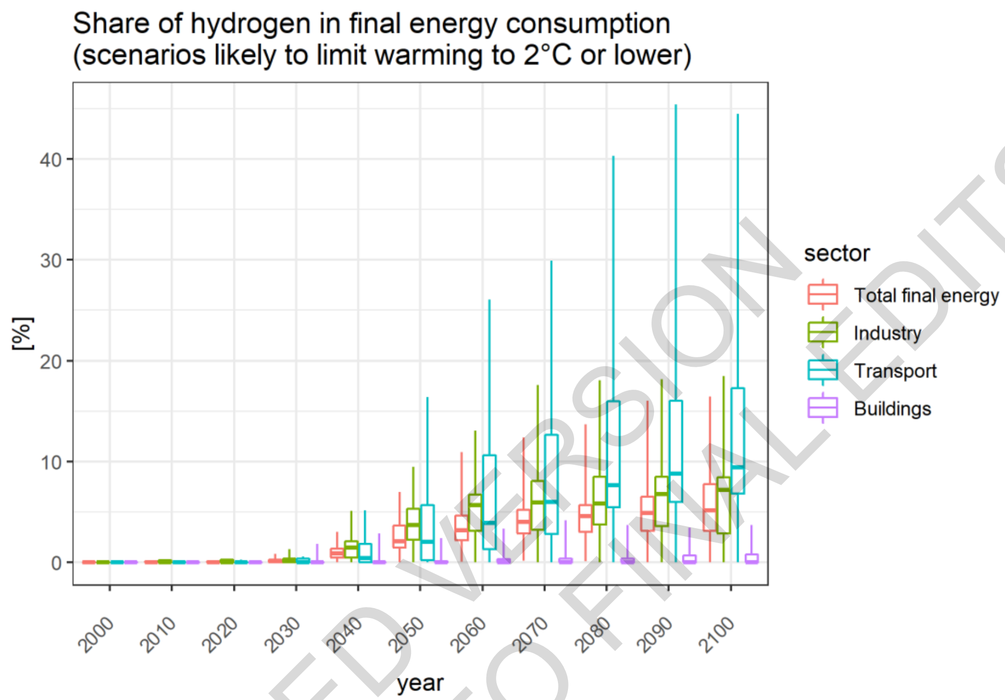
An overview report (IEA 2019b) already sees opportunities in 2030 for buildings, road freight and passenger vehicles. This report also suggests a high potential application in iron and steel production, aviation and maritime transport, and for electricity storage. Several industry roadmaps have been published that map out a possible role for hydrogen until 2050. The most well-known and ambitious is the roadmap by the Hydrogen Council (2017), which sketches a global scenario leading to 78 EJ hydrogen use in 2050, mainly for transport, industrial feedstock, industrial energy and to a lesser extent for buildings and power generation. Hydrogen makes up 18% of total final energy use in this vision. An analysis by IRENA on hydrogen from renewable sources comes to a substantially lower number: 8 EJ (excluding hydrogen use in power production and feedstock uses). On a regional level, most roadmaps and scenarios have been published for the European Union, e.g. by the Fuel Cell and Hydrogen Joint Undertaking (Blanco et al. 2018; EC 2018; FCH 2019; Navigant 2019). All these reports have scenario variants with hydrogen share in final energy use of 10% to over 20% by 2050.

When it comes to the production of low-carbon hydrogen, the focus of the attention is on production from electricity from renewable sources via electrolysis, so-called 'green hydrogen'. However, 'blue hydrogen', produced out of natural gas with CCS is also often considered. Since a significantly increasing role for hydrogen would require considerable infrastructure investments and would affect existing trade flows in raw materials, governments have started to set up national hydrogen strategies, both potential exporting (e.g. Australia) and importing (e.g. Japan) countries (METI 2017; COAG Energy Council 2019).

As already reported in Chapter 6 (Section 6.2.4.1) production costs of green hydrogen are expected to come down from the current levels of above 100 USD MWh-1. Price expectations are: 40–60 € MWh-1 for both green and blue hydrogen production in the EU by 2050 (Navigant 2019) with production costs already being lower in North Africa; 42–87 USD MWh-1 for green hydrogen in 2030 and 20 – 41 USD MWh-1 in 2050 (BNEF 2020); 75 € MWh-1 in 2030 (Glenk and Reichelstein 2019). For fossil-based technologies combined with CCS, prices may range from 33 – 80 USD MWh-1 (Table 6.8 in Chapter 6,). Such prices can make hydrogen competitive for industrial feedstock applications, and probably for several transportation modes in combination with fuel cells, but without further incentives, not necessarily for stationary applications in the coming decades: wholesale natural gas prices are expected to range from 7–31 USD MWh-1 across regions and scenarios, according to the World Energy Outlook (IEA 2020a); coal prices mostly are even lower than natural gas prices (all fossil fuel prices refer to unabated technology and untaxed fuels). The evaluation of macro-economic impacts is relatively rare. A study by (Mayer et al. 2019b) indicated that a shift to hydrogen in iron and steel production would lead to regional GDP losses in the range of 0.4–2.7% in 2050 across EU+3 with some regions making gains under a low-cost electricity scenario.

The IAM scenarios imply a modest role played by hydrogen, with some scenarios featuring higher levels of penetration. The consumption of hydrogen is projected to increase by 2050 and onwards in scenarios likely limiting global warming to 2°C or below, and the median share of hydrogen in total final energy consumption is 2.1% in 2050 and 5.1% in 2100 (Box 12.4, Figure 1) (Numbers are based on the AR6 scenarios database.) There is large variety in hydrogen shares, but the values of 10% and more of final energy use that occur in many roadmaps are only rarely reached in the scenarios. Hydrogen is predominantly used in the industry and transportation sectors. In the scenarios, hydrogen is produced mostly by electrolysis and by biomass energy conversion with CCS (Box 12.5, Figure 1). Natural gas with CCS is expected to only play a modest role; here a distinct difference between the roadmaps quoted before and the IAM results is observed.

It is concluded that there is increasing confidence that hydrogen can play a significant role, especially in the transport sector and the industrial sector. However, there is much less agreement on timing and volumes, and there is also a range of perspectives on role of the various production methods of hydrogen.



Box 12.5, Figure 1 Fraction of hydrogen (H2, red) in total final energy consumption, and those for each sector. Hinges represent the interquartile ranges and whiskers extend to 5 and 95 percentiles.

END BOX 12.5 HERE

12.6.2 Sectoral policy interactions (synergies and trade-offs)

A taxonomy of policy types and attributes is provided by Section 13.6. In addition, the sectoral chapters provide an in-depth discussion of important mitigation policy issues such as policy overlaps, policy mixes, and policy interaction as well as policy design considerations and governance. The point of departure for the assessment in this chapter is a focus on cross-sectoral perspectives aiming at maximising policy synergies and minimising policy trade-offs.

Synergies and trade-offs resulting from mitigation policies are not clearly discernible from either sector-level studies or global and regional top-down studies. Rather, they would require a cross-sectoral integrated policy framework (von Stechow et al. 2015; Singh et al. 2019; Monier et al. 2018; Pardoe et al. 2018) or multiple-objective-multiple-impact policy assessment framework identifying key co-impacts and avoiding trade-offs (Ürge-Vorsatz et al. 2014) *(robust evidence, high agreement).*

Sectoral studies typically cover differentiated response measures while the IAM literature mostly uses uniform efficient market-based measures. This has important implications for understanding the differences in magnitude and distribution of mitigation costs and potentials of Section 12.2 (Rausch and Karplus 2014; Karplus et al. 2013). There is a comprehensive literature on the efficiency of uniform carbon pricing compared to sector-specific mitigation approaches, but relatively less literature on the distributional impacts of carbon taxes and measures to mitigate potential adverse distributional impacts (Åhman et al. 2017; Rausch and Reilly 2015; Mu et al. 2018; Wang et al. 2016b; Rausch and Karplus 2014). For example, in terms of cross-sectoral distributional implications, studies find negative competitiveness impacts for the energy intensive industries (Wang et al. 2016b; Åhman et al. 2017; Rausch and Karplus 2014). *(robust evidence, medium agreement)*

Strong inter-dependencies and cross-sectoral linkages create both opportunities for synergies and the need to address trade-offs. This calls for coordinated sectoral approaches to climate change mitigation policies that mainstream these interactions (Pardoe et al. 2018). Such an approach is also called for in the context of cross-sectoral interactions of adaptation and mitigation measures, examples are in the agriculture, biodiversity, forests, urban, and water sectors (Di Gregorio et al. 2017; Arent et al. 2014; Berry et al. 2015). Integrated planning and cross-sectoral alignment of climate change policies are particularly evident in developing countries' NDCs pledged under the Paris Agreement, where key priority sectors such as agriculture and energy are closely aligned between the proposed mitigation and adaptation actions in the context of sustainable development and the SDGs. An example is the integration between smart agriculture and low carbon energy (Antwi-Agyei et al. 2018; England et al. 2018). Yet, there appear to be significant challenges relating to institutional capacity and resources to coordinate and implement such cross-sectoral policy alignment, particularly in developing country contexts (Antwi-Agyei et al. 2018) *(robust evidence, high agreement).*

Another dimension of climate change policy interactions in the literature is related to trade-offs and synergies between climate change mitigation and other societal objectives. For example, in mitigation policies related to energy, trade-offs and synergies between universal electricity access and climate change mitigation would call for complementary policies such as pro-poor tariffs, fuel subsidies, and broadly integrated policy packages (Dagnachew et al. 2018). In agriculture and forestry, research suggests that integrated policy programs enhance mitigation potentials across the land-use-agriculture-forestry nexus and lead to synergies and positive spill-overs (Galik et al. 2019). To maximise synergies and deal with trade-offs in such a cross-sectoral context, evidence-based/informed and holistic policy analysis approaches like nexus approaches and multi-target back-casting approaches that take into account unanticipated outcomes and indirect consequences would be needed (Klausbruckner et al. 2016; van der Voorn et al. 2020; Hoff et al. 2019; see Box 12.6) *(robust evidence, high agreement).*

The consequences of large-scale land-based mitigation for food security, biodiversity, (Dasgupta 2021) the state of soil, water resources, etc. can be significant depending on many factors, such as economic development (including distributional aspects), international trade patterns, agronomic development, diets, land use governance and policy design, and not least climate change itself (Fujimori et al. 2018; Hasegawa et al. 2018; Van Meijl et al. 2018; Winchester and Reilly 2015). Policies and regulations that address other aspects apart from climate change can indirectly influence the attractiveness of land-based mitigation options. For example, farmers may find it attractive to shift from annual food/feed crops to perennial grasses and short rotation woody crops (suitable for bioenergy) if the previous land uses become increasingly restricted due to impacts on groundwater quality and eutrophication of water bodies (Sections 12.4 and 12.5) (*robust evidence, medium agreement).*

Finally, there are knowledge gaps in the literature particularly in relation to policy scalability and in relation to the extent and magnitude of policy interactions when scaling the policy to a level consistent with low GHG emissions pathways such as 2ºC and 1.5ºC.

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Box 12.6: Case Study, Sahara Forest Project in Aqaba, Jordan

Nexus Framing

Shifting to renewable (in particular solar) energy reduces dependency on fossil fuel imports and greenhouse gas emissions, which is crucial for mitigating climate change. Employing renewable energy for desalination of seawater and for cooling of greenhouses in integrated production systems can enhance water availability, increase crop productivity and generate co-products and co-benefits (e.g., algae, fish, dryland restoration, greening of the desert).

Nexus Opportunities

The Sahara Forest project integrated production system uses amply available natural resources, namely solar energy and seawater, for improving water availability and agricultural/biomass production, while simultaneously providing new employment opportunities. Using hydroponic systems and humidity in the air, water needs for food production are 50% lower compared to other greenhouses.

Technical and Economic Nexus Solutions

Several major technologies are combined in the Sahara Forest Project, namely electricity production through the use of solar power (PV or CSP), freshwater production through seawater desalination using renewable energy, seawater-cooled greenhouses for food production, and outdoor revegetation using run-off from the greenhouses.

Stakeholders Involved

The key stakeholders which benefit from such an integrated production system are from the water sector which urgently requires an augmentation of irrigation (and other) water, as well as from the agricultural sector, which relies on the additional desalinated water to maintain and increase agricultural production. The project also involves public and private sector partners from Jordan and abroad, with little engagement of civil society so far.

Framework Conditions

The Sahara Forest Project has been implemented at pilot scale so far, including the first pilot with one hectare and one greenhouse pilot in Qatar and a larger "launch station" with three hectares and two greenhouses in Jordan). These pilots have been funded by international organisations such as the Norwegian Ministry of Climate and Environment, Norwegian Ministry of Foreign Affairs and the European Union. Alignment with national policies, institutions and funding as well as upscaling of the project is underway or planned.

Monitoring and Evaluation and Next Steps

The multi-sectoral planning and investments that are needed to up-scale the project require cooperation among the water, agriculture, and energy sectors and an active involvement of local actors, private companies, and investors. These cooperation and involvement mechanisms are currently being established in Jordan. Given the emphasis on the economic value of the project, public-private partnerships are considered as the appropriate business and governance model, when the project is up-scaled. Scenarios for upscaling (seawater use primarily in low lying areas close to the sea, to avoid energy-intensive pumping) include 50MW of CSP, 50 hectares of greenhouses, which would produce 34,000 tons of vegetables annually, provide employment for over 800 people, and sequester more than 8,000 tons of CO2 annually.

Source: SFP Foundation; Hoff et al. 2019

END BOX 12.6 HERE

12.6.3 International trade spill-over effects and competitiveness

International spill-overs of mitigation policies are effects that carbon-abatement measures implemented in one country have on sectors in other countries. These effects include 1) carbon leakage in manufacture, 2) the effects on energy trade flows and incomes related to fossil fuel exports from major exporters, 3) technology and knowledge spill-overs; 4) transfer of norms and preferences via various approaches to establish sustainability requirements on traded goods, e.g., EU-RED and environmental labelling systems to guide consumer choices *(robust evidence, medium agreement)*. This section focuses on cross-sectoral aspects of international spill-overs related to the first two effects.

12.6.3.1 Cross-sectoral aspects of carbon leakage

Carbon leakage occurs when mitigation measures implemented in one country/sector lead to the rise in emissions in other countries/sectors. Three types of spill-overs are possible: 1) domestic cross-sectoral spill-overs when mitigation policy in one sector leads to the re-allocation of labour and capital towards the other sectors of the same country; 2) international spill-overs within a single sector when mitigation policy leads to substitution of domestic production of carbon-intensive goods with their imports from abroad; 3) international cross-sectoral spill-overs when mitigation policy in one sector in one country leads to the rise in emissions in other sectors in other countries. While the first two are described in Section 13.6, this section focuses on the third. Though some papers address this type of leakage, there is still significant lack of knowledge on this topic.

One possible channel of cross-sectoral international carbon leakage is through global value chains. Mitigation policy in one country not only leads to shifts in competitiveness across industries producing final goods but also across those producing raw materials and intermediary goods all over the world.

This type of leakage is especially important because the countries that provide basic materials are usually emerging or developing economies, many of which have no or limited regulation of GHG emissions. For this reason, foreign direct investment in developing economies usually leads to an increase in emissions (Bakhsh et al. 2017; Shahbaz et al. 2015; Kivyiro and Arminen 2014): in case of basic materials the effect of expansion of economic activity on emissions exceeds the effect of technological spill-overs, while for developed countries the effect is opposite (Pazienza 2019; Shahbaz et al. 2015). Meng et al. (2018) calculated that environmental costs for generating one unit of GDP through international trade was 1.4 times higher than that through domestic production in 1995. By 2009, this difference increased to 1.8 times. Carbon leakage due to the differences in environmental regulation was the main driver of this increase.

In order to address emissions leakage through global value chains, Liu and Fan (2017) propose the value-added-based emissions accounting principle, that makes possible to account for GHG emissions within the context of the economic benefit principle. Davis et al. (2011) notice that the analysis of value chains gives an opportunity to find the point where regulation would be the most efficient and the least vulnerable to leakage. For instance, transaction costs of global climate policy and the risks of leakage may be reduced if emissions are regulated at the extraction stage as there are far fewer agents involved in this process than in burning of fossil fuels or consumption of energy-intensive goods. Li et al. (2020)

calls for coordinated efforts to reduce emissions in trade flows in pairs of the economies with the highest leakage such as China and the United States, China and Germany, China and Japan, Russia and Germany.

Unfortunately, these proposals either face difficulties in collection and verification of data on emissions along value chains or require a high level of international cooperation which is hardly achievable at the moment. (Neuhoff et al. 2016; Pollitt et al. 2020) focus on the regulation of emissions embodied in global value chains through national policy instruments. They propose implementation of a charge on consumption of imported basic materials into the European emissions trading system. Such a charge, equivalent to around €80 tCO_2^{-1}, could reduce the EU's total CO_2 emissions by up to 10% by 2050 (Pollitt et al. 2020) without significant effects on competitiveness. This proposal is very close to border carbon adjustment introduced in the EU and described in more detail in Sections 13.2 and 13.6.

Cross-sectoral effects of carbon leakage also occur through the multiplier effect, when the mitigation policy in any sector in country A leads to the increase of relative competitiveness and therefore production of the same sector in country B that automatically leads to the expansion of economic activity in other sectors of country B. This expansion may in turn lead to the rise of production and emissions in country A as a result of feedback effects. These spill-overs should be taken into consideration while designing climate policy, along with potential synergies that may appear due to joint efforts. However, the scale of these effects with regards to leakage shouldn't be overestimated. Even for intrasectoral leakage, many *ex-ante* modelling studies generally suggest limited carbon leakage rates (Chapter 13). Intersectoral leakage should be even less significant. Interregional spill-over and feedback effects are well-studied in China (Zhang 2017; Ning et al. 2019). Even within a single country, interregional spill-over effects are much lower than intraregional effects, and feedback effects are even less intense. Cross-sectoral spill-overs across national borders as a result of mitigation policy should be even smaller, although these are less well-studied. In future, if the differences in carbon price between regions increase, leakage through cross-sectoral multipliers may play a more important role.

Another important cross-sectoral aspect of carbon leakage concerns the transport sector. If mitigation policy leads to the substitution of domestic carbon-intensive production with imports, one of the side effects of this substitution is the rise of emissions from transportation of imported goods. International transport is responsible for about a third of worldwide trade-related emissions, and over 75 percent of emissions for major manufacturing categories (Cristea et al. 2013). Carbon leakage would potentially increase the emissions from transportation significantly as the trade of major consuming economies of the EU and US would shift towards distant trading partners in East and South Asia. Meng et al. (2018) consider more distant transportation as one of the major contributors to the rise in emissions embodied in international trade from 1995 to 2009.

Emissions leakage due to international trade, investment and value chains is a significant obstacle to more ambitious climate policies in many regions. However, it doesn't mean that disruption of trade would reduce global emissions. Zhang et al. (2020) show that deglobalisation and the drop in international trade may result in emissions reductions in the short term, but in the longer term it will make each country build more complete industrial systems to satisfy their final demand, although they have comparative disadvantages in some production stages. As a result, emissions would increase. According to Zhang et al. (2020) for China, the decrease of the degree of global value chain participation (which ranges from 0 to 1) by 0.1 would lead to an increase in gross carbon intensity of China's exports of 11.7%. On distributional implications, Parrado and De Cian (2014) report that trade-driven spill-overs effects transmitted through imports of materials and equipment result in significant inter-sectoral distributional effects with some sectors witnessing substantial expansion in activity and emissions and others witnessing a decline in activities and emissions.

It should also be mentioned that international trade leads to important knowledge and technology spill-overs (Sections 16.3 and 16.5) and is critically important for achieving other Sustainable Development Goals (Section 12.6.1). Any policies imposing additional barriers to international trade should be therefore implemented with great caution and require comprehensive evaluation of various economic, social and environmental effects.

12.6.3.2 The spill-over effects on the energy sector

Cross-sectoral trade-related spill-overs of mitigation policies include their effect on energy prices. Other things being equal, regulation of emissions of industrial producers decreases the demand for fossil fuels that would reduce prices and encourage the rise of fossil fuel consumption in regions with no or weaker climate policies *(robust evidence, medium agreement).*

Arroyo-Currás et al. (2015) study the energy channel of carbon leakage with the REMIND IAM of the global economy. They come to the conclusion that the leakage rate through the energy channel is less than 16% of the emission reductions of regions who introduce climate policies first. This result doesn't differ much for different sizes and compositions of the early mover coalition.

Bauer et al. (2015) built a multi-model scenario ensemble for the analysis of energy-related spill-overs of mitigation policies and reveal huge uncertainty: energy-related carbon leakage rates vary from negative values to 50%, primarily depending on the trends in inter-fuel substitution.

Another kind of spill-over in energy sector concerns the "green paradox"; announcement of future climate policies causes an increase in production and trade in fossil-fuels in the short term (Jensen et al. 2015; Kotlikoff et al. 2016). The delayed carbon tax should therefore be higher than an immediately implemented carbon tax in order to achieve the same temperature target (van der Ploeg 2016). Studies also make a distinction between a "weak" and "strong" green paradox (Gerlagh 2011). The former refers to a short-term rise in emissions in response to climate policy, while the latter refers to rising cumulative damage.

The green paradox may work in different ways for different kinds of fossil fuels. For instance, Coulomb and Henriet (2018) show that climate policies in the transport and power-generation sectors increase the discounted profits of the owners of conventional oil and gas, compared to the no-regulation baseline, but will decrease these profits for coal and unconventional oil and gas producers.

Many studies also distinguish different policy measures by the scale of green paradox they provide. The immediate carbon tax is the first-best instrument from the perspective of the global welfare. Delayed carbon tax leads to some green paradox but it is less than in the case of the support of renewables (Michielsen 2014; van der Ploeg and Rezai 2019). With respect to the latter, support of renewable electricity has a lower green paradox than the support of biofuels (Gronwald et al. 2017; Michielsen 2014). The existence of the green paradox is an additional argument in favour of more decisive climate policy now: any postponements will lead to additional consumption of fossil fuels and consequently the need for more ambitious and costly efforts in future.

The effect of fossil fuel production expansion as a result of anticipated climate policy may be compensated by the effect of divestment. Delayed climate policy creates incentives for investors to divest from fossil fuels. Bauer et al. (2018) show that this divestment effect is stronger and thus announcing of climate policies leads to the reduction of energy-related emissions.

The implication of the effects of mitigation policies through the energy related spill-overs channel is of particular significance to oil-exporting countries *(medium evidence, medium agreement)*. Emissions reduction-measures lead to the decreasing demand for fossil fuels and consequently to the decrease in its exports from major oil- and gas- exporting countries. The case of Russia is one of the most illustrative. Makarov et al. (2020) show that the fulfilment of Paris Agreement parties of their NDCs would lead to 25% reduction of Russia's energy exports by 2030 with significant reduction of its economic growth rates. At the same time, the domestic consumption of fossil fuels is anticipated to increase in response to the drop of external demand that would provoke carbon leakage (Orlov and Aaheim 2017). Such spill-overs demonstrate the need for the dialogue between exporters and importers of fossil fuels while implementing the mitigation policies.

12.6.4 Implications of finance for cross-sectoral mitigation synergies and trade-offs

Finance is a principal enabler of GHG mitigation and an essential component of countries' NDC packages submitted under the Paris climate agreement (UNFCCC 2016). The assessment of investment requirements for mitigation along with their financing at sectoral levels are addressed in detail by sectoral chapters while the assessment of financial sources, instruments, and the overall mitigation financing gap is addressed by Chapter 15 (Sections 15.3, 15.4, and 15.5). The focus in this chapter with respect to finance is on the scope and potential for financing integrated solutions that create synergies between and among sectors.

Cross-sectoral considerations in mitigation finance are critical for the effectiveness of mitigation action as well as for balancing the often conflicting social, developmental and environmental policy goals at the sectoral level. True measures of mitigation policy impacts and hence plans for resource mobilisation that properly address costs and benefits cannot be developed in isolation of their cross-sectoral implications. Unaddressed cross-sectoral coordination and interdependency issues are identified as major constraints in raising the necessary financial resources for mitigation in a number of countries (Bazilian et al. 2011; Welsch et al. 2014; Hoff et al. 2019a).

Integrated financial solutions to leverage synergies between sectors, as opposed to purely sector-based financing at international, national, and local levels are needed to scale up GHG mitigation potentials. At the international level, Finance from Multilateral Development Banks (MDBs) is a major source of GHG mitigation finance in developing countries (World Bank Group 2015; Ha et al. 2016; Bhattacharya et al. 2016, 2018) *(medium evidence, medium agreement).* In 2018, MDBs reported a total of USD 30,165 million in financial commitments to climate change mitigation, with 71% of total mitigation finance being committed through investment loans and the rest in the form of equity, guarantees, and other instruments. GHG reduction activities eligible for MDB finance are limited to those compatible with low-emission pathways recognising the importance of long-term structural changes, such as the shift in energy production to low-carbon energy technologies and the modal shift to low-carbon modes of transport leveraging both greenfield and energy efficiency projects. Sector-wise, the MDBs mitigation finance for 2018 is allocated to renewable energy (29%), transport (18%), energy efficiency (18%), lower-carbon and efficient energy generation (7%), agriculture, forestry and land use (8%), waste and waste-water (8%), and other sectors (12%) (MDB 2019). Unfortunately, due to institutional and incentives issues MDBs finance has mostly focused on sectoral solutions and has not been able to properly leverage cross-sectoral synergies. At the national level, applied research has shown that integrated modelling of land, energy and water resources not only has the potential to identify superior solutions, but also reveals important differences in terms of investment requirements and required financing arrangements compared to the traditional sectoral financing toolkits (Welsch et al. 2014). Agriculture, forestry, nature-based-solutions (NBS) and other forms of land use are promising sectors for leveraging financing solutions to scale up GHG mitigation efforts (Section 15.4). Moving to more productive and resilient forms of land use is a complex task given the crosscutting nature of land-use that necessarily results in apparent trade-offs between mitigation, adaptation, and development objectives. Finance is one area to manage these trade-offs where there may be opportunities to redirect the hundreds of billions spent annually on land use around the world towards green activities, without sacrificing either productivity or economic development (Falconer et al. 2015). Nonetheless, that would require active public support in design of land use mitigation and adaptation strategies, coordination between public and private instruments across land-use sectors, and leveraging of policy and financial instruments to redirect finance toward greener land-use practices (*limited evidence, medium agreement*). For example, the Welsch et al. (2014) study on Mauritius shows that the promotion of a local biofuel industry from sugar cane could be economically favourable in the absence of water constraints, leading to a reduction in petroleum imports and GHG emissions while enhancing energy security. Yet, under a water-constrained scenario as a result of climate change, the need for additional energy to expand irrigation to previously rain-fed sugar plantations and to power desalination plants yields the opposite result in terms of GHG emissions and energy costs, making biofuels a sub-optimal option, and negatively affects their economics and the prospects for financing.

At the local level, integrated planning and financing are needed to achieve more sustainable outcomes. For example, at a city level integration is needed across sectors such as transport, energy systems, buildings, sewage and solid waste to optimise emissions footprints. How a city is designed will affect transportation demands, which makes it either more or less difficult to implement efficient public transportation, leading in turn to more or less emissions. Under such cases, solutions in terms of public and private investment paths and financing policies based on purely internal sector considerations are bound to cause adverse impacts on other sectors and poor overall outcomes (Gouldson et al. 2016).

Availability and access to finance are among the major barriers to GHG emissions mitigation across various sectors and technology options *(robust evidence, high agreement)*. Resource maturity mismatches and risk exposure are two main factors limiting ability of commercial banks and other private lenders to contribute to green finance (Mazzucato and Semieniuk 2018). At all levels, mobilising the necessary resources to leverage cross-sectoral mitigation synergies would require the combination of public and private financial sources (Jensen and Dowlatabadi 2018). Traditional public financing would be required to synergise mitigation across sectors where the risk-return and time profiles of investment are not sufficiently attractive for the business sector. Over the years, private development financing through public-private partnerships (PPP) and other related variants has been a growing source of finance to leverage cross-sectoral synergies and manage trade-offs (Ishiwatari et al. 2019; Attridge and Engen 2019; Anbumozhi and Timilsina 2018). Promoting such blended approaches to finance along with result-based financing architectures to strengthen delivery institutions are advocated as effective means to mainstream cross-sectoral mitigation finance (Ishiwatari et al. 2019; Attridge and Engen 2019) *(limited evidence, high agreement)*. The World Bank group and the International Financial Corporation (IFC) have used the blended finance results-based approach to climate financing that addresses institutional, infrastructure, and service needs across sectors targeting developing countries and marginalised communities (GPRBA 2019; IDA 2019).

12.7 Knowledge Gaps

Finally, the literature review and analysis in Chapter 12 has taken account of the post-AR5 literature available and accessible to the chapter authors. Nonetheless, the assessment of the chapter is incomplete without mentioning knowledge gaps encountered during the assessment. These knowledge gaps include:

1) Interactions (synergies and trade-offs) between different CDR methods when deployed together are under-researched.

- Co-benefits and trade-offs with biodiversity and ecosystem services associated with the implementation of CDR methods.
- Constraining technical costs and potentials for CDR methods to define realistically achievable costs and potentials. Such research is useful for improving the representation of CDR methods in IAMs and country-level mitigation pathway modelling.

2) More work is required on how framing and communication of mitigation actions in terms of mitigation versus co-benefits potential affects public support in different contexts.

3) Additional research work is required to determine the cross-sectoral mitigation potential of emerging General Purpose Technologies.

4) Lack of literature on mitigation finance frameworks promoting cross-sectoral mitigation linkages.

5) Additional research is needed to better quantify the net GHG emissions and co-benefits and adverse effects of emerging food technologies.

- Research in social and behavioural sciences should invest in assessing effectiveness of instrument aiming at shifting food choices in different national contexts.
- A better evidence basis is required to understand synergistic effects of policies in food system policy packages.

6) Literature on regional/global mitigation potential of biomass production systems that are strategically deployed in agriculture/forestry landscapes, to achieve specific co-benefits.

7) Knowledge on land occupation and associated co-benefits and adverse side-effects from large-scale deployment of non-AFOLU mitigation options, and how such options can be integrated with agriculture and forestry to maximise synergies and minimise trade-offs.

Frequently Asked Questions (FAQs)

FAQ 12.1 How could new technologies to remove carbon dioxide from the atmosphere contribute to climate change mitigation?

Limiting the increase in warming to well below 2°C, and achieving net zero CO_2 or GHG emissions, will require anthropogenic CO_2 removal (CDR) from the atmosphere.

The CDR methods studied so far have different removal potentials, costs, co-benefits and side effects. Some biological methods for achieving CDR, like A/R or wetland restoration, have long been practiced. If implemented well, these practices can provide a range of co-benefits, but they can also have adverse side effects such as biodiversity loss or food price increases. Other chemical and geochemical approaches to CDR include Direct Air Carbon Capture and Storage (DACCS), Enhanced Weathering or Ocean Alkalinity Enhancement. They are generally less vulnerable to reversal than biological methods.

DACCS uses chemicals that bind to CO_2 directly from the air; the CO_2 is then removed from the sorbent and stored underground or mineralised. Enhanced Weathering involves the mining of rocks containing minerals that naturally absorb CO_2 from the atmosphere over geological timescales, which are crushed to increase the surface area and spread on soils (or elsewhere) where they absorb atmospheric CO_2. Ocean Alkalinity Enhancement involves the extraction, processing, and dissolution of minerals and addition to the ocean where they enhance sequestration of CO_2 as bicarbonate and carbonate ions in the ocean.

FAQ 12.2 Why is it important to assess mitigation measures from a systemic perspective, rather than only looking at their potential to reduce Greenhouse Gas (GHG) emissions?

Mitigation measures do not only reduce GHGs, but have wider impacts. They can result in decreases or increases in GHG emissions in another sector or part of the value chain to where they are applied. They can have wider environmental (e.g., air and water pollution, biodiversity), social (e.g., employment creation, health) and economic (e.g., growth, investment) co-benefits or adverse side effects. Mitigation and adaptation can also be linked. Taking these considerations into account can help to enhance the benefits of mitigation action, and avoid unintended consequences, as well as provide a stronger case for achieving political and societal support and raising the finances required for implementation.

FAQ 12.3 Why do we need a food systems approach for assessing GHG emissions and mitigation opportunities from food systems?

Activities associated with the food system caused about one-third of total anthropogenic GHG emissions in 2015, distributed across all sectors. Agriculture and fisheries produce crops and animal-source food, which are partly processed in the food industry, packed, distributed, retailed, cooked, and finally eaten. Each step is associated with resource use, waste generation, and GHG emissions.

A food systems approach helps identify critical areas as well as novel and alternative approaches to mitigation on both supply side and demand side of the food system. But complex co-impacts need to be considered and mitigation measures tailored to the specific context. International cooperation and governance of global food trade can support both mitigation and adaptation.

There is large scope for emissions reduction in both cropland and grazing production, and also in food processing, storage and distribution. Emerging options such as plant-based alternatives to animal food products and food from cellular agriculture are receiving increasing attention, but their mitigation potential is still uncertain and depends on the GHG intensity of associated energy systems due to relatively high energy needs. Diet changes can reduce GHG emissions and also improve health in groups with excess consumption of calories and animal food products, which is mainly prevalent in developed countries. Reductions in food loss and waste can help reduce GHG emissions further.

Recommendations of buying local food and avoiding packaging can contribute to reducing GHG emissions but should not be generalised as trade-offs exist with food waste, GHG footprint at farm gate, and accessibility to diverse healthy diets.

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Chapter 13: National and Sub-national Policies and Institutions

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Date of Draft: 28/11/2021

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Executive Summary

Long-term deep emission reductions, including the reduction of emissions to net zero, is best achieved through institutions and governance that nurture new mitigation policies, while at the same time reconsidering existing policies that support continued Greenhouse Gas (GHG) emissions (*robust evidence, high agreement)*. To do so effectively, the scope of climate governance should include both direct efforts to target GHG emissions and indirect opportunities to tackle GHG emissions that result from efforts directed towards other policy objectives*)*. {13.2, 13.5, 13.6, 13.7, 13.9}

Institutions and governance underpin mitigation by providing the legal basis for action. This includes setting up implementing organisations and the frameworks through which diverse actors interact *(medium evidence, high agreement)*. Institutions can create mitigation and sectoral policy instruments; policy packages for low-carbon system transition; and economy wide measures for systemic restructuring. {13.2, 13.7, 13.9}

Policies have had a discernible impact on mitigation for specific countries, sectors, and technologies *(robust evidence, high agreement)***, avoiding emissions of several $GtCO_2$-eq yr^{-1}** *(medium evidence, medium agreement).* Both market-based and regulatory policies have distinct, but complementary roles. The share of global GHG emissions subject to mitigation policy has increased rapidly in recent years, but big gaps remain in policy coverage, and the stringency of many policies falls short of what is needed to achieve strong mitigation outcomes *(robust evidence, high agreement).* {13.6, Cross-chapter box 10 in Chapter 14}

Climate laws enable mitigation action by signalling the direction of travel, setting targets, mainstreaming mitigation into sector policies, enhancing regulatory certainty, creating law-backed agencies, creating focal points for social mobilization, and attracting international finance *(medium evidence, high agreement)*. By 2020, 'direct' climate laws primarily focused on GHG reductions were present in 56 countries covering 53% of global emissions, while more than 690 laws, including 'indirect' laws, may also have an effect on mitigation. Among direct laws, 'framework' laws set an overarching legal basis for mitigation either by pursuing a target and implementation approach, or by seeking to mainstream climate objectives through sectoral plans and integrative institutions. {13.2}

Institutions can enable improved governance by coordinating across sectors, scales and actors, building consensus for action, and setting strategies *(medium evidence, high agreement)*. Institutions are more stable and effective when they are congruous with national context, leading to mitigation-focused institutions in some countries and the pursuit of multiple objectives in others. Sub-national institutions play a complementary role to national institutions by developing locally-relevant visions and plans, addressing policy gaps or limits in national institutions, building local administrative structures and convening actors for place-based decarbonisation. {13.2}

Sub-national actors are important for mitigation because municipalities and regional governments have jurisdiction over climate-relevant sectors such as land-use, waste and urban policy; are able to experiment with climate solutions; and can forge partnerships with the private sector and internationally to leverage enhanced climate action *(robust evidence, high agreement)*. More than 10,500 cities and nearly 250 regions representing more than 2 billion people have pledged largely voluntary action to reduce emissions. Indirect gains include innovation, establishing norms and developing capacity. However, sub-national actors often lack national support, funding, and capacity to mobilize finance and human resources, and create new institutional competences. {13.5}

Climate governance is constrained and enabled by domestic structural factors, but it is still possible for actors to make substantial changes *(medium evidence, high agreement)*. Key structural factors are domestic material endowments (such as fossil fuels and land-based resources); domestic political systems; and prevalent ideas, values and belief systems. Developing countries face additional material constraints in climate governance due to development challenges and scarce economic or natural resources. A broad group of actors influence how climate governance develop over time, including a range of civic organizations, encompassing both pro-and anti-climate action groups. {13.3, 13.4}

Mitigation strategies, instruments and policies that fit with dominant ideas, values and belief systems within a country or within a sector are more easily adopted and implemented *(medium evidence, medium agreement).* Ideas, values and beliefs may change over time. Policies that bring perceived direct benefits, such as subsidies, usually receive greater support. The awareness of co-benefits for the public increases support of climate policies *(robust evidence, high agreement)*. {13.2, 13.3, 13.4}

Climate litigation is growing and can affect the outcome and ambition of climate governance *(medium evidence, high agreement)***.** Since 2015, at least 37 systemic cases have been initiated against states that challenge the overall effort of a state to mitigate or adapt to climate change. If successful, such cases can lead to an increase in a country's overall ambition to tackle climate change. Climate litigation has also successfully challenged governments' authorizations of high-emitting projects setting precedents in favour of climate action. Climate litigation against private sector and financial institutions is also on the rise. {13.4}

The media shapes the public discourse about climate mitigation. This can usefully build public support to accelerate mitigation action, but may also be used to impede decarbonisation *(medium evidence, high agreement)***.** Global media coverage (across a study of 59 countries) has been growing, from about 47,000 stories in 2016-17 to about 87,000 in 2020-21. Generally the media representation of climate science has increased and become more accurate over time. On occasion, the propagation of scientifically misleading information by organized counter-movements has fuelled polarization, with negative implications for climate policy. {13.4}

Explicit attention to equity and justice is salient to both social acceptance and fair and effective policymaking for mitigation *(robust evidence, high agreement)*. Distributional implications of alternative climate policy choices can be usefully evaluated at city, local and national scales as an input to policymaking. Institutions and governance frameworks that enable consideration of justice and just transitions are likely to build broader support for climate policymaking. {13.2, 13.6, 13.8, 13.9}

Carbon pricing is effective in promoting implementation of low-cost emissions reductions *(robust evidence, high agreement).* While the coverage of emissions trading and carbon taxes has risen to over 20 percent of global CO_2 emissions, both coverage and price are lower than is needed for deep reductions. The design of market mechanisms should be effective as well as efficient, balance distributional goals and find social acceptance. Practical experience has driven progress in market mechanism design, especially of emissions trading schemes *(robust evidence, high agreement)*. Carbon pricing is limited in its effect on adoption of higher-cost mitigation options, and where decisions are often not sensitive to price incentives such as in energy efficiency, urban planning, and infrastructure *(robust evidence, medium agreement)*. Subsidies have been used to improve energy efficiency, encourage the uptake of renewable energy and other sector-specific emissions saving options *(robust evidence, high agreement)* {13.6}

Regulatory instruments play an important role in achieving specific mitigation outcomes in sectoral applications *(robust evidence, high agreement).* Regulation is effective in particular applications and often enjoys greater political support, but tends to be more economically costly, than pricing instruments *(robust evidence, medium agreement).* Flexible forms of regulation (e.g., performance standards) have achieved aggregate goals for renewable energy generation, vehicle efficiency and fuel standards, and energy efficiency in buildings and industry *(robust evidence, high agreement)*. Infrastructure investment decisions are significant for mitigation because they lock in high- or low- emissions trajectories over long periods. Information and voluntary programs can contribute to overall mitigation outcomes *(medium evidence, high agreement).* Designing for overlap and interactions among mitigation policies enhances their effectiveness *(robust evidence, high agreement)*. {13.6}

Removing fossil fuel subsidies could reduce emissions by 1-10% by 2030 while improving public revenue and macroeconomic performance *(robust evidence, medium agreement).* {13.6}

National mitigation policies interact internationally with effects that both support and hinder mitigation action *(medium evidence, high agreement).* Reductions in demand for fossil fuels tend to negatively affect fossil fuel exporting countries *(medium evidence, high agreement)*. Creation of markets for emission reduction credits tends to benefit countries able to supply credits. Policies to support technology development and diffusion tend to have positive spillover effects *(medium evidence, high agreement)*. There is no consistent evidence of significant emissions leakage or competitiveness effects between countries, including for emissions-intensive trade-exposed industries covered by emission trading systems *(medium evidence, medium agreement).* {13.6}

Policy packages are better able to support socio-technical transitions and shifts in development pathways toward low carbon futures than are individual policies *(robust evidence, high agreement)*. For best effect, they need to be harnessed to a clear vision for change and designed with attention to local governance context. Comprehensiveness in coverage, coherence to ensure complementarity, and consistency of policies with the overarching vision and its objectives are important design criteria. Integration across objectives occurs when a policy package is informed by a clear problem framing and identification of the full range relevant policy sub-systems. {13.7}

The co-benefits and trade-offs of integrating adaptation and mitigation are most usefully identified and assessed prior to policy making rather than being accidentally discovered (*robust evidence, high agreement*). This requires strengthening relevant national institutions to reduce silos and overlaps, increasing knowledge exchange at the country and regional levels, and supporting engagement with bilateral and multilateral funding partners. Local governments are well placed to develop policies that generate social and environmental co-benefits but to do so require legal backing and adequate capacity and resources. {13.8}

Climate change mitigation is accelerated when attention is given to integrated policy and economy wide approaches, and when enabling conditions (governance, institutions, behaviour, innovation, policy, and finance), are present *(robust evidence, medium agreement)*. Accelerating climate mitigation includes simultaneously weakening high carbon systems and encouraging low carbon systems; ensuring interaction between adjacent systems (e.g. energy and agriculture); overcoming resistance to policies (e.g., from incumbents in high carbon emitting industries), including by providing transitional support to the vulnerable and negatively affected by distributional impacts; inducing changes in consumer practices and routines; providing transition support; and addressing coordination challenges in policy and governance. {13.7, 13.9}

Economy wide packages, including economic stimulus packages, can contribute to shifting sustainable development pathways and achieving net zero outcomes whilst meeting short term economic goals *(medium evidence, high agreement)*. The 2008-9 Global Recession showed that policies for sustained economic recovery go beyond short-term fiscal stimulus to include long-term commitments of public spending on the low carbon economy; pricing reform; addressing affordability; and minimising distributional impacts. COVID-19 spurred stimulus packages and multi-objective recovery policies that may have the potential to meet short-term economic goals while enabling longer-term sustainability goals. {13.9}

13.1 Introduction

This chapter assesses national and sub-national policies and institutions. Given the scale and scope of the climate challenge, an immediate challenge for this assessment is defining its scope. Because a very wide range of institutions and policies at multiple scales carry implications for climate change, the approach followed here is to embrace a broad approach. Consequently, institutions and policies discussed include dedicated climate laws and organisations (Section 13.2) and direct mitigation policies such as carbon taxes (Section 13.6), but also those, such as sectoral ministries and their policies (Sections 13.6 and 13.7) and sub-national entities such as regional bodies, cities, and their policies (Section 13.5), the implications of which are salient to mitigation outcomes. This approach recognises that there are important linkages with international climate governance (Chapter 14), notably the role of internationally mandated Nationally Determined Contributions' in stimulating domestic policy development (Section 13.2), transnational networks in spurring sub-national action (Section 13.5), and international effects of domestic policies (Section 13.6).

This encompassing approach to climate governance is also built on a recognition that climate policymaking is routinely formulated in the context of multiple policy objectives such as energy security, energy access, urban development, and mitigation-adaptation linkages. This informs policymaking based on an understanding that to fully maximise direct and indirect climate mitigation potential, maximising co-benefits and minimising trade-offs should be explicitly sought rather than accidentally discovered and policies designed accordingly. This understanding also informs the design of institutions (Section 13.2) and policies (Sections 13.6 and 13.7) as well as the linkage between mitigation and adaptation (Section 13.8).

The chapter also engages with several new developments and an expansion of the literature since AR5.

A growing literature assesses how national policymaking on climate mitigation is dependent on national politics around, and building consensus on, climate action. This, in turn, is shaped by both nationally specific structural features (Section 13.3) and the role of different actors in the policy making process (Section 13.4). Important new avenues through which climate policy making is shaped, such as climate litigation (Section 13.4.2), and channels for public opinion formation, such as the media (Section 13.4.3) are also assessed. The chapter weaves discussions of the role of justice, understood through a discussion of procedural justice (Section 13.2), distributional justice (Section 13.6) and vulnerability (Section 13.8), and its role in creating public support for climate action (Section 13.9).

A significant new theme is the focus on the dynamic elements of policymaking, that is, how policy can be designed to accelerate mitigation. This includes through technological transitions, socio-technical transitions, shifts in development pathways and economy wide measures. This literature emphasizes the importance of examining not just individual policies, but packages of policies (Section 13.7) and how these are enabled by the alignment of policy, institutions, finance, behaviour and innovation. (Section 13.9). Also new is attention to the opportunities for economy-wide system change presented by consideration of post-COVID recovery packages, and wider efforts at sustainable economic restructuring (Section 13.9). Consistent with the discussion in Chapter 4, these larger approaches offer opportunities to undertake systemic restructuring and shift development pathways.

Finally, the chapter addresses core themes from earlier assessment reports, but seeks to do so in an enhanced manner. The discussion of climate institutions assesses a growing literature on climate law, as well as both purpose-built climate organisations and the layering of climate responsibilities on existing organisations at national and sub-national scales (Section 13.2). The discussion of policies focuses on an ex post assessment of policies, as well as the interaction among them, and learnings on how they can be combined in packages (Sections 13.6 and 13.7). It also lays out a framework for their assessment that encompasses environmental effectiveness, economic effectiveness, distributional outcomes, co-benefits, institutional requirements, as well as a new criterion of transformational potential (Section 13.6).

The aim of this chapter is to assess the full range of the multi-stranded and diverse literature on climate institutions and policy, reflecting the richness of real-world climate governance.

13.2 National and sub-national institutions and governance

Institutions and governance arrangements can help address 'policy gaps' and 'implementation gaps' (Cross-Chapter Box 4 in Chapter 4) that hinder climate mitigation. While the need for institutions and governance is universal, individual country approaches vary, based on national approaches and circumstances, as discussed in this section.

Since AR5, the understanding of climate governance has become more encompassing and complex, involving multiple actors, decision-making arenas, levels of decision-making and a variety of political goals. Climate governance sometime directly targets GHG emissions; at other times mitigation results from measures that primarily aim to solve other issues, for instance relating to food production, forest management, energy markets, air pollution, transport systems or technology development, but with mitigation or adaptation effects (Karlsson et al. 2020).

Consistent with usage in this assessment, institutions are rules, norms and conventions that guide, constrain or enable behaviours and practices, including the organisations through which they operate, while governance is the structure, processes and actions that public and private actors use to address societal goals (See Glossary for complete definitions). Multiple terms are used in the literature to discuss climate governance, often varying across countries. Climate laws, or legislation, is passed by legislatures, and often sets the overarching governance context, but the term is also used to refer to legislation that is salient to climate outcomes even if not centrally focused on climate change. National strategies, often referred to as plans, most often operate through executive action by government, set guidance for action and often are not legally binding, although strategies may also be enshrined in law. Both laws and strategies may elaborate targets, or goals, for emissions outcomes, although these are not necessary components of laws and strategies. While laws typically operate at the national level (states may also make laws in federal nations), strategies, plans and targets may also operate at the sub-national level.

This section begins with a discussion of national laws for climate action (Section 13.2.1), followed by a discussion of national strategies (Section 13.2.2). The third section examines institutions (Section13.2.3), including organisations that are established to govern climate actions, and the final section explores sub-national institutions and their challenges in influencing climate mitigation (Section 13.2.4).

13.2.1 Climate laws

National laws that govern climate action often set the legal basis for climate action (Averchenkova et al. 2021). This legal basis can serve several functions: establish a platform for transparent target setting and implementation (Bennett 2018); provide a signal to actors by indicating intent to harness state authority behind climate action (Scotford and Minas 2019); promise enhanced regulatory certainty (Scotford et al. 2017); create law-backed agencies for coordination, compliance and accountability (Scotford and Minas 2019); provide a basis for mainstreaming mitigation into sector action, and create focal points for social mobilisation (Dubash et al. 2013) *(medium evidence, high agreement)*. For lower/middle income countries, in particular, the existence of a law may also attract international finance by serving as a signal of credibility (Fisher et al. 2017). The realisation of these potential governance gains depends on local context, legal design, successful implementation, and complementary action at different scales.

There are both narrow and broad definitions of what counts as 'climate laws'. The literature distinguishes direct climate laws that explicitly considers climate change causes or impacts -- for example through mention of greenhouse gas reductions in its objectives or title (Dubash et al. 2013) -- from indirect laws that have 'the capacity to affect mitigation or adaptation' through the subjects they regulate, for example, through promotion of co-benefits, or creation of reporting protocols (Scotford and Minas 2019). Closely related is a 'sectoral approach' based on the layering of climate considerations into existing laws in the absence of an overarching framework law (Rumble 2019). Many countries also adopt executive climate strategies (discussed in Section 13.2), which may either coexist with or substitute for climate laws, and that may also be related to a country's NDC process under the Paris Agreement.

The prevalence of both direct and indirect climate laws has increased considerably since 2007, although definitional differences across studies complicate a clear assessment of their relative importance (Nachmany and Setzer 2018; Iacobuta et al. 2018) *(medium evidence, high agreement)*. Direct climate laws – with greenhouse gas limitation as a direct objective -- had been passed in 56 countries (of 194 studied) covering 53% of emissions in 2020, with most of that rise happening between 2010 and 2015 (see Figure 13.1). Both direct and indirect laws - those that have an effect on mitigation even if this is not the primary outcome – is most closely captured by the "Climate Change Laws of the World" database, which illustrates the same trend of growing prevalence, documenting 694 mitigation-related laws by 2020 versus 558 in 2015 and 342 in 2010 (Nachmany and Setzer 2018; LSE Grantham Research Institute on Climate Change and the Environment 2021).[1] Among these, the majority are accounted for by sectoral indirect laws. For example, a study of Commonwealth countries finds that a majority of these countries have not taken the route of a single overarching law, but rather have an array of laws across different areas, for example, Indian laws on energy efficiency and Ghana's laws on renewable energy promotion (Scotford et al. 2017).

Some direct climate laws may serve as 'framework' laws (Averchenkova et al. 2017; Rumble 2019) that set an overarching legal context within which other legislation and policies operate. Framework laws are intended to provide a coherent legal basis for action, to integrate past legislation in related areas, set clear directions for future policy, and create necessary processes and institutions (Townshend et al. 2013; Fankhauser et al. 2018; Averchenkova et al. 2017; Rumble 2019; Averchenkova et al. 2021) *(medium evidence, medium agreement)*. There are a variety of approaches to framework laws. Reviews of climate legislation, many of which draw particularly from the long-standing UK Climate Change Act, suggest the need for statutory targets with a long-term direction, shorter term instruments such as carbon budgets to induce action toward targets, a clear assignment of duties and responsibilities including identification of policies and responsibility for their implementation, annual reporting to Parliament; an independent body to support evidence-based decision making and rules to govern information collection and provision (Barton and Campion 2018; Fankhauser et al. 2018; Averchenkova et al. 2021; Abraham-Dukuma et al. 2020).

However, country examples also suggest other, different approaches to framework laws. Korea's Framework Act on Low Carbon, Green Growth seeks to shift business and society toward green growth through a process of strategy setting and action plans (Jang et al. 2010). Kenya's framework Climate Change Act creates an institutional structure to mainstream climate considerations into sectoral decisions, one of several examples across Africa of efforts to create framework legislation to promote mainstreaming (Rumble 2019). Mexico's General Law on Climate Change includes sectoral emission targets, along with the creation of coordinating institutions across ministries and sub-national authorities (Averchenkova and Guzman Luna 2018). Consequently, different countries have placed emphasis on different aspects of framework laws, although the most widely prevalent approach is that exemplified by the UK.

Climate laws spread through multiple mechanisms, including the impetus provided by international negotiation events, diffusion by example across countries, and domestic factors such as business cycles *(medium evidence, medium agreement)*. Major landmark events under the UNFCCC have been associated with increases in national legislation (Iacobuta et al. 2018), with a stronger effect in countries where international commitments are binding (Fankhauser et al. 2016). Diffusion through example of legislation

FOOTNOTE [1] Data from climate-laws.org, search for mitigation focused legislation for different time frames. Accessed Oct 31, 2021.

from other countries has been documented (Fleig et al. 2017; Torney 2017; Inderberg 2019; Torney 2019; Fankhauser et al. 2016). For example, the UK Climate Change Act was an important influence in pursuing similar acts in Finland and Ireland (Torney 2019) and was also considered in the formulation of Mexico's General Law on Climate Change (Averchenkova and Guzman Luna 2018). The presence of a framework law is positively associated with creation of additional supportive legislation (Fankhauser et al. 2015). Domestic contextual factors can also affect the likelihood of legislation such as a weak business cycle that can impact the political willingness to pass legislation (Fankhauser et al. 2015). In some cases, civil society groups play a role as advocates for legislation, as occurred in the UK (Lockwood 2013; Lorenzoni and Benson 2014; Carter and Childs 2018; Devaney et al. 2020) and in Germany in the build up to passage of their respective Climate Change Act (Flachsland and Levi 2021).

The performance of framework laws suggests a mixed picture. While the structure of the UK Act successfully sets a direction of travel and has resulted in a credible independent body, it performs less well in fostering integration across sectoral areas and providing an enforcement mechanism (Averchenkova et al. 2021). A review of seven European climate change acts concludes that overall targets may not be entirely aligned with planning, reporting and evaluation mechanisms, and that sanction mechanisms are lacking across the board (Nash and Steurer 2019), which limit the scope for legislation to perform its integrative task. These observations suggest the need for careful attention to the design of framework laws.

There is extremely limited evidence on the aggregate effects of climate laws on climate outcomes, although there is a broader literature assessing climate policies (see Section 13.6 in this Chapter and Cross-Chapter Box 10 in Chapter 14). A single assessment of direct and indirect climate laws as well as relevant executive action across a global database finds a measurable and positive effect: global annual emissions have reduced by about 5.9GtCO_2 compared to an estimation of what they otherwise would have been (Eskander and Fankhauser 2020). Climate laws require further research, including on the quantification of impact, framework versus sectoral approaches, and the various mechanisms through which laws act - target setting, creating institutional structures, mainstreaming and ensuring compliance.

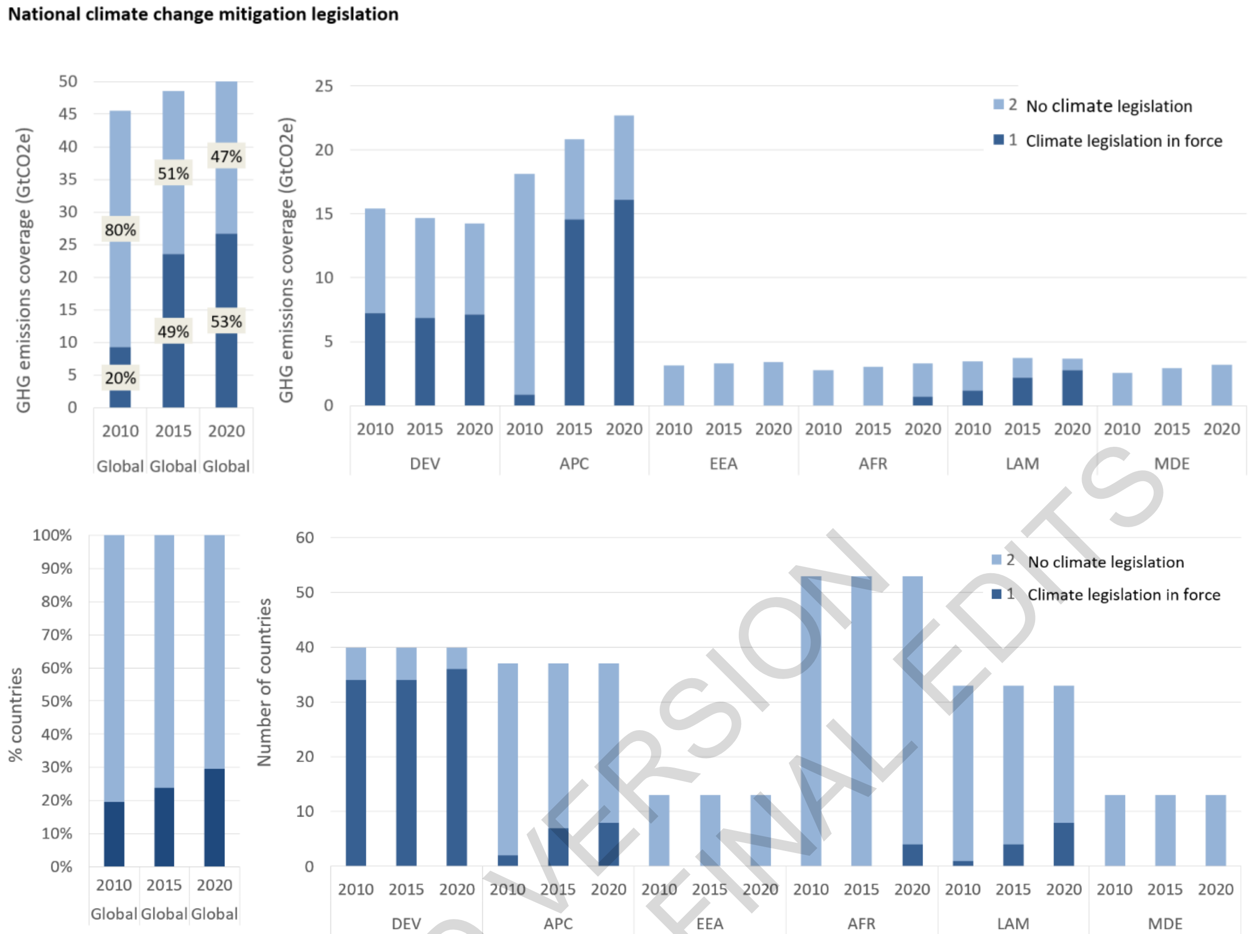

Figure 13.1 Prevalence of legislation by emissions and number of countries across regions

Top: Shares of global GHG emissions under national climate change legislations – in 2010, 2015 and 2020. Emissions data used are for 2019, since emissions shares across regions deviated from past patterns in 2020 due to COVID.

Bottom: Number of countries with national climate legislation - in 2010, 2015, and 2020

Climate legislation is defined as an act passed by a parliament that includes in its title or objectives reductions in GHGs.

AR6 regions: DEV = Developed countries; APC = Asia and developing Pacific; EEA = Eastern Europe and West-Central Asia; AFR = Africa; LAM = Latin America and the Caribbean; MDE = Middle East.

Source: Updated and adapted from (Iacobuta et al. 2018) to reflect AR6 regional aggregation and recent data.

13.2.2 National strategies and Nationally Determined Contributions

National climate strategies, which are often formulated through executive action, contribute to climate governance in several ways. Strategies enable discussion of low-emissions pathways while accounting for uncertainty, national circumstances and socio-economic objectives (Falduto and Rocha 2020).

They frequently set out long term emission goals and possible trajectories over time, with analysis of technological and economic factors (Levin et al. 2018; WRI 2020). This can include quantitative modelling of low-emissions transitions and their economic effects to inform policymakers and stakeholders of potential outcomes (Waisman et al. 2019; Weitzel et al. 2019). Scenario analysis can be used to explore how to make strategies more robust in the face of uncertainty (Sato and Altamirano 2019). Strategies and their regular revision can support long-term structural change by stimulating deliberation and learning (Voß et al. 2009), and to make the link between mitigation and adaptation objectives and actions (Watkiss and Klein 2019; Hans et al. 2020). As part of the Paris Agreement process, several countries have prepared and submitted long-term low-emissions development strategies (Levin et al. 2018), while others have different forms of national climate change strategies independently of the UNFCCC process. Strategies set over time by the European Union are discussed in Box 13.1.

Nationally Determined Contributions (NDCs) prepared under the Paris Agreement may be informed by national strategies (Rocha and Falduto 2019). But the process of preparing NDCs can itself raise political awareness, encourage institutional innovation and coordination, and engage stakeholders (Röser et al. 2020). Nationally determined contributions (NDCs) illustrate a diversity of approaches: direct mitigation targets, strategies, plans and actions for low GHG emission development, or the pursuit of mitigation co-benefits resulting from economic diversification plans and/or adaptation actions (UNFCCC Secretariat 2021). Figure 13.2 shows that the prevalence of emission targets increased across all regions between 2010 and 2020, the period during which the Paris Agreement was reached.

The NDCs vary in their scope, content and time frame, reflecting different national circumstances, and are widely heterogeneous in both stringency and coverage of mitigation efforts (Pauw et al. 2018; Campagnolo and Davide 2019; Pauw et al. 2019; UNFCCC Secretariat 2016, 2021). The mitigation targets in the new or updated NDCs range from economy-wide absolute emission reduction targets to strategies, plans and actions for low-emission development, with specific timeframes or implementation periods specified. Less than 10% of parties' NDCs specify when their emissions are expected to peak and some of these parties express their target as a carbon budget (UNFCCC Secretariat 2021). Many long term strategies submitted by Parties to the UNFCCC refer to net zero emissions or climate neutrality, carbon neutrality, or GHG neutrality with reference to 2050, 2060 or mid-century targets (UNFCCC Secretariat 2021). The growing prevalence and coverage of emission targets is documented in Figure 13.2.

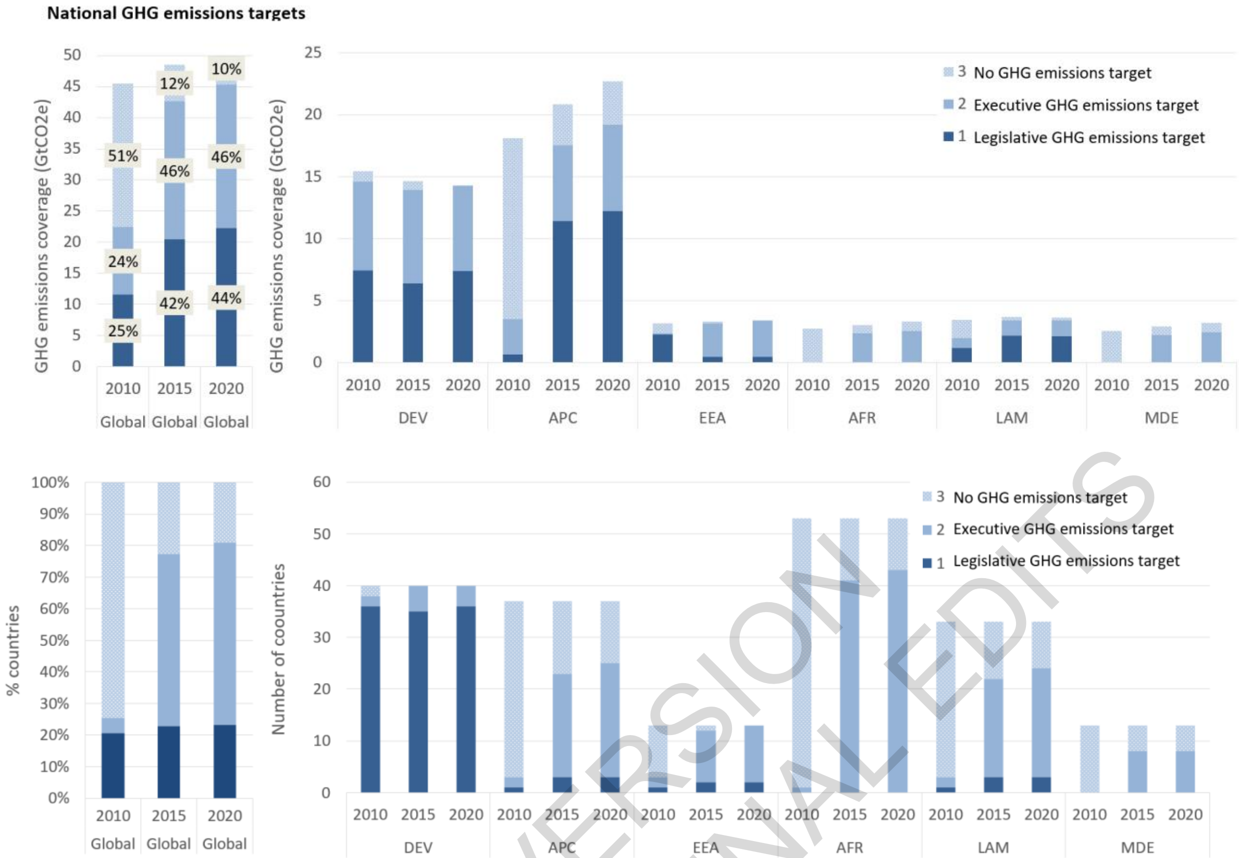

Figure 13.2 Prevalence of targets by emissions and number of countries across region

Top: Shares of global GHG emissions under national climate emission targets – in 2010, 2015 and 2020. Emissions data used are for 2019, since emissions shares across regions deviated from past patterns in 2020 due to COVID.

Bottom: Number of countries with national climate emission targets - in 2010, 2015, and 2020

Emissions reductions targets were taken into account as a legislative target when they were defined in a law or as part of a country's submission under the Kyoto Protocol, or as an executive target when they were included in a national policy or official submissions under the UNFCCC. Targets were included if they were economy wide or included at least the energy sector. The proportion of national emissions covered are scaled to reflect coverage and whether targets are in GHG or CO_2 terms.

AR6 regions: DEV = Developed countries; APC = Asia and developing Pacific; EEA = Eastern Europe and West-Central Asia; AFR = Africa; LAM = Latin America and the Caribbean; MDE = Middle East.

Source: Updated and adapted from (Iacobuta et al. 2018) to reflect AR6 regional aggregation and recent data.

Almost all Parties outlined domestic mitigation measures as key instruments for achieving mitigation targets in specific priority areas such as energy supply (89%), transport (80%), buildings (72%), industry (39%), agriculture (67%), LULUCF (75%) and waste (68%). Renewable energy generation was the most frequently indicated mitigation option (84%), followed by improving energy efficiency of buildings (63%) and multisector energy efficiency improvement (48%); afforestation, reforestation and revegetation (48%); and improving energy efficiency of transport (45%) (UNFCCC Secretariat 2021). Parties often communicated mitigation options related to the circular economy, including reducing waste (29%) and recycling waste (30%) and promoting circular economy (25%). Many Parties highlighted policy coherence and synergies between their mitigation measures and development priorities, which included long-term low-emission development strategy(ies) (LT-LEDS), the sustainable development goals (SDGs) and, for some, green recovery from the COVID-19 pandemic.

Some countries approach NDCs as an opportunity to integrate mitigation objectives and broader economic shifts or sectoral transformations *(medium evidence, medium agreement)*. For example, Brazil's 2016 NDC focussed on emissions from land use change, including agricultural intensification, to align mitigation with a national development strategy of halting deforestation in the Amazon, and increasing livestock production (De Oliveira Silva et al. 2018). While the forest sector accounts for the bulk of Madagascar's mitigation potential, its NDC promotes GHG mitigation in both AFOLU and energy sectors to maximize co-benefits, and achieve a higher number of sustainable development goals (SDGs) (Nogueira et al. 2020).

START BOX 13.1 HERE

Box 13.1 EU climate policy portfolio and the European Green Deal

The European Union (EU)[2] has developed an encompassing climate governance framework (Kulovesi and Oberthür 2020), having ratified the Kyoto Protocol in 2002. In 2003 the EU adopted an Emissions Trading System for sectors with large GHG emitters, which started in 2005. From 2007 to 2009, the EU revised its climate policies, including for vehicle emissions, renewable energy and energy efficiency, and adopted targets for 2020 for GHG emissions reductions, renewable energy shares and energy efficiency improvements. It also adopted in 2009 an Effort Sharing Decision for Member States' emissions reductions for the period 2013 - 2020 in sectors not covered by the ETS (Boasson and Wettestad 2013; Bertoldi 2018). The ETS has been improved multiple times, including through a 2015 Market Stability Reserve to reduce the surplus of emission allowances (Wettestad and Jevnaker 2019; Chaton et al. 2018). In 2010, the European Commission created a directorate-general (equal to a ministry at the domestic level) for Climate Action. Between 2014 and 2018, the EU agreed on emission reduction targets for 2030 of 30% GHG emission reductions compared to 1990, and again revised its climate policy portfolio including new targets for renewable energies and energy efficiency and a new Effort Sharing Regulation (Fitch-Roy et al. 2019a; Oberthür 2019).

From 2018, climate planning and reporting has been regulated by the EU Governance Regulation (Regulation (EU) 2018/1999), requiring member states to develop detailed and strategic National Energy and Climate Plans (Knodt et al. 2020). In 2019, the European Commission, backed by the European Council (heads of states and government in the EU) and the European Parliament, launched a new broad climate and environment initiative; the 'European Green Deal', implying the revision of many EU polices and introducing the Climate Pact (European Commission 2019a). This roadmap develops a 'new growth strategy for the EU' aimed at reaching climate neutrality by 2050 and spans multiple sectors. In 2020, the European Commission introduced a new climate law establishing the framework for achieving the climate neutrality by 2050 principle, and upgraded its 2030 GHG emission reduction target to at least net 55% reduction, which was adopted in June 2021 (European Commission 2020a). In June 2021, the new policy package "Fit for 55" was adopted by the Commission; the packages included a proposal for the revision of the ETS, including its extension to shipping and a separate emission trading system for road transport and buildings, a revision of the effort sharing regulation, an amendment of the regulation setting CO_2 emission standards for cars and vans, a revision of the energy tax directive, a new carbon border adjustment mechanism, a revision of renewable energy and energy efficiency targets and directives, and a new social climate funds to make the transition to climate neutrality fair.

FOOTNOTE [2] The European Union is an international organization that is discussed here because it plays a large role in shaping climate obligations and policies of its Member States.

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13.2.3 Approaches to national institutions and governance

13.2.3.1 The forms of climate institutions

Universal 'best-practice' formulations of organisations may not be applicable across country contexts, but institutions that are suited to national context can be ratcheted up over time in their scope and effectiveness *(medium evidence, medium agreement)*. National climate institutions take diverse forms because they emerge out of country specific interactions between national climate politics and existing institutional structures. Certain institutional forms tend to be common across countries, such as expert climate change commissions; a review finds eleven such institutions in existence as of mid-2020. Although this institutional form may be common, these commissions vary in terms of expertise, independence and focus (Abraham-Dukuma et al. 2020), reinforcing the important shaping role of national context.

A review of institutions in eight countries suggests three broad processes through which institutions emerge: 'purpose-built' dedicated institutions focused explicitly on mitigation; 'layering' of mitigation objectives on existing institutions; and 'latent' institutions created for other purposes that nonetheless have implications for mitigation outcomes (Dubash 2021). In relatively few countries do new, purpose-built, legally-mandated bodies created specifically for climate mitigation exist although this number is growing; examples include the UK (Averchenkova et al. 2018), China (Teng and Wang 2021), Australia (Keenan et al. 2012) and New Zealand (Timperley 2020). These cases indicate that dedicated and lasting institutions with a strategic long-term focus on mitigation emerge only under conditions of broad national political agreement around climate mitigation as a national priority (Dubash 2021). However, the specific forms of those institutions differ, as illustrated by the case of the UK's Climate Change Committee established as an independent agency (see Box 13.2) and China, which is built around a top-down planning structure (See Box 13.3).

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Box 13.2 Climate change institutions in the UK

The central institutional arrangements of climate governance in the UK were established by the 2008 Climate Change Act (CCA): statutory five-year carbon budgets; an independent advisory body, the Committee on Climate Change (CCC); mandatory progress monitoring and reporting to Parliament; and continuous adaptive planning following a five-yearly cycle. The CCC is noteworthy as an innovative institution that has also been emulated by other countries.

The design of the CCC was influenced by the concept of independent central banking (Helm et al. 2003). It has established a reputation for independent high quality analysis and information dissemination, is frequently referred to in Parliament and widely used by other actors in policy debates, all of which suggest a high degree of legitimacy (Averchenkova et al. 2018). However, since the CCC only recommends rather than sets budgets (McGregor et al. 2012), accountability for meeting the carbon budgets works primarily through reputational and political effects rather than legal enforcement.

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Box 13.3 China's climate change institutions

Climate governance in China features a combination of top-down planning and vertical accountability (Sims Gallagher and Xuan 2019; Teng and Wang 2021). An overarching coordination role is performed by the Leading Group on Carbon Peaking and Carbon Neutrality, appointed by and reporting to the Central Committee of the Chinese Communist Party, and the National Leading Group on Climate Change Response, Energy Conservation, and Emissions Reduction (NLGCCR), headed by the Premier and consisting of more than 30 ministers (Wang et al. 2018a). The Department of Climate Change (DCC) under the Ministry of Ecology and Environment (MEE) is the primary agency in charge of climate issues, with a corresponding local Bureau of Ecology and Environment in each province or city. While MEE is the leading agency for climate policy, the National Development and Reform Commission (NDRC) is the leading agency for setting overall and industry-specific targets in five-year plans, and thus has a key role in coordinating carbon emissions targets with energy and industrial development targets (Wang et al. 2019; Yu 2021). Involvements of ministries related to foreign affairs, public finance, science and technology, as well as sector ministries such as transportation, construction, and manufacturing industries are also needed to push forward sector-specific climate initiatives. At subsidiary levels of government carbon intensity targets are enforced through a "targets and responsibilities" system that is directly linked to the evaluation of governments' performances (Lin 2012a; Li et al. 2016).

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Where economy-wide institutions do not exist, new institutions may still address sub-sets of the challenge. In Australia, while political conditions resulted in the repeal of an overarching Clean Energy Act in 2014, although a Climate Change Authority continued, other institutions primarily focused on the energy sector such as the Clean Energy Regulator, the Clean Energy Finance Corporation, and the Australia Renewable Agency continued to shape energy outcomes (MacNeil 2021).

Where new dedicated organisations have not emerged, countries may layer climate responsibilities on existing institutions; the addition of mitigation to the responsibilities of the US Environmental Protection Agency is an example (Mildenberger 2021). Layering is also a common approach when climate change is embedded within consideration of multiple objectives of policy. In these cases, climate institutions tend to be layered on sectoral institutions for the pursuit of co-benefits or broader development concerns. Examples include India, where energy security was an important objective of renewable energy promotion policy (Pillai and Dubash 2021), Brazil's mitigation approach focused on sectoral forest policy (Hochstetler 2021) and South Africa's emphasis on job creation as a necessary factor in mitigation policy (Chandrashekeran et al. 2017; Rennkamp 2019). Prior to this process of layering, sectoral institutions, such as in forest and energy sectors, may play an important latent role in shaping climate outcomes, before climate considerations are part of their formal mandate.

New rules and organisations are not only created, they are also dismantled or allowed to wither away. Cases of institutional dismantling or neglect include the Australian Clean Energy Act (Crowley 2017; MacNeil 2021), the Indian Prime Minister's Council on Climate Change, which, while formally functional, effectively does not meet (Pillai and Dubash 2021), and the weakening of climate units inside sectoral ministries in Brazil (Hochstetler 2021). While there is limited literature on the robustness of climate institutions, case studies suggest institutions are more likely to emerge, persist and be effective when institutions map to a framing of climate change that has broad political support *(medium evidence, medium agreement)*. Thus while mitigation focused framings and institutions may win political support in some countries, in other cases sectorally focused or multiple objectives oriented institutions may be most useful and resilient (Dubash 2021).

13.2.3.2 Addressing climate governance challenges

Climate governance challenges include ensuring coordination, building consensus by mediating conflict, and setting strategy *(medium evidence, high agreement)*. Coordination is important because climate change is an all-of-economy and society problem that requires cross-sectoral and cross-scale action; building consensus is needed because large scale transformations can unsettle established interests; and strategy setting is required due to the transformative and time-bound nature of climate mitigation (Dubash et al. 2021). Yet, climate institutions have a mixed record in addressing these challenges.

Institutions that provide coordination, integration across policy areas and mainstreaming are particularly important given the scope and scale of climate change (See Section 13.7) (Candel and Biesbroek 2016; Tosun and Lang 2017). Ministries of environment are often appointed as *de facto* agents of coordination, but have been hampered by their limited regulative authority and ability to engage in intra-governmental bargaining with ministries with larger budgets and political heft (Aamodt 2018).

Creation of a high-level coordinating body to coordinate across departments and mainstream climate into sectoral actions is another common approach (Oulu 2015). For example, Kenya has created a National Climate Change Council, which operates through a climate change directorate in the environment ministry to mainstream climate change at the county level (Guey and Bilich 2019). Zhou and Mori (2011) suggest that well-functioning inter-agency coordination mechanisms require support from heads of government, involvement by industry and environment agencies; and engagement by multiple sectoral agencies. However, coordination mechanisms without a clear authority and basis for setting directions run the risk of 'negative coordination', a process through which ministries comment on each other's proposals, removing any ideas that run counter to the interests of their own ministry, leading to even weaker decisions (Flachsland and Levi 2021). Countries with dedicated, new climate institutions tend to have a more explicit and authorised body for climate coordination, such as China's National Leading Group' (See Box 13.3).

Without explicit coordination with finance ministries, there is a risk of parallel and non-complementary approaches. For example, the South African Treasury pursued a carbon tax without clear indication of how it interfaced with a quantitative sectoral budget approach espoused by the environment ministry (Tyler and Hochstetler 2021). Skovgaard (2012) suggests that there is an important distinction between finance ministries that bring a limiting 'budget frame' to climate action, versus a 'market failure frame' that encourages broader engagement by relevant ministries.

Coordination within federal systems poses additional complexities, such as overlapping authority across jurisdictions, multiple norms in place, and approaches to coordination across scales (Brown 2012). Multilevel governance systems such as the EU can influence the design and functioning of climate policies and institutions in member states, such as Germany (Skjærseth 2017; Jänicke and Wurzel 2019; Flachsland and Levi 2021) and the UK (Lockwood 2021a). In some cases, this can result in distinct European modes of governance as has been suggested occurred in the case of wind energy (Fitch-Roy 2016).

Within countries, institutional platforms allow federal and subnational governments to negotiate and agree on policy trajectories (Gordon 2015). In Germany, cooperation is channelled through periodic meetings of environment ministers and centre-state working groups (Weidner and Mez 2008; Brown 2012), and in Canada through bilateral negotiations and side-payments between scales of government (Rabe 2007; Gordon 2015). Federal systems might allow for sub-national climate action despite constraints at the federal level, as has occurred in Australia (Gordon 2015; MacNeil 2021) and the United States (Rabe 2011; Jordaan et al. 2019; Bromley-Trujillo and Holman 2020; Thompson et al. 2020). Where agenda-setting rests with the central government, coordination may operate through targets, as with China (Qi and Wu 2013), or frameworks for policy action, as in India (Vihma 2011; Jogesh and Dubash 2015).

Because transition to a low-carbon future is likely to create winners and losers over different time scales; institutions are needed to mediate these interests and build consensus on future pathways (Kuzemko et al. 2016; Lockwood et al. 2017; Finnegan 2019; Mildenberger 2020). Institutions that provide credible knowledge can help support ambition. For example, analysis by the UK Climate Change committee has been harnessed, including by non-state actors, to prevent backsliding on decisions (Lockwood 2021a). Institutions can also help create positive feedback by providing spaces in decision making for low carbon interests

(Aklin and Urpelainen 2013; Roberts et al. 2018; Lockwood et al. 2017; Finnegan 2019). For example, a renewable energy policy community emerged in China through key agenda setting meetings (Shen 2017), and in India, a National Solar Mission provided a platform for the renewable energy industry (Pillai and Dubash 2021). Conversely, institutions can also exert a drag on change through 'regulatory inertia,' as in the case of the UK energy regulator Ofgem, which has exercised veto powers in ways that may limit a low carbon transition (Lockwood et al. 2017).

Institutions can also create spaces to accommodate concerns of other actors (Upadhyaya et al. 2021). Deliberative bodies, such as Germany's Enquete Commission (Weidner and Mez 2008; Flachsland and Levi 2021) or the Brazilian Forum on Climate Change (Tyler and Hochstetler 2021) provide a space for reconciling competing visions and approaches to climate change. Many countries are creating deliberative bodies to forge 'Just Transition' strategies (Section 13.9). A recent innovation is the creation of Citizens' Assemblies that bring together representative samples of citizens to deliberate on policy questions with the intent of informing them (Sandover et al. 2021; Devaney et al. 2020). The ability of institutions to forge agreement also rests on attention to procedural justice (See Box 13.4).

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Box 13.4 Procedural justice

Decision making consistent with energy and climate justice requires attention to procedural justice (McCauley and Heffron 2018), which includes how decisions are made, and who is involved and has influence on decisions (Sovacool and Dworkin 2015). Procedural justice emphasizes the importance of equitable access to decision-making processes and non-discriminatory engagement with all stakeholders (Jenkins et al. 2016), attention to the capability, particularly of marginalised groups, to shape decisions (Holland 2017) and recognition of their specific vulnerabilities in collective political processes (Schlosberg 2012). Consensus-building institutions should avoid reducing normative questions to technical ones, recognising that values, interests and behaviours are all shaped by ongoing climate governance (Schwanen 2021; Ryder 2018). Additionally, communities affected by low-carbon transition may face challenges in articulating their understandings and experiences, which needs to be addressed in the design of climate institutions (Schwanen 2021; Ryder 2018).

Spatially localized alternative discourses of justice are often more recognised socially than national and universal framings of climate justice (Bailey 2017). Participatory forms of governance such as climate assemblies and citizen juries (Ney and Verweij 2015) can help enhance the legitimacy of institutional decisions, even while empirical assessments suggest that these approaches continue to face practical challenges (Sandover et al. 2021; Creasy et al. 2021; Devaney et al. 2020).

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Since addressing climate change requires transformative intent and shifting development pathways (Section 13.9 in this Chapter, Section 1.6 in Chapter 1, Section 3.6 in Chapter 3, Sections 4.3 and 4.4 in Chapter 4, Section 17.3.2 in Chapter 17, and Cross-Chapter Box 5 in Chapter 4), institutions that can devise strategies and set trajectories are useful enablers of transformation. Strategy setting often requires an overarching framework such as through framework laws that set targets (Averchenkova et al. 2017), or identify key sectors and opportunities for low-carbon transition (Hochstetler and Kostka 2015) and innovation (UNEP 2018). Few countries have built deliberate and lasting institutions that provide strategic intent, and those that have, have pursued different approaches. The UK's approach rests on five-yearly targets (Box 13.2); Germany requires sectoral budgets enforced through the Bundestag (Flachsland and Levi 2021); and China uses an apex decision-body to set targets (Box 13.3) (Teng and Wang 2021).

Addressing all of these governance concerns – coordination, mediating interests, and strategy setting – require attention to institutional capacity. These include the capacity to address ‘upstream’ policy issues of agenda setting, framing, analysis and policy design; pursue goals even while mediating interests (Upadhyaya et al. 2021); identify and manage synergies and trade-offs across climate and development objectives (Ürge-Vorsatz et al. 2014; von Stechow et al. 2015; McCollum et al. 2018); identify and choose amongst possible policy options (Howlett and Oliphant 2010); identify areas for transformation and the means to induce innovation (Patt 2017; UNEP 2018); and developing the ability to monitor and evaluate outcomes (Upadhyaya et al. 2021) (See Box 13.5). Domorenok et al. (2021) highlight different aspects of the capacity challenge particularly necessary for integrated policy making including: the capacity for horizontal and vertical coordination; implementation capacity including the independence of the state from interests; and administrative capacity required to address compound problems. At a basic level, questions of governmental capacity – the numbers and training of personnel – can shape the choices available for climate institutions and their ability to be strategic (Richerzhagen and Scholz 2008; Harrison and Kostka 2014; Kim 2016). Box 13.5 describes South Africa’s approach to building monitoring and evaluation capacity.

The perceived need for attention to institutional capacity is highlighted by the fact that the NDCs of 113 developing countries out of 169 countries studied list capacity building as a condition of NDC implementation (Pauw et al. 2020). While international support for capacity is widely articulated as essential for many countries (Khan et al. 2020), ensuring the form of capacity is appropriate, effective and led domestically remains a challenge (Nago and Krott 2020; Sokona 2021).

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Box 13.5 South Africa’s monitoring and evaluation system

South Africa’s national monitoring and evaluation system provides high-level guidance on information requirements and assessment methodologies (DEA 2015). The country is developing a comprehensive, integrated National Climate Change Information System, to enable tracking, analysis and enhancement of South Africa’s progress towards the country’s transition to a low-carbon economy and climate-resilient society (DFFE Republic of South Africa 2021). It includes information on GHG emission reductions achieved, observed and projected climate change, impacts and vulnerabilities, the impact of adaptation and mitigation actions, financial flows and technology transfer activities. South Africa’s approach is premised upon continuous learning and improvement through a phased implementation approach (DEA 2019).

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13.2.4 Institution building at the sub-national level

Jurisdiction over significant mitigation-related arenas like planning, housing and community development reside at the subnational level. To address linkages between mitigation and local concerns, subnational actors engage in institution building within a broader socio-economic and political context, with actors and institutions at a multitude of scales shaping the effectiveness of subnational-scale interventions (Romero-Lankao et al. 2018a). Mitigation policies may demand coordination between sectoral and jurisdictional units that historically have not collaborated; they may require subnational actors to confront politically sensitive issues such as carbon taxes or increases in utility rates; and they may demand a redistribution of resources to protect endangered ecosystems or vulnerable populations (Hughes and Romero-Lankao 2014).

Subnational actors have built climate institutions by creating new visions and narratives, by setting new entities or committing existing offices, providing them with funds, staff and legal authority, or by experimenting with innovative solutions that could be transferred to other local governments or scaled nationally (Hoffmann 2011; Hoornweg et al. 2011; Aylett 2015; Hughes 2019b; Hughes and Romero-Lankao

2014; Romero-Lankao et al. 2015). These actors have also created task forces, referendums, coordination of financial and human resources, technical assistance, awareness campaigns and funding (Castán Broto 2017; Romero-Lankao et al. 2018a; Hughes 2019b). National governments can play a key role supporting planning for climate change at the regional and national level, for example, through the articulation of climate change action in national urban politics (Cobbinah et al. 2019; Van Den Berg et al. 2018).

13.2.4.1 Significance of subnational networks

Multi-jurisdictional and multi-sectoral sub-national networks in dozens of countries globally have helped build climate institutions. They have also facilitated social and institutional learning, and addressed gaps in national policy (Holden and Larsen 2015; Jordan et al. 2015; Setzer 2015; Haarstad 2016; Hermwille 2018; Kammerer and Namhata 2018; Rashidi and Patt 2018; Westman and Castan Broto 2018; Lee 2019; Schwartz 2019; Lee and Jung 2018).

Transnational networks have opened opportunities for subnational actors to play a crucial mitigation role in political stalemates (Jones 2014; Schwartz 2019). The C40, the Global Covenant of Mayors for Climate and Energy, and ICLEI have disseminated information on best practices and promoted knowledge sharing between subnational governments (Lee 2013; Hakelberg 2014; Heidrich et al. 2016; Kona et al. 2016; Di Gregorio et al. 2020) (see Section 14.5.5 in Chapter 14). Organizations such as the US Carbon Cycle Working Group of the United States Global Change Research Program, the Australian Climate Action Network, and the Mexican Metropolitan Environmental Commission have helped facilitate coordination and learning across multiple jurisdictions and sectors, and connected ambiguous spaces between public, private and civil society actors (Horne and Moloney 2019; Romero-Lankao et al. 2015; Hughes 2019b).

Transnational networks have limited influence on climate policies where national governments exert top-down control (e.g., in the city of Rizhao, China) (Westman et al. 2019); where subnational actors face political fragmentation, lack regulations, and financial and human resources; or where vertically-integrated governance exists, as in State of São Paulo, Santiago de Chile, and Mexico City (Setzer 2017; Romero-Lankao et al. 2015).

Public support for sub-national climate institutions increases when climate policies are linked to local issues such as travel congestion alleviation or air pollution control (Puppim de Oliveira 2013; Romero-Lankao et al. 2013; Simon Rosenthal et al. 2015; Romero-Lankao et al. 2015; Ryan 2015), or when embedded in development priorities that receive support from the national government or citizens (Jörgensen et al. 2015b; Floater et al. 2016; Dubash et al. 2018). For example, Indian cities have engaged in international climate cooperation seeking innovative solutions to address energy, water and infrastructure problems (Beermann et al. 2016).

13.2.4.2 Factors influencing institution building at the subnational level

Availability of federal funding is a fundamental pillar of city actors' capacity to develop mitigation policies. Administrative structures, such as the presence of a professional city manager and staff assigned specifically to climate efforts (Simon Rosenthal et al. 2015). Cooperation between administrative departments, and the creation of knowledge and data on energy use and emissions are also essential for mitigation planning (Hughes and Romero-Lankao 2014; Ryan 2015). For example, the high technical competency of Tokyo's bureaucracy combined with availability of historical and current data enabled the city's unique cap-and-trade system on large building facilities (Roppongi et al. 2017).

Visions and narratives about the future benefits or risks of climate change are often effectively advanced at the subnational level, drawing on local governmental abilities to bring together actors involved in place-based decarbonisation across sectors. (Hodson and Marvin 2009; Bush et al. 2016; Huang et al. 2018; Prendeville et al. 2018; Levenda et al. 2019). For example, in the plans of 43 C40 Cities, climate action is framed as part of a vision for vibrant, economically prosperous, and socially just cities, that are habitable, secure, resource-efficient, socially and economically inclusive, and competitive internationally (Romero-Lankao and Gnatz 2019).

However, institution building is often constrained by a lack of national support, funding, human resources, coalitions, coordination across old and new organizations, and the ability to create new institutional competences (Valenzuela 2014; Jörgensen et al. 2015a; Anderton and Setzer 2018; Cointe 2019; Di Gregorio et al. 2019; Jaccard et al. 2019; Ryan 2015; Dubash et al. 2018; Romero-Lankao et al. 2018a; Hughes 2019b). Climate mitigation can also be limited by cultural norms and values of policy actors with varying levels of power, and shifting alliances (Lachapelle et al. 2012; Damsø et al. 2016; Giampieri et al. 2019; Romero-Lankao et al. 2018a).

Institution building is constrained by inequities; resources, legal remit, knowledge, and political clout vary widely within and among subnational governments globally (Genus and Theobald 2016; Joffe and Smith 2016; Klinsky 2018; Markkanen and Anger-Kraavi 2019; Jörgensen et al. 2015b; Reckien et al. 2018). Dominant discourses tend to prioritize scientific and technical expertise and, thus, they focus on infrastructural and economic concerns over the concerns and needs of disadvantaged populations (Heikkinen et al. 2019; Romero-Lankao and Gnatz 2019).

In addition, expert driven, technical solutions such as infrastructural interventions can undermine the knowledge of lower income countries, communities or indigenous knowledge holders, yet are often used by subnational governments (Ford et al. 2016; Brattland and Mustonen 2018; Nagorny-Koring 2019; Whyte 2017, 2020). Technical solutions, such as electric vehicles or smart grids rarely address the needs and capabilities of disadvantaged communities that may not be able to afford these technologies (Mistry 2014; Romero-Lankao and Nobler 2021). However, mitigation strategies in sectors such as transport and buildings have often focused on technical and market outcomes, the benefits of which are limited to some, while others experience negative externalities or face health risks (Carley and Konisky 2020; Markard 2018; Williams and Doyon 2019). Delivering climate justice requires community-driven approaches to understanding the problem addressing structural inequities and fostering justice, while reducing carbon emissions (Romero-Lankao et al. 2018b; Carley and Konisky 2020; Lewis et al. 2020).

To address this situation requires procedural justice that involves all communities, particularly disadvantaged, in climate mitigation decisions and policies (Box 13.4). Also essential is recognition justice, that addresses past inequities through tools such as subsidies, tariffs, rebates, and other policies (Agyeman 2013; Rydin 2013; UN Habitat 2016). Both tenets are key to ensure the fair distribution of benefits or negative impacts from mitigation policies (distributional justice) (McCauley and Heffron 2018; Lewis et al. 2020). However, the benefits of inclusive approaches are often overlooked in favour of growth oriented mitigation and planning (Rydin 2013; Altenburg 2011; Smith 2019; Lennon 2020). Box 13.6 discusses how the city of Durban has internalized climate change with attention to considerations of justice.

Moreover, deep mitigation requires moving beyond existing technological responses (Mulugetta and Castán Broto 2018) to policies that correspond to the realities of developing countries (Bouteligier 2013). However, best practice approaches tend to be fragmented due to the requirements of different contexts, and often executed as pilot projects that rarely lead to structural change (Nagorny-Koring 2019). Instead, context-specific approaches that include consideration of values, cultures and governance better enable successful translation of best practices (Affolderbach and Schulz 2016; Urpelainen 2018).

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Box 13.6 Institutionalising climate change within Durban's local government

Durban has effectively linked climate change agendas with ongoing sustainability actions and goals. To do so, adaptation has been broadened to include a just transition to a low carbon future to address development, energy security and GHG reduction (Roberts et al. 2016).

Durban has mainstreamed climate and justice concerns within local government through strong local leadership by key individuals and departments; included climate concerns within various municipal short-term and long-term planning processes; mobilised civil society; enhanced local and international networking; explored funding opportunities; and restructured institutions (Roberts et al. 2016).

Durban shows that embedding responses to climate change within local government activities requires that climate change is made relevant locally and framed within a broader environmental justice framework (Roberts 2010). Civil society has been key in balancing the influence of the private sector on Durban's dynamic political process (Aylett 2013).

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13.3 Structural factors that shape condition climate governance

A growing literature suggests that ambitious climate policy emerges out of strong domestic political support (Colgan et al. 2021; Aklin and Mildenberger 2020; Lamb and Minx 2020)(*medium evidence, medium agreement).* Such support is the outcome of political interest constellations and struggles that vary from country to country. Structural factors (such as economic wealth and natural resources, the character of the national political system, and the dominant ideas, values and beliefs) shape how climate change is governed (Hochstetler 2020; Boasson 2015) (*medium evidence, high agreement*). This section assesses the ways these structural factors affect political dynamics and decision making, and ultimately constrain, sustain or enable development of domestic climate governance.

While these structural factors are crucial, they do not determine the outlook of given countries' climate governance, as civic, corporate and/or political groups or individuals can be mobilized and seek to counteract these structural effects, as indicated in the following Section 13.4 that examines the role of various actors and agencies in shaping governance processes. Taken together, Sections 13.3 and 13.4 show that domestic climate governance is not fully constrained by structural factors, but rather that diverse actors can and do achieve substantial changes.

13.3.1 Material endowments

Material endowments are natural and economic resources, such as fossil fuels and renewable energy, forests and land, and economic or financial resources, which tend to shape developments of domestic climate governance (Friedrichs and Inderwildi 2013; Lachapelle and Paterson 2013; Bang et al. 2015; Lamb and Minx 2020) (*medium evidence, high agreement*). Most countries' social and economic systems are largely developed on the basis of their material endowment, and thus they contribute to shape the distribution of political power in that country (Hall and Soskice 2001). Material endowments are by no means the only influencing factor, and actors may succeed to either circumvent or exploit material endowments to impact climate governance (Boasson 2015; Green and Hale 2017; Aklin and Mildenberger 2020) (*limited evidence, medium agreement*).

Since countries are not bound by their material endowment, countries with similar material endowments may differ in climate governance, whereas those with notable differences in material endowments may have similar policies. For instance, countries with rich fossil fuel endowments are found either adopting rather ambitious emission reduction targets and measures, or remaining weak in developing domestic climate policies (Eckersley 2013; Farstad 2019). Further, countries with radically different electricity systems and energy resource potentials are found developing rather similar renewables support schemes such as feed-in-tariff subsidies and competitive tendering programmes (Vanegas Cantarero 2020; Dobrotkova et al. 2018; Boasson et al. 2021). Some policy instruments are widely applied in both developed and developing countries with similar or different material endowment. For example, renewable energy auctions have been experimented by over 100 countries by the end of 2018 (IRENA 2019).

Rich carbon-intensive resources and well developed infrastructure can make low-carbon activities relatively less economically profitable, and negatively influence some perceptions of climate mitigation potential (Bertram et al. 2015a; Erickson et al. 2015). If effective climate policies are introduced despite this, they can alter the importance of country's material endowments in a way that underpin more forceful climate governance over time. For instance, policy interventions to limit fossil fuel exploitation or support renewable energy deployment may change the value of these energy resources over time (Schmitz et al. 2015; Ürge-Vorsatz et al. 2018; Chailleux 2020; Colgan et al. 2021).

Developing countries face additional material constraints in climate governance due to challenges associated with underdevelopment and scarce economic or natural resources (*medium evidence, high agreement*). Hence, many developing countries design domestic climate mitigation policies in combination with policy goals that address various developmental challenges (von Stechow et al. 2016; Deng et al. 2017; Thornton and Comberti 2017; Campagnolo and Davide 2019), such as air quality, urban transportation, energy access, and poverty alleviation (Geall et al. 2018; Klausbruckner et al. 2016; Li et al. 2016; Melamed et al. 2016; Slovic et al. 2016; Xie et al. 2018; Khreis et al. 2017). Combining climate and developmental policies for beneficial synergies should not overlook potential trade-offs and challenges (Dagnachew et al. 2018; Ellis and Tschakert 2019; Peñasco et al. 2021) (see Section 13.7.2 for wider discussion).

13.3.2 Political systems

The effectiveness of domestic climate governance will significantly rely on how well it fits with the features of the countries' specific political systems (Schmitz 2017; Lamb and Minx 2020) (*limited evidence, high agreement*). Political systems have developed over generations and constitute a set of formal institutions, such as laws and regulations, bureaucratic structures, political executives, legislative assemblies and political parties (Pierson 2004; Egeberg 1999). Different political systems create differing conditions for climate governance to emerge and evolve, but because political systems are so politically and historically entrenched they are not likely to change quickly even though this could facilitate domestic climate mitigation efforts (Duit and Galaz 2008; Boasson et al. 2021) (*medium evidence, high agreement*). In addition, variations in governance capacities also affect climate policy making and implementation (Meckling and Nahm 2018).

Broader public participation and more open contestation spaces tend to nurture more encompassing climate policies, facilitate stronger commitments to international agreements (Bättig and Bernauer 2009; Böhmelt et al. 2016), achieve more success in decoupling economic growth from CO_2 emissions (Lægreid and Povitkina 2018), reduce more CO_2 emissions (Clulow 2019; von Stein 2020), and maintain lower deforestation rates (Buitenzorgy and Mol 2011) (*medium evidence, medium agreement*). States with less public participation and contestation space can also develop ambitious climate emission reduction targets and institutions (Eckersley 2016; Zimmer et al. 2015; Han 2017; Engels 2018), but the drivers and effects of climate policies within less open and liberal political contexts has not yet been sufficiently investigated.

Election systems based on proportional representation tend to have lower emissions, higher energy efficiency, higher renewable energy deployment, and more climate friendly investment than systems where leadership candidates have to secure a majority of the votes to be elected (Fredriksson and Millimet 2004; Finnegan 2019; Lachapelle and Paterson 2013) (*medium evidence, high agreement).* Such systems better enable voters supporting ambitious climate positions to influence policymaking (Harrison and Sundstrom 2010; Willis 2018), place less political risks on legislators from additional costs incurred from climate actions on voters (Finnegan 2018, 2019), and strengthen credible commitments to climate policy (Lockwood

2021b). Similarly, rules that govern the relationship between governments and civic societies in decision-making have also been shown to matter in climate governance. Corporatist societies, where economic groups are formally involved in public policy making, have better climate-related outcomes (lower CO_2 emissions and higher low-carbon investments) than liberal-pluralist countries, where a larger array of non-governmental organizations compete for informal influence, often through lobbying (Jahn 2016; Liefferink et al. 2009; Finnegan 2018) (*medium evidence, medium agreement*).

Political parties with similar ideological roots in different countries (for instance social democratic or conservative parties) may have different positions on climate governance across countries (Boasson et al. 2021). Nevertheless, on average, a higher share of green parties in a parliament is associated with lower greenhouse gas emissions (Neumayer 2003; Jensen and Spoon 2011; Mourao 2019), and left-wing parties tend to adopt more pro-climate policy positions (Carter 2013; Tobin 2017; Farstad 2018; Ladrech and Little 2019) (*medium evidence, high agreement*). There is also evidence, however, that conservative parties in some countries support climate measures (Båtstrand 2015) and consensus can be achieved on climate actions across the political spectrum (Thonig et al. 2021). At the same time, it seems harder to get support for new climate governance initiatives in systems where many political groups can block decision due to many veto points, for instance in systems with bicameralism (the legislature is divided into two separate assemblies) and/or in federalist governments (where regions have national political representation, e.g. US and Brazil) (Madden 2014; von Stein 2020) (*medium evidence, high agreement*) although federal systems hold out the possibility of sub-national action when federal agreement is limited (Section 13.2). There remains a limited literature on the role of green parties and veto points in developing countries (Haynes 1999; Kernecker and Wagner 2019).

In any political system, climate policy adoption and implementation may be obstructed by corrupt practices (Rafaty 2018; Fredriksson and Neumayer 2016) that entail an abuse of entrusted power for private gain (Treisman 2000) (*medium evidence, high agreement*). Evidence shows that CO_2 emissions increase with corruption, either through the direct negative effect of corruption on law enforcement, including in the forestry sector (Sundström 2016), or through the negative effect of corruption on countries' income (Welsch 2004).These early findings are reinforced by studies of a global sample of countries (Cole 2007) and from across the developing world (Bae et al. 2017; Wang et al. 2018b; Sahli and Rejeb 2015; Habib et al. 2020; Ridzuan et al. 2019). Corruption also disrupts public support of climate policies by affecting the levels of trust (Harring 2013; Davidovic and Harring 2020; Fairbrother et al. 2019) (*medium evidence, high agreement*), which then impact on the compliance of climate policies. More research is required to further understand the causal mechanisms between corrupt practices and emissions.

13.3.3 Ideas, values and belief systems

Ideas, values and beliefs affect climate governance by shaping people's perceptions, attitude, and preferences on specific policy and governance issues (Schifeling and Hoffman 2019; McCright et al. 2016b; Boasson 2015; Boasson et al. 2021; Leipold et al. 2019) (*medium evidence, high agreement*). While these are often entrenched, they can also change, for instance when facing growing exposures to climate risks, stronger scientific evidence, and dominant public or political discourse (Mayer et al. 2017; Diehl et al. 2021). While change tend to be incremental, the pace of change may vary substantially across countries and specific climate issue areas.

However, new norms sometimes only influence political discussion and not actual governance. For instance, more ambitious climate emission reduction targets may not lead to more effective mitigation actions or policy instruments. Put another way, words do not replace actions (Geden 2016).

Different sets of beliefs can shape climate related policies, targets, and instruments (Boasson et al. 2021; Boasson and Wettestad 2013; Boasson 2015). First, beliefs link climate governance with social justice concerns; policies, targets and instruments may therefore reflect justice issues (Fuller and McCauley 2016;

Reckien et al. 2017; McCauley and Heffron 2018; Routledge et al. 2018; Bäckstrand and Lövbrand 2006, 2019). Second, climate mitigation may be seen as primarily a market correction issue and mitigation compatible with economic growth, as exemplified by ecological modernization (Bäckstrand and Lövbrand 2006, 2019; Mol et al. 2009), climate capitalism (Newell and Paterson 2010), market logics (Boasson et al. 2021; Boasson 2015) or a global commons approach (Bernstein and Hoffmann 2019). Third, climate governance may be understood relative to policies on technological innovation and progress, often conceptualised as social-technical transformations (Geels et al. 2017a).

Significant variation in ideas, values and beliefs related to climate governance are detected across and within regions, countries, societies, organisations, and individuals (Shwom et al. 2015; Boasson et al. 2021; Knox-Hayes 2016; Wettestad and Gulbrandsen 2018) (*medium evidence*, *medium agreement*). These factors provide the context for climate policymaking and include differences in countries' histories (Aamodt 2018; Aamodt and Boasson 2020); the political culture and regulatory traditions in governing environmental and energy issues (Tosun 2018; Aamodt 2018; Boasson et al. 2021); and even bureaucrats' educational background (Rickards et al. 2014). Structural factors in a country, such as deeply held value systems, are not changed rapidly, just as political systems or natural endowments, are not changed rapidly. Consequently climate policy and governance is more effective if it takes into account these deep-rooted values and beliefs.

Differences in dominant individual preferences may also be important. The factors that shape individual ideas, values and beliefs about climate governance include trust in politicians, the state and other people in general (Drews and van den Bergh 2016; Harring et al. 2019; Huber et al. 2020), fairness beliefs, variation in political orientation (left leaning more concerned), and class (Schmitz et al. 2018; Inglehart and Norris 2017) (*medium evidence*, *medium agreement*).

Levels of climate change concern on the individual level have increased in most countries (Shwom et al. 2015), and vary with gender (females are more concerned), and place of residence (urban residents are more concerned) (McCright et al. 2016a; Shwom et al. 2015; Ziegler 2017). The higher educated in developing countries tend to be more concerned (Lee et al. 2015) while individuals working in polluting industries tend to oppose forceful climate governance (Bechtel et al. 2019; Mildenberger 2020).

Shifts in mainstream ideas, values and beliefs can underpin changes in climate policy choices and policy outcomes (Mildenberger and Tingley 2019; Schleich et al. 2018) (*limited evidence, medium agreement).* For example, emission trading schemes are welcomed as a new regulatory instrument in China in the context of its market-oriented reforms and ideological shift in the past decades (Lo 2013). Based on the study of 167 nation-states and 95 subnational jurisdictions with carbon pricing, researchers find that that high public belief in climate science underpin adoption of systems that produce a rather high carbon price (Levi et al. 2020). These public opinions need to be identified and leveraged in supporting specific policy choices or changes (Mildenberger and Tingley 2019). Policy support tends to be greater if people believe effective measures are being taken by other actors, including other households (Bostrom et al. 2018; Marlon et al. 2019), and other countries and at the international level (Schleich et al. 2018).

On the other hand, anti-climate ideas or beliefs may arise due to the introduction of more constraining or ambitious climate policies, for example protests in reaction to toll roads in Norway, which increase the cost of driving, or protests in France against increasing carbon taxes (Grossman 2019; Wanvik and Haarstad 2021). The policy implication is that vulnerable or effected groups should be considered when introducing policy change, and that participation, transparency, and good communication all helps to reduce climate related discontent.

Survey based studies of public perceptions on hypothetical policy instruments or activities, such as carbon taxes or energy infrastructure, suggest that linking climate policy to other economic and social reforms can increase public support for climate governance (Carattini et al. 2019; Bergquist et al. 2020). People and politicians tend to underestimate other peoples' and politicians' willingness to support mitigation policies (Mildenberger and Tingley 2019; Hurlstone et al. 2014), but if actors are informed about other actors actual perceptions and behaviours this may reduce the tendency to underestimate climate governance support (Mildenberger and Tingley 2019).

13.4 Actors shaping climate governance

While Section 13.3 shows that structural factors condition climate governance, their ultimate importance also depends on whether and how various actors are mobilised (Hochstetler 2020; Boasson 2015). A wide range of regional and local governments as well as non-governmental actors have become increasingly engaged in climate governance, for instance through public-private partnerships and transnational networks (Jordan et al. 2018b; Dorsch and Flachsland 2017; Jordan et al. 2015) and through the media and litigation, as discussed here.

Climate governance processes result from both slow-moving incremental changes to policy and more rapid bursts of change due to, for example, responses to dramatic weather-events, general elections or global climate summits (Aamodt and Stensdal 2017; Jordan and Moore 2020; Boasson et al. 2021) (*medium evidence, high agreement)*. While Section 13.3 assessed how entrenched structural factors conditions climate governance developments, this section examines how actors are able to alter climate governance by engaging the climate policy process, undertaking litigation and interacting with media.

13.4.1 Actors and agency in the public process

A broad array of actors are engaged in shaping mitigation policy processes, including politicians and political parties, corporate actors, citizen groups, indigenous peoples organizations, labour unions and international organizations. Actors aiming to influence the climate-related policymaking process are studied together to understand climate policy dynamics and outcomes (Bulkeley 2000; Fisher 2004; Fisher and Leifeld 2019; Jasny et al. 2015; Jasny and Fisher 2019; Jost and Jacob 2004) and collaboration and influence within climate policy networks (Ingold and Fischer 2014; Kammerer et al. 2021; McAllister et al. 2014; Wagner and Ylä-Anttila 2018). Most research, however, focuses on one particular type of actor.

Political actors are decision-makers, and also influence whether climate governance is perceived as urgent and appropriate (Okereke et al. 2019; Ferrante and Fearnside 2019; Boasson et al. 2021). They include political parties, legislative assemblies and committees, governmental executives and the political leaders of governmental ministries (Boasson 2015). They are more likely to pay attention to climate issues when polling indicates high political salience with the public (Carter 2006, 2014), or when it becomes a contested issue among differing political parties (Boasson et al. 2021). Fluctuations in the public's interest and attention may underpin a disjointed approach in politicians' engagement (Willis 2017, 2018). Policy implementation can be hampered if political actors propose frequent policy changes (Boasson et al. 2021).

Corporate actors often influence policies and their adoption (Pulver and Benney 2013; Mildenberger 2020; Goldberg et al. 2020). Corporate actors acting individually or through industry associations, have worked to sway climate policy in different countries (Meckling 2011; Falkner 2008; Bernhagen 2008; Newell and Paterson 2010; Mildenberger 2020). Their ability varies by country and issue (Skjærseth and Skodvin 2010; Boasson and Wettestad 2013; Boasson 2015; Boasson et al. 2021) (*medium evidence, medium agreement*) and depends on material endowments (Moe Singh 2012), access to the political system (Dillon et al. 2018; Mildenberger 2020), and the ability to shape ideas, values and belief systems (Boasson 2015). Corporate actors tend to change their climate policy preferences over time, as indicated by longitudinal studies of some European countries (Boasson and Wettestad 2013; Boasson 2015; Boasson et al. 2021).

Corporate actors are crucial to policy implementation because they are prominent emitters of the greenhouse gases and owners of carbon-intensive technologies and potential providers of solutions as developers, owners and adopters of low emission practices and technologies (Perrow and Pulver 2015; Falkner 2008). Many climate policies and measures rely on businesses' willingness to exploit newly created economic opportunities, such as support schemes for renewable energy and energy efficiency sector or carbon pricing (Shen 2015; Olsen 2007; Newell and Paterson 2010; World Bank 2019). Some corporate actors provide climate solutions, such as renewable energy deployment, and have successfully influenced climate policy development related to feed-in tariffs, taxations, quotas, or emission trading schemes, in the EU (Boasson 2019), Germany (Leiren and Reimer 2018), the US (Stokes and Breetz 2018), the Nordic countries (Kooij et al. 2018), China (Shen 2017) and Japan (Li et al. 2019).

Fossil fuel industries have been important agenda-setters in many countries, including the USA (Dunlap and McCright 2015; Supran and Oreskes 2017; Downie 2018), the EU (Skjærseth and Skodvin 2010; Boasson and Wettestad 2013), Australia (Ayling 2017), China (Shen and Xie 2018; Tan et al. 2021), India (Blondeel and Van de Graaf 2018; Shen 2017; Schmitz 2017), and Mexico (Pulver 2007), with differing positions and impacts across countries (Kim et al. 2016; Nasiritousi 2017). In the US, the oil industry has underpinned emergence of climate scepticism (Farrell 2016a; Dunlap and McCright 2015; Supran and Oreskes 2017), and its spread abroad (Dunlap and Jacques 2013; Engels et al. 2013; Painter and Gavin 2016). Corporate opposition to climate policies is often facilitated by a broad coalition of firms (Cory et al. 2021).

Conservative foundations, sometimes financed by business revenues, have funded a diversity of types of groups, including think-tanks, philanthropic foundations, or activist networks to oppose climate policy (Brulle 2014, 2019). However, there is limited knowledge about the conditions under which actors opposed to climate action succeed in shaping climate governance (Kinniburgh 2019; Martin and Islar 2021).

Some labour unions have developed positions and programmes on climate change (Snell and Fairbrother 2010; Stevins 2013; Räthzel et al. 2018), formed alliances with other actors in the field of climate policy (Stevis 2018) and participated in domestic policy networks on climate change (Jost and Jacob 2004), but we know little about their relative importance or success. In countries with significant fossil fuel resources such as Australia, Norway, and the United States, labour unions, particularly industrial unions, tend to contribute to reducing the ambition of domestic climate policies mainly due to the concern of job losses (Mildenberger 2020). Other studies find that the role of labour unions varies across countries (Glynn et al. 2017).

Civil society actors can involve citizens working collectively to change individual behaviours that have climate implications. For example, environmental movements that involve various forms of collective efforts encourage their members to make personal lifestyle changes that reduce their individual carbon footprints (Ergas 2010; Middlemiss 2011; Haenfler et al. 2012; Cronin et al. 2014; Saunders et al. 2014; Büchs et al. 2015; Wynes et al. 2018). These efforts seek to change individual members' consumer behaviours by reducing car-use and flying, shifting to non-fossil fuel sources for individual sources of electricity, and eating less dairy or meat (Cherry 2006; Salt and Layzell 1985; Stuart et al. 2013; Thøgersen et al. 2021; Wynes and Nicholas 2017; Büchs et al. 2015; Cronin et al. 2014; Ergas 2010; Haenfler et al. 2012; Middlemiss 2011; Saunders et al. 2014; Wynes et al. 2018). Consumer/citizen engagement is sometimes encouraged through governmental directives, such as the "renewable energy communities" granted by the EU renewable energy directive 2018/2001 (The European Parliament and the Council of the European Union 2018). To date, there are only a limited number of case studies that measure the direct effect of participation in these types of movements as it relates to climate outcomes (Vestergren et al. 2018, 2019; Saunders et al. 2014).

Citizens with less access to resources and power also participate by challenging nodes of power—policymakers, regulators, and businesses—to change their behaviours and/or accelerate their efforts. Tactics include lobbying, legal challenges, shareholder activism, coop board stewardship, and voting (Bratton and McCahery 2015; Clemens 1997; Gillan and Starks 2007; Olzak et al. 2016; Schlozman et al. 2012; Viardot 2013; Yildiz et al. 2015). Citizens provide the labour and political will needed to pressure political and economic actors to enact emission-reducing policies, as well as providing resistance to them (McAdam 2017; Oreskes and Conway 2012; Fox and Brown 1998; Boli and Thomas 1999).

Other citizen engagement involves a range of more confrontational tactics, such as boycotting, striking, protesting, and direct action targeting politicians, policymakers, and businesses (Chamorel 2019; Cock 2019; Eilstrup-Sangiovanni and Bondaroff 2014; Fisher 2010, 2019b; Fisher et al. 2005; Hadden 2014, 2015; Hadden and Jasny 2019; Meyer and Tarrow 1997; O'Brien et al. 2018; Saunders et al. 2012; Swim et al. 2019; Tarrow 2005; Wahlström et al. 2013; Walgrave et al. 2012). Climate strikes and other more confrontational forms of climate activism have become increasingly common (Boulianne et al. 2020; de Moor et al. 2021; Evensen 2019; Fisher and Nasrin 2021a; Martiskainen et al. 2020; Fisher 2019b; O'Brien et al. 2018). Very few studies look specifically at the effect of these tactics on actual climate-related outcomes and more research is needed to understand the climate effects of citizen engagement and activism (Fisher and Nasrin 2021b).

Citizen engagement has also become common among indigenous groups who tend to have limited structural power but often aim to shape the formation and effects of projects that have implications to climate change. These include opposing extraction and transportation of fossil fuels on their traditional lands (especially in the Americas) (Bebbington and Bury 2013; Hindery 2013; Coryat 2015; Claeys and Delgado Pugley 2017; Wood and Rossiter 2017); large-scale climate mitigation projects that may affect traditional rights (Brannstrom et al. 2017; Moreira et al. 2019; Zárate-Toledo et al. 2019); supporting deployment of small-scale renewable energy initiatives (Thornton and Comberti 2017); seeking to influence the development of REDD+ policies through opposition (Reed 2011); and participation in consultation processes and multi-stakeholder bodies (Bushley 2014; Gebara et al. 2014; Astuti and McGregor 2015; Kashwan 2015; Jodoin 2017). Indigenous groups have been reported to have had some influence on some climate discussions, particularly forest management and siting of renewable energy (Claeys and Delgado Pugley 2017; Jodoin 2017; Thornton and Comberti 2017). Further, more scientific assessments are required on the role of indigenous groups in climate activism and policy (Jodoin 2017; Claeys and Delgado Pugley 2017; Thornton and Comberti 2017).

Activism, including litigation, as well as the tactics of protest and strikes, have played a substantial role in pressuring governments to create environmental laws and environmental agencies tasked with enforcing environmental laws that aimed to maintain clean air and water in countries around the world (McCloskey 1991; Schreurs 1997; Rucht 1999; Brulle 2000; Steinhardt and Wu 2016; Wong 2018; Longhofer et al. 2016) (*medium evidence, high agreement*). Several studies find environmental NGOs have a positive effect on reductions in carbon emissions, whether through effects that operate across countries or (Schofer and Hironaka 2005; Jorgenson et al. 2011; Longhofer and Jorgenson 2017; Grant et al. 2018; Frank et al. 2000; Baxter et al. 2013) through impact of NGOs within nations (Dietz et al. 2015; Grant and Vasi 2017; Shwom 2011)

At the same time, other research has documented various forms of backlash against climate policies, both in terms of voting behaviour, as well as other collective efforts (Boudet et al. 2016; Fast et al. 2016; Hill et al. 2010; Krause et al. 2016; Lyon 2016; Mayer 2016; McAdam and Boudet 2012; Muradian and Pascual 2020; Stokes 2016; Stokes and Warshaw 2017; Stokes 2020; Walker et al. 2014; Williamson et al. 2011; Wright and Boudet 2012). In a systematic analysis that includes movements against fossil fuel investments along with those against low-carbon emitting projects around the world, research finds that a quarter of all projects (no matter their targets) were cancelled after facing resistance (Temper et al. 2020).

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Box 13.7 Civic engagement: The school strike movement

On Friday August 20th 2018, Greta Thunberg participated in the first climate school strike. Since then, Fridays for Future—the name of the group coordinating this tactic of skipping school on Fridays to protest inaction on climate change—has spread around the world.

In March 2019, the first *global* climate strike took place, turning out more than 1 million people around the world (Carrington 2019). Six months later in September 2019, young people and adults responded to a call to participate in climate strikes as part of the 'Global Week for Future' surrounding the UN Climate Action Summit (Thunberg 2019), and the number of participants globally jumped to an estimated 6 million people (Taylor et al. 2019). Although a handful of studies have reported on who was involved in these strikes, how they were connected, and their messaging (Marris 2019; Wahlström et al. 2019; Bevan et al. 2020; Han and Ahn 2020; Holmberg and Alvinius 2020; Jung et al. 2020; Martiskainen et al. 2020; de Moor et al. 2021; Thackeray et al. 2020; Trihartono et al. 2020; Evensen 2019; Fisher 2019a; Boulianne et al. 2020; Fisher and Nasrin 2021b), its consequences in terms of political outcomes and emissions reductions have yet to be fully understood (Fisher and Nasrin 2021b).

Although digital activism makes it easier to connect globally, it is unclear how digital technology will affect the youth climate movement, and its effects on carbon emissions. Research suggests that online activism is likely to involve a more limited range of participants and perspectives (Bennett 2013; Elliott and Earl 2018). Digital tactics could also mean that groups are less embedded in communities and less successful at creating durable social ties, factors that have been found to lead to longer term engagement (Rohlinger and Bunnage 2018; Tufekci 2017; Shirky 2010).

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A range of international organizations can be important, particularly in developing countries, for instance by assisting in framing of national climate governance and supporting the design of climate policies through technical assistance projects (Talaei et al. 2014; Ortega Díaz and Gutiérrez 2018; Bhamidipati et al. 2019; Charlery and Trærup 2019; Kukkonen et al. 2018). Yet for these climate aid initiatives to work effectively requires improved institutional architecture, better appreciation of local contexts, and more inclusive and transparent governance, based on evidence from many multilateral mechanisms like REDD+, CDM, GEF and GCF (Gomez 2013; Arndt and Tarp 2017), and bilateral programmes on energy, agriculture and land use sectors (Rogner and Leung 2018; Moss and Bazilian 2018; Arndt and Tarp 2017).

13.4.2. Shaping climate governance through litigation

Outside the formal climate policy processes, climate litigation is another important arena for various actors to confront and interact over how climate change should be governed (Calzadilla 2019; Peel and Osofsky 2015, 2018; Setzer and Vanhala 2019; Paiement 2020; Wegener 2020; Wilensky 2015; Bouwer 2018; Setzer and Byrnes 2019) (*robust evidence, high agreement)*. Climate litigation is an attempt to control, order or influence the behaviour of others in relation to climate governance, and it has been used by a wide variety of litigants (governments, private actors, civil society and individuals) at multiple scales (local, regional, national and international) (Osofsky 2007; Lin 2012b; Keele 2017; McCormick et al. 2018; Peel and Osofsky 2018; Setzer and Vanhala 2019). Climate litigation has become increasingly common (United Nations Environment Programme 2020), but its prevalence varies across countries (Peel and Osofsky 2015; Wilensky 2015; Bouwer 2018; Setzer and Higham 2021; Lin and Kysar 2020) (*medium evidence, high agreement)*. This is not surprising, given that courts play differing roles across varying political systems and law traditions (La Porta et al. 1998).

This sub-section focuses on relevant climate litigation for policies and institutions. Climate litigation is further discussed in Sections 14.5.1.2 (linkages between mitigation and human rights) and 14.5.3 (cross-country implications and international courts/tribunals).

The vast majority of climate cases have emerged in United States, Australia and Europe, and more recently in developing countries (Humby 2018; Kotze and du Plessis 2019; Peel and Lin 2019; Setzer and Benjamin 2019; Zhao et al. 2019; Rodríguez-Garavito 2020). As of 31 May 2021, 1,841 cases of climate change litigation from around the world had been identified. Of these, 1,387 were filed before courts in the United

States, while the remaining 454 were filed in 39 other countries and 13 international or regional courts and tribunals (including the courts of the European Union). Outside the US, Australia (115), the UK (73) and the EU (58) remain the jurisdictions with the highest volume of cases. The majority of cases, 1,006, have been filed since 2015 (Setzer and Higham 2021). The number of climate litigation cases in developing countries is also growing. There are at least 58 cases in 18 Global South jurisdictions (Setzer and Higham 2021; Humby 2018; Kotze and du Plessis 2019; Peel and Lin 2019; Setzer and Benjamin 2019; Zhao et al. 2019; Rodríguez-Garavito 2020) (*robust evidence, high agreement).*

Overall, courts have also played a more active role for climate governance in democratic political systems (Peel and Osofsky 2015; Eskander et al. 2021), but recently legal reforms have also developed in other countries, such as the environmental public interest law in China that allows individuals and groups to initiate environmental litigation (Xie and Xu 2021; Zhao et al. 2019). Whether and to what extent differing law traditions and political systems influence the role and importance of climate litigation has, however, not been examined enough scientifically (Peel and Osofsky 2020; Setzer and Vanhala 2019).

The majority of climate change litigation cases are brought against governments, by civic and non-governmental organisations and corporations (Eisenstat 2011; Markell and Ruhl 2012; Fisher et al. 2017; Wilensky 2015; Setzer and Higham 2021). Many, although not all of these cases, seek to ensure that governmental action on climate change is more ambitious, and better aligned with the need to avert or respond to climate impacts identified and predicted by the scientific community (Setzer and Higham 2021; Markell and Ruhl 2012). Climate aligned cases against governments can be divided into two distinct categories: claims challenging the overall effort of a State or its organs to mitigate or adapt to climate change (sometimes referred to as 'systemic climate litigation') (Jackson 2020) and claims regarding authorisation of third-party activity (Bouwer 2018; Gerrard 2021; Ghaleigh 2021).

Systemic climate litigation that seeks an increase in a country's ambition to tackle climate change has been a growing trend since the first court victories in the Urgenda case in the Netherlands (see Box 13.8 below) and the Leghari case in Pakistan in 2015. These cases motivated a wave of similar climate change litigation across the world (Sindico et al. 2021; Roy and Woerdman 2016; Mayer 2019; Ferreira 2016; Peeters 2016; Paiement 2020; Barritt 2020). Between 2015 and 2021, individuals and communities initiated at least 37 cases (including Urgenda and Leghari) against states (Setzer and Higham 2021), challenging the effectiveness of legislation and policy goals (Setzer and Higham 2021; Jackson 2020). Some cases also seek to shape new legal concepts such as 'rights of nature' recognized in the Future Generations case in Colombia (Savaresi and Auz 2019; Rodríguez-Garavito 2020) and 'ecological damage' in the case of Notre Affaire à Tous and others v. France (Torre-Schaub 2021).

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Box 13.8 An example of systemic climate litigation: Urgenda v State of the Netherlands

The judgment in *Urgenda v. State of the Netherlands* established the linkage between a state's international duty, domestic actions, and human rights commitments as to the recommendations of IPCC's AR5 (Burgers and Staal 2019; Antonopoulos 2020). It was the first to impose a specific emissions reduction target on a state (de Graaf and Jans 2015; Cox 2016; Loth 2016). The District Court of The Hague ordered the Dutch Government to reduce emissions by at least 25% by the end of 2020. Following the decision of the district court of The Hague in 2015 the Dutch government announced that it would adopt additional measures to achieve the 25% emissions reduction target by 2020 (Mayer 2019). The decision was upheld by the Court of Appeal in 2018 and the Supreme Court in 2019. Since the first judgment in 2015 significant changes in the climate policy environment have been reported, the results of which have included the introduction of a Climate Act and the decision to close all remaining coal fired power plants by 2030 (Verschuuren 2019; Wonneberger and Vliegenthart 2021).

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Moreover, there are a number of regulatory challenges to state authorisation of high-emitting projects, which differs from systemic cases against states (Bouwer 2018; Hughes 2019a). For instance, the High Court in Pretoria, South Africa, concluded that climate change is a relevant consideration for approving coal-fired power plants (Humby 2018). Similarly, the Federal Court of Australia concluded that the Minister for the Environment owed a duty of care to Australian children in respect to climate impacts when exercising a statutory power to decide whether to authorise a major extension to an existing coal mine (Peel and Markey-Towler 2021)

Climate change litigation has also been brought against corporations by regional or local governments and non-governmental organisations (Ganguly et al. 2018; Wilensky 2015; Foerster 2019). One type of private climate change litigation alleges climate change-related damage and seeks compensation from major carbon polluters (Ganguly et al. 2018; Wewerinke-Singh and Salili 2020). The litigators claim that major oil producers are historically responsible for a significant portion of global greenhouse gas emissions (Heede 2014; Frumhoff et al. 2015; Ekwurzel et al. 2017; Stuart-Smith et al. 2021). These cases rely on advancements in climate science, specifically climate attribution (Marjanac et al. 2017; Marjanac and Patton 2018; McCormick et al. 2018; Minnerop and Otto 2020; Burger et al. 2020b; Stuart-Smith et al. 2021). It is alleged that major carbon emitters had knowledge and awareness of climate change and yet took actions to confound or mislead the public about climate science (Supran and Oreskes 2017). Strategic climate change litigation has also been used to hold corporations to specific human rights responsibilities (Savaresi and Auz 2019; Savaresi and Setzer 2021) (see further Box 13.8).

In addition to direct cases targeting high emitters, litigation is also now being used to argue against financial investments in the fossil fuel industry (Franta 2017; Colombo 2021). In May 2021, the Hague District Court of the Netherlands issued a ground-breaking judgment holding energy company Royal Dutch Shell (RDS) legally responsible for greenhouse gas emissions from its entire value chain (Macchi and Zeben 2021). Claims have also been brought against banks, pension funds and investment funds for failing to incorporate climate risk into their decision-making, and to disclose climate risk to their beneficiaries (Solana 2020; Wasim 2019; Bowman and Wiseman 2020). These litigation cases also impact on the financial market without directly involving specific financial institutions into the case (Solana 2020) but somehow aim to change their risk perceptions and attitude on high carbon activities (Griffin 2020).

The outcomes of climate litigation can affect the stringency and ambitiousness of climate governance (McCormick et al. 2018; Eskander et al. 2021). In the United States, pro-regulation litigants more commonly win in relation to renewable energy and energy efficiency cases, and more frequently lose in relations to coal-fired power plant cases (McCormick et al. 2018). Outside the US, more than half (58%) of litigation have outcomes that are aligned with climate action (Setzer and Higham 2021). But these cases can also have impacts outside of the legal proceedings before, during and after the case has been brought and decided (Setzer and Vanhala 2019). These impacts include changes in the behaviour of the parties (Peel and Osofsky 2015; Pals 2021), public opinion (Hilson 2019; Burgers 2020), financial and reputational consequences for involved actors (Solana 2020), and impact on further litigation (Barritt 2020). Individual cases have also attracted considerable media attention, which in turn can influence how climate policy is perceived (Nosek 2018; Barritt and Sediti 2019; Paiement 2020; Hilson 2019). While there is evidence to show the influence of some key cases on climate agenda-setting (Wonneberger and Vliegenthart 2021), it is still unclear the extent to which climate litigation actually results in new climate rules and policies (Peel and Osofsky 2018; Setzer and Vanhala 2019; Peel and Osofsky 2020) and to what degree this holds true for all cases (Jodoin et al. 2020). However, there is now increasing academic agreement that climate litigation has become a powerful force in climate governance (Bouwer 2018; Peel and Osofsky 2020; United Nations Environment Programme 2020; Burgers 2020). In general, litigations can be applied to constrain both public and private entities, and to shape structural factors mentioned in Section 13.3, such as the beliefs and institutions around climate governance.

13.4.3 Media as communicative platforms for shaping climate governance

Media is another platform for various actors to present, interpret and shape debates around climate change and its governance (Tindall et al. 2018). The media coverage of climate change has grown steadily since 1980's (O'Neill et al. 2015; Boykoff et al. 2019), but the level and type of coverage differs over time and from country to country (Boykoff 2011; Schmidt et al. 2013; Schäfer and Schlichting 2014) (*robust evidence, high agreement*). Media can be a useful conduit to build public support to accelerate mitigation action, but may also be utilized to impede decarbonisation endeavours (Farrell 2016b; Carmichael et al. 2017; Carmichael and Brulle 2018; Boykoff 2011; O'Neill et al. 2015). Different media systems in different regions and countries and with unique cultural and political traditions also affect how climate change is communicated (Eskjær 2013).

A broad variety of media platforms cover climate change issues, including traditional news media, such as newspapers and broadcasting, digital social media (Walter et al. 2018), creative narratives such as climate fiction and films (Svoboda 2016); humour and entertainment media (Brewer and McKnight 2015; Skurka et al. 2018; Boykoff and Osnes 2019); and strategic communications campaigns (Hansen and Machin 2008; Hoewe and Ahern 2017). Media coverage can have far-reaching consequences on policy processes, but we know less about its relative importance compared to other policy shaping factors (Liu et al. 2011; Hmielowski et al. 2014; Boykoff 2011) (*medium evidence, medium agreement*).

Popular culture images, science fictions and films of ecological catastrophe can dramatically and emotively convey the dangers of climate change (Bulfin 2017). The overall accuracy of the media coverage on climate change has improved from 2005 to 2019 in the United Kingdom (UK), Australia, New Zealand, Canada, and the US (McAllister et al. 2021). Moreover, coverage of climate science is increasing. One study (MeCCO) has tracked media coverage of climate change from over 127 sources from 59 countries in North and Latin America, Europe, Middle East, Africa, Asia and Oceania (Boykoff et al. 2021). It shows the number of media science stories in those sources grew steadily from 47376 per annum to 86587 per annum between 2017 and 2021 across print, broadcast, digital media and entertainment (Boykoff et al. 2021).

However, increasing media coverage does not always lead to more accurate coverage of climate change mitigation, as it can also spur diffusion of misinformation (Boykoff and Yulsman 2013; van der Linden et al. 2015; Whitmarsh and Corner 2017; Fahy 2018; Painter 2019). In addition, media professionals have at times drawn on the norm of representing both sides of a controversy, bearing the risk of the disproportionate representation of scepticism of anthropogenic climate change despite the convergent agreement in climate science that humans contribute to climate change, (Freudenburg and Muselli 2010; Boykoff 2013; McAllister et al. 2021; Tindall et al. 2018; Painter and Gavin 2016) (*robust evidence, high agreement*). This occurs despite increasing consensus among journalists regarding the basic scientific understanding of climate change (Brüggemann and Engesser 2017).

Accurate transference of the climate science has been undermined significantly by climate change counter-movements, particularly in the US (McCright and Dunlap 2000, 2003; Jacques et al. 2008; Brulle et al. 2012; Boussalis and Coan 2016; Boykoff and Farrell 2019; Farrell 2016a; Carmichael et al. 2017; Carmichael and Brulle 2018; Almiron and Xifra 2019) in both legacy and new/social media environments through misinformation (van der Linden et al. 2017) (*robust evidence, high agreement*), including about the causes and consequences of climate change (Brulle 2014; Farrell 2016b; Supran and Oreskes 2017; Farrell 2016a). Misinformation can rapidly spread through social media (Walter et al. 2018). Together with the proliferation of suspicions of 'fake news' and 'post-truth', some traditional and social media contents have fuelled polarization and partisan divides on climate change in many countries (Feldman et al. 2017; Hornsey et al. 2018), which can further deter development of new and ambitious climate policy (Tindall et al. 2018).

Further, the ideological stance of media also influences the intensity and content of media coverage, in developed and developing countries alike (Dotson et al. 2012; Stoddart and Tindall 2015).

Who dominates the debate on media, and how open the debate can be varies significantly across countries (Takahashi 2011; Poberezhskaya 2015) based on participants' material and technological power. Fossil fuel industries have unique access to mainstream media (Geels 2014) via advertisements, shaping narratives of media reports, and exerting political influence in countries like Australia and the US (Holmes and Star 2018; Karceski et al. 2020). For social media, novel technical tools, such as automated bots, are emerging to shape climate change discussion on major online platforms such as Twitter (Marlow et al. 2021). Open debates can underpin the adoption of more ambitions climate policy (Lyytimäki 2011). Media coverage on energy saving, patriotism, and social justice in the countries like US and the UK have helped connect mitigation of climate change with other concerns, thereby raising support to climate action (Leiserowitz 2006; Trope et al. 2007; Doyle 2016; Corner and Clarke 2017; Markowitz and Guckian 2018; Whitmarsh and Corner 2017). Further, media coverage of climate change mitigation has influenced public opinions through discussions on political, economic, scientific and cultural themes about climate change (Irwin and Wynne 1996; Smith 2000; Boykoff 2011; O'Neill et al. 2015) (*medium evidence, high agreement*).

Common challenges in reporting climate change exist around the world (Schäfer and Painter 2021; Schmidt et al. 2013), but particularly so in the developing countries, due to lower capacities, lack of journalists' training in complex climate subjects, and lack of access to clear, timely and understandable climate-related resources and images in newsrooms (Harbinson 2006; Shanahan 2009; Broadbent et al. 2016; Lück et al. 2018) (*robust evidence, high agreement*). Ugandan journalist Patrick Luganda has said, "Those most at risk from the impacts of climate change typically have had access to the least information about it through mass media." (Boykoff, 2011), indicating that information availability and capacity is a manifestation of global climate (in)justice.

13.5 Subnational actors, networks, and partnerships

In many countries, subnational actors and networks are a crucial component of climate mitigation as they have remit over land use planning, waste management, infrastructure, housing and community development, and their jurisdictions are often where the impacts of climate change are felt *(robust evidence, high agreement)*. Depending on the legal framework and other institutional constraints, subnational actors play crucial roles in developing, delivering and contesting decarbonisation visions and pathways (Schroeder et al. 2013; Ryan 2015; Amundsen et al. 2018; Fuhr et al. 2018; Bäckstrand et al. 2017; Abbott et al. 2016) (Section 13.3.3).

Sub-national actors include organizations, jurisdictions, and networks (e.g., a coalition of cities or state authorities). These are either formal or informal, profit or non-profit and public or private (Avelino and Wittmayer 2016). For example, corporations are formal, private, and for-profit, the state and labour organizations are formal, public, and non-profit, and communities are private, informal, and non-profit. An intermediary sector, crossing the boundaries between private and public, for profit and non-profit, includes energy cooperatives, not-for-profit energy enterprises, and the scientific community (Avelino and Wittmayer 2016).

To address the challenge of climate mitigation, a range of actors across sectors and jurisdictions have created coalitions for climate governance, operating as actor-networks. For example, mitigation policies are particularly effective when they are integrated with co-benefits such as health, biodiversity, and poverty reduction (Romero-Lankao et al. 2018a). Transnational business and public-private partnerships and initiatives, as well as international co-operation at the sub-national and city levels are discussed in Chapter 14.

13.5.1 Actor-networks, and policies

The decision adopting the Paris Agreement welcomed contributions of subnational actors to mobilizing and scaling up ambitious climate action (see also Chapter 14). They engage in climate relevant mechanisms, such as the Sustainable Development Goals and the New Urban Agenda. Subnational actors fill a gap in national policies, participate in transnational and subnational climate governance networks and facilitate learning and exchange among governmental, community, and private organizations at multiple levels, gathering knowledge and best practices such as emission inventories and risk management tools that can be applied in multiple contexts (Kona et al. 2016; Sharifi and Yamagata 2016; Michaelowa and Michaelowa 2017; Warbroek and Hoppe 2017; Bai et al. 2018; Busch et al. 2018; Hsu et al. 2018; Lee and Jung 2018; Marvin et al. 2018; Romero-Lankao et al. 2018b; Ürge-Vorsatz and Seto 2018; Heikkinen et al. 2019; Amundsen et al. 2018; Hultman et al. 2020).

Subnational climate change policies exist in more than 142 countries and exemplify the increasing significance of mitigation policy at the subnational level (Hsu et al. 2018). However, estimations of the number of subnational actors pledging voluntary climate action are challenging and underreporting is a concern (Chan and Morrow 2019; Hsu et al. 2018). As can be seen in Figure 13.3 more than 10,500 cities and nearly 250 regions representing more than 2 billion people, factoring for overlaps in population between these jurisdictions, have pledged climate action as of December 2020 (Hsu et al. 2020a). More jurisdictions in Europe and North America have pledged action, but in terms of population almost all regions are substantially engaged in subnational action.

Many of these efforts are organised around transnational or regional networks. For example, a coalition of 130 subnational (i.e., state, and regional) governments, representing 21% of the global economy and 672 million people, has pledged about 9% emissions reduction compared to a base year (CDP 2020). More than 10,000 cities, representing more than 10 percent of the global population, participate in the Global Covenant of Mayors, C40 Cities (Global Covenant of Mayors for Climate and Energy 2018), and ICLEI's - Local Governments for Sustainability carbon registry (Hsu et al. 2018). In Europe alone, more than 6,000 cities have adopted their own climate action plans (Palermo et al. 2020a) and nearly 300 U.S. subnational actors – cities and states - were committed to maintaining momentum for climate action as part of 'We Are Still In coalition' (We Are Still In coalition 2020) in the absence of national U.S. climate legislation. Further, as of October 2020, more than 826 cities and 103 regional governments had made specific pledges to decarbonize, whether in a specific sector (e.g., buildings, electricity, or transport) or through their entire economies, pledging to reduce their overall emissions by at least 80 percent or greater (NewClimate Institute and Data Driven EnviroLab 2020). Cities such as Barcelona, Spain and Seattle, Washington have adopted net zero goals for 2050 in policy legislation, while many more cities throughout the world, including the Global South such as Addis Ababa in Ethiopia, have net zero targets under consideration (Energy & Climate Intelligence Unit 2019, 2021).

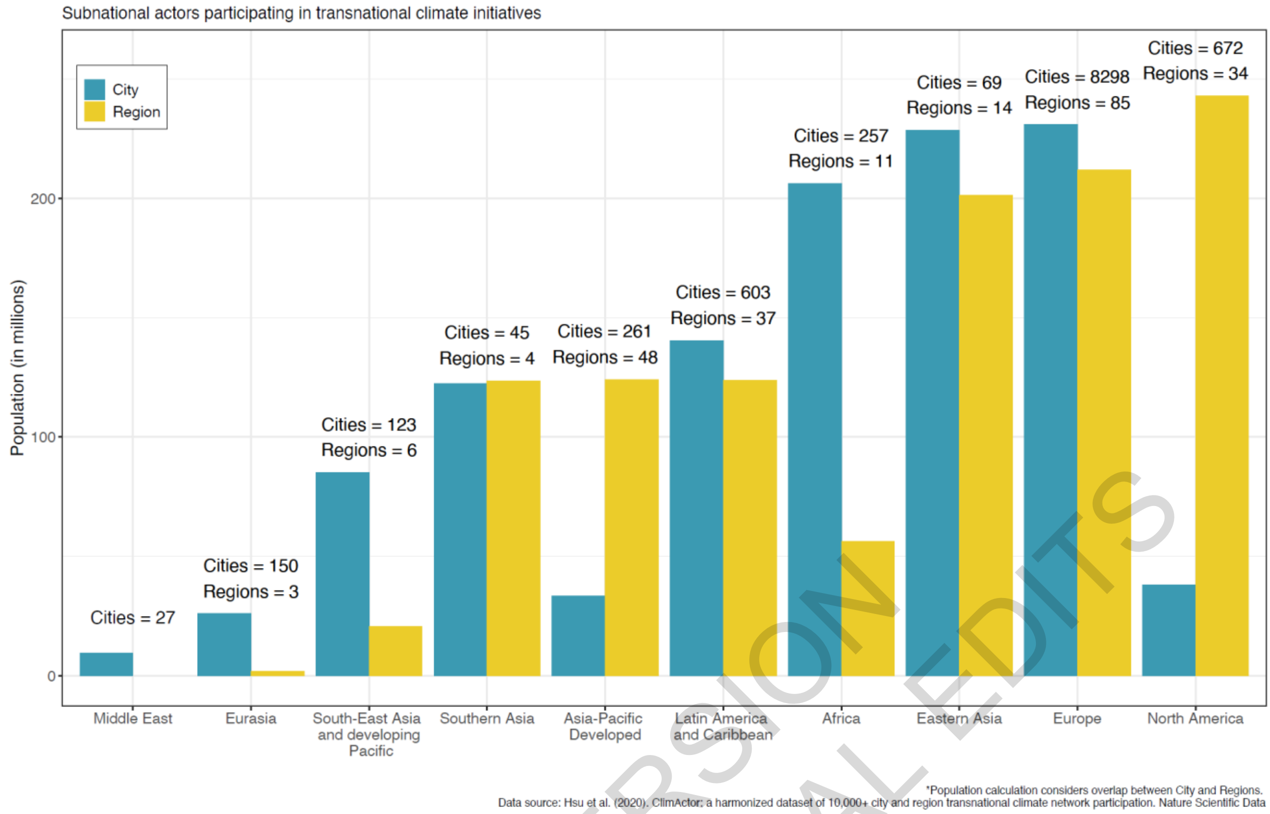

Figure 13.3 Sub-national GHG mitigation commitments: Total population by IPCC region

Population of subnational actors (cities and regions) recording climate action commitments as captured in the ClimActor dataset. Population calculation considers overlap between City and Regions by only accounting for population once for Cities and Regions that are nested jurisdictions

Source: Adapted from (Hsu et al. 2020a) to reflect IPCC AR6 aggregation. Compiled in 2020 from multiple sources based on most recent year of data available.

Sub-national mitigation policies are highlighted below, based on the taxonomy of policies in 13.6.1:

a) Economic instruments: As of 2020, there were carbon pricing initiatives (ETS, carbon tax or both) in 24 subnational jurisdictions (World Bank 2021a). Examples include emission trading systems within the U.S. the Regional Greenhouse Gas Initiative (RGGI) and Western Climate Initiative, tax rebates for the purchase of EVs, a carbon tax in British Columbia, and a cap-and-trade scheme in Metropolitan Tokyo (Houle et al. 2015; Murray and Rivers 2015; Hibbard et al. 2018; Bernard and Kichian 2019; Raymond 2019; Xiang and Lawley 2019; Chan and Morrow 2019).

b) Regulatory instruments: Policies such as land use and transportation planning, performance standards for buildings, utilities, transport electrification, and energy use by public utilities, buildings and fleets are widely prevalent (Bulkeley 2013; Jones 2013; C40 and ARUP 2015; Martinez et al. 2015; Hewitt and Coakley 2019; Palermo et al. 2020b). Policies such as regulatory restrictions, low emission zones, parking controls, delivery planning and freight routes, focus on traffic management and reduction of local air pollution but also have a mitigation impact (Slovic et al. 2016; Khreis et al. 2017; Letnik et al. 2018). For instance, in coordination with national governments, subnational actors in China, Europe and US have introduced access to priority lanes, free parking and other strategies fostering the roll-out of EVs (Creutzig 2016; Zhang and Bai 2017; Teske et al. 2018; Zhang and Qin 2018; Romero-Lankao et al. 2021).

c) Land-use planning addresses building form, density, energy, and transport, which are relevant for decarbonisation (Creutzig et al. 2015; Torabi Moghadam et al. 2017; Teske et al. 2018). Its effectiveness is limited by absent or fragmented jurisdiction, financial resources and powers, competition between authorities and policy domains, and national policies that restrict local governments' ability to enact more ambitious policies (Fudge et al. 2016; Gouldson et al. 2016; Petersen 2016). Most rapidly growing smaller cities in Latin America, Asia and Africa lack capacity for urban planning and enforcement (Romero-Lankao et al. 2015; Creutzig 2016).

d) Other policies: These include information and capacity building, such as carbon labelling aimed at providing carbon footprint information to consumers (Liu et al. 2016); disclosure and benchmarking policies in buildings to increase awareness of energy issues and track mitigation progress (Hsu et al. 2017; Papadopoulos et al. 2018); and procurement guidelines developed by associations (Sustainable Purchasing Leadership Council 2021). For instance, a building retrofit program was initiated in New York and Melbourne to foster energy efficiency improvements through knowledge provision, training, and consultation (Trencher et al. 2016; Trencher and van der Heijden 2019). Also significant is government provision of public good, services, and infrastructure (Romero Lankao et al. 2019), which includes provision of electric buses or buses on renewable fuels for public transportation (Kamiya and Teter 2019) and zero emission urban freight transport (Quak et al. 2019), sustainable food procurement for public organizations in cities (Smith et al. 2016), decentralized energy resources (Marquardt 2014; Hirt et al. 2021; Kahsar 2021), and green electricity purchase via community choice aggregation programs and franchise agreements (Armstrong 2019).

13.5.2 Partnerships and experiments

Partnerships, such as those among private and public, or transnational and subnational entities, have been found to enable better mitigation results in areas outside direct government control such as residential energy use, emissions from local businesses, or private vehicles (Fenwick et al. 2012; Castán Broto and Bulkeley 2013; Aylett 2014; Hamilton et al. 2014; Bulkeley et al. 2016; Wakabayashi and Arimura 2016; Grandin et al. 2018). Partnerships take advantage of investments that match available grants or enable a local energy project, or enhance the scope or impact of mitigation (Burch et al. 2013).

Subnational actors have also been associated with experiments and laboratories, which promise to achieve the deep change required to address the climate mitigation gap (Smeds and Acuto 2018; Marvin et al. 2018). Experiments span smart technologies (e.g., in Malmö, Sweden (Parks 2019), Eco-Art, Transformation-Labs and other approaches that question the cultural basis of current energy regimes and seek reimagined or reinvented futures (Guy et al. 2015; Voytenko et al. 2016; Hodson et al. 2018; Peng and Bai 2018; Culwick et al. 2019; Pereira et al. 2019; Sengers et al. 2019; Castán Broto and Bulkeley 2013; Smeds and Acuto 2018). They may include governance experiments, from formally defined policy experiments to informal initiatives that mobilise new governance concepts (Kivimaa et al. 2017a; Turnheim et al. 2018), and co-design initiatives and grassroots innovations (Martiskainen 2017; Sheikh and Bhaduri 2021). These initiatives often expand the scope for citizen participation. For example, Urban Living Labs foster innovation, coproducing responses to existing problems of energy use, energy poverty and mobility that integrate scientific and expert knowledge with local knowledge and common values (Voytenko et al. 2016; Marvin et al. 2018). The European Network of Living Labs- with a global outreach- has established a model of open and citizen-centric innovation for policy making. The proliferation of Climate Assemblies at the national and sub-national level further emphasises the increasing role that citizens can play in both innovating and planning for carbon mitigation (Sandover et al. 2021).

State and local authorities are often central to initiating and implementing experiments and use an incremental, 'learning by doing' governing approach (Bai et al. 2010; Nevens et al. 2013; Mcguirk et al. 2015; Nagorny-Koring and Nochta 2018; Castán Broto and Bulkeley 2013; Hodson et al. 2018; Peng and

Bai 2018; Smeds and Acuto 2018; Culwick et al. 2019; Sengers et al. 2019). Experiments relate to technological learning and changes in policies, practices, services, user behaviour, business models, institutions, and governance (Wieczorek et al. 2015; Kivimaa et al. 2017a; Laurent and Pontille 2018; Torrens et al. 2019; Castán Broto and Bulkeley 2013).

Experimentation has contributed to learning, changes in outcomes when implemented, and shifts in the political landscape (Turnheim et al. 2018). Experiments, however, are often isolated and do not always result in longer-term, more widespread changes. The transformative potential (understood as changes in the fundamental attributes of natural and human systems, see Glossary) of experiments is constrained by uncertainty about locally relevant climate change solutions and effects; a lack of comprehensive, and sectorally inclusive national policy frameworks for decarbonisation; budgetary and staffing limitations; and a lack of institutional and political capacity to deliver integrated and planned approaches (Evans and Karvonen 2014; Wittmayer et al. 2016; Webb et al. 2017; Hölscher et al. 2018; Mcguirk et al. 2015; Bulkeley et al. 2016; Grandin et al. 2018; Nagorny-Koring 2019; Sengers et al. 2019; Voytenko et al. 2016).

13.5.3 Performance and global mitigation impact

The performance of subnational actors' mitigation policies have been measured using criteria such as existence of mitigation targets, incentives for mitigation, definition of a baseline, and existence of a monitoring, reporting, and verification procedure (Hsu et al. 2019). Existing evaluations range from small-scale studies assessing the mitigation potential of commitments by subnational regions, cities and companies in the U.S. or in ten high-emitting economies (Roelfsema 2017; Hsu et al. 2019), to larger studies finding that over 9,149 cities worldwide could mitigate 1,400 $MtCO_2$-eq in 2030 (Global Covenant of Mayors for Climate and Energy 2018; Hsu et al. 2018, 2019). These subnational mitigation potential estimates vary since a range of approaches exists for accounting for overlaps between subnational governments and their nested jurisdictions (e.g., states, provinces, and national governments) (Roelfsema et al. 2018; Hsu et al. 2019). One analysis found that the cities of New York, Berlin, London, Greater Toronto, Boston, and Seattle have achieved on average a 0.27 tCO_2-eq per capita per year reduction (Kennedy et al. 2012). Hsu et al. (Hsu et al. 2020c) found that 60 percent of more than 1,000 European cities, representing 6 percent of the EU's total emissions, are on track to achieving their targets, reducing more than 51 million tons $MtCO_2$-eq. While evidence is limited, there are concerns that implementation challenges persist with city level plans, particularly tied to management of initiatives and engagement of the population (Messori et al. 2020).

Whether participation in transnational climate initiatives impacts subnational governments' achievement on climate mitigation goals is uncertain. Some find that higher ambition in climate mitigation commitments did not translate into greater mitigation (Kona et al. 2016; Hsu et al. 2019). Other studies associate participation in networks with increased solar PV investment (Khan and Sovacool 2016; Steffen et al. 2019), and with potential to achieve carbon emissions reductions per capita in line with a global 2 °C scenario (Kona et al. 2016).

Reporting networks may attract high-performing actors, suggesting an artificially high level of cities interested in taking climate action or piloting solutions (self-selection bias) that may not be effective elsewhere (van der Heijden 2018). Many studies present a conservative view of potential mitigation impact because they draw upon publicly reported mitigation actions and exclude subnational actions that are not reported (Kuramochi et al. 2020)

In addition to direct mitigation contributions, climate action partnerships may deliver indirect effects that, while difficult to quantify, ensure long-term change (Chan et al. 2015). Experimentation and policy innovation helps to establish best practices (Hoffmann 2011); set new norms for ambitious climate action that help build coalitions (Bernstein and Hoffmann 2018; Chan et al. 2015); and translate into knowledge sharing or capacity building (Lee and Koski 2012; Purdon 2015; Acuto and Rayner 2016; Hakelberg 2014).

Emergent research explores whether, in addition to realising outcomes, mitigation initiatives also provide the resources, skills and networks that governments and other stakeholders currently use to target other development goals (Shaw et al. 2014; Wolfram 2016; Wiedenhofer et al. 2018; Amundsen et al. 2018; Heikkinen et al. 2019).

13.6 Policy instruments and evaluation

Institutions and governance processes described in previous section result in specific policies, that governments then implement and that shape actions of many stakeholders. This section assesses the empirical experience with the range of policy instruments available to governments with which to shape mitigation outcomes. Section 13.7 that follows deals with how these instruments are combined into packages, and Section 13.9 addresses economy-wide measures and issues.

Many different policy instruments for GHG reduction are in use. They fall into a few major categories that share key characteristics. This section provides one possible taxonomy of these major types of policy instruments, presents a set of criteria for policy evaluation, and synthesizes the literature on the most common mitigation policies. The emphasis is on recent empirical evidence on the performance of different policy instruments and lessons that can be drawn from these experiences. This builds on and enhances the AR5 Chapter 15, which provided a more theoretical treatment of policy instruments for mitigation.

13.6.1 Taxonomy and overview of mitigation policies

13.6.1.1 Taxonomy of mitigation policies

A large number of policies and policy instruments can affect GHG emissions and/or sequestration, whether their primary purpose is climate change mitigation or not. Consequently, consistent with the approach in this chapter, this section adopts a broad interpretation to what is considered mitigation policy. Also, the section recognizes the multiplicity of policies that overlap and interact.

Environmental policy instruments, including for climate change mitigation, have long been grouped into three main categories – (1) economic instruments, (2) regulatory instruments, and (3) other instruments – although the specific terms differ across disciplines and additional categories are common (Kneese and Schultze 1975; Jaffe and Stavins 1995; Nordhaus 2013; Wurzel et al. 2013). Examples of common policies in each category are shown in Table 13.1, but this is not a comprehensive list. Principles of and empirical experience with the various instruments are synthesized in Sections 13.6.3 to 13.6.5, international interactions are covered in 13.6.6.

Table 13.1 Classification of mitigation policies

Category	Examples of common types of mitigation policy instruments
Economic instruments	Carbon taxes, GHG emissions trading, fossil fuel taxes, tax credits, grants, renewable energy subsidies, fossil fuel subsidy reductions, offsets, R&D subsidies, loan guarantees
Regulatory instruments	Energy efficiency standards, renewable portfolio standards, vehicle emission standards, ban on SF_6 uses, biofuel content mandates, emission performance standards, methane regulations, land-use controls
Other instruments	Information programs, voluntary agreements, infrastructure, government technology procurement policies, corporate carbon reporting

13.6.1.2 Coverage of mitigation policies

An increasing share of global emissions sources is subject to mitigation policies, though coverage is still incomplete (Nascimento et al. 2021; Eskander and Fankhauser 2020).

While consistent information on global prevalence of policies is not available, in G20 countries the use of various policy instruments has increased steadily over the past two decades (Nascimento et al. 2021). The share of countries that had mitigation policy instruments in place rose across all sectoral categories, albeit to different extents in different sectors and for different policy instruments (Figure 13.4). Among G-20 countries the electricity and heat generation has the greatest number of policies in place, and the agriculture and forestry sector the fewest (Nascimento et al. 2021).

The mix of policies has shifted towards more regulatory instruments and carbon pricing relative to information policies and voluntary action (Schmidt and Fleig 2018; Eskander and Fankhauser 2020).

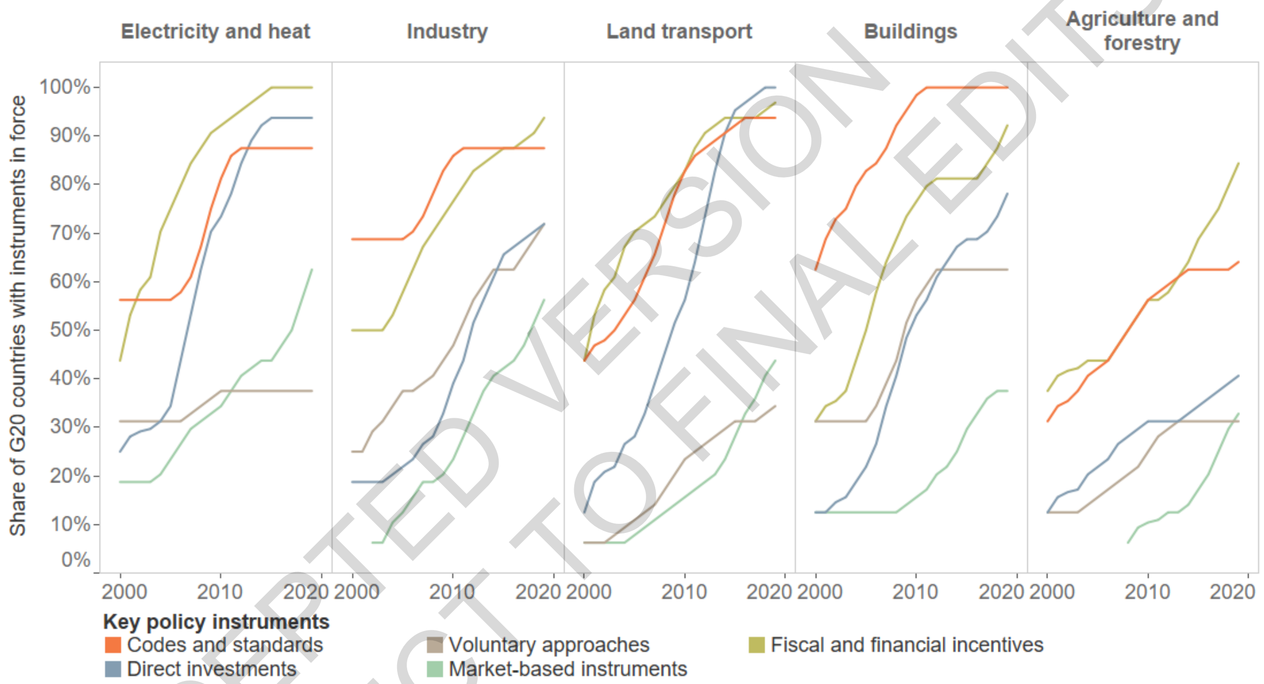

Figure 13.4 Share of countries that adopted different policy instruments in different sectors, 2000-2020 (three year moving average).

Source: Reproduced from (Nascimento et al. 2021).

The IEA database, which tracks renewable energy and energy efficiency policies at the national and sub-national levels for about 160 countries, indicates an average of about 225 new renewable energy and energy efficiency policies annually from 2010 through 2019 with a peak in the number of new renewable energy policies in 2011 (IEA 2021).

While an increasing share of CO_2 emissions from fossil fuel combustion is subject to mitigation policies, there remain many countries and sectors where no dedicated mitigation policies apply to fuel combustion. Fossil fuel use is subject to energy taxes in the majority but not all jurisdictions, and in some instances, it is subsidised.

The main gaps in current mitigation policy coverage are non-CO_2 emissions and CO_2 emissions associated with production of industrial materials and chemical feedstocks, which are connected to broader questions of shifting to cleaner production systems (Bataille et al. 2018a; Davis et al. 2018). Sequestration policies focus mainly on forestry and CCS with limited support for other carbon dioxide removal and use options (Geden et al. 2019; Vonhedemann et al. 2020).

13.6.1.3 Stringency and overall effectiveness of mitigation policies

The stringency of mitigation policies varies greatly by country, sector and policy (see Box 13.9). Stringency can be increased through sequential changes to policies (Pahle et al. 2018).

Estimates of the effective carbon price (as an estimate of overall stringency across policy instruments) differ greatly between countries and sectors (World Bank 2021a). Countries with higher overall effective carbon prices tend to have lower carbon intensity of energy supply and lower emissions intensity of the economy, as shown in an analysis of 42 G20 and OECD countries (OECD 2018). The carbon price that prevails under a carbon tax or ETS is not directly a measure of policy stringency across an economy, as the carbon prices typically only cover a share of total emissions, and rebates or free allowance allocations can limit effectiveness (OECD 2018). At low emissions prices, mitigation incentives are small; as of April 2021, seventeen jurisdictions with a carbon pricing policy had a tax rate or allowance price less than USD5 per tCO_2 (World Bank 2021a).

START BOX 13.9 HERE

Box 13.9 Comparing the stringency of mitigation policies

Comparing the stringency of policies over time or across jurisdictions is very challenging and there is no single widely accepted metric or methodology (Tosun and Schnepf 2020; Fekete et al. 2021; Compston and Bailey 2016; Burck et al. 2019). Policies are also assessed for their estimated effect on emissions, however this requires estimation of a counterfactual baseline and isolation of other effects (see Cross-Chapter Box 10 in Chapter 14). Economic instruments can be compared on the basis of their price or cost per tCO_2-eq. Even that is fraught with complexity in the context of different definitions and estimations for fossil fuel taxes and subsidies. For non-price policies an implicit or equivalent carbon price can be estimated. Factors such as the tax treatment of compliance costs can increase complexity. Accounting for the combined effect of overlapping policies presents additional challenges and such estimates are subject to numerous limitations.

END BOX 13.9 HERE

Other policies, such as fossil fuel subsidies, may provide incentives to increase emissions thus limiting the effectiveness of the mitigation policy (Section 13.6.3.6). Those effects may be complex and difficult to identify. In most countries trade policy provides an implicit subsidy to CO_2 emissions (Shapiro 2020). The analysis of emissions from energy use in buildings in Chapter 9 illustrates the factors that support and counteract mitigation policies.

Furthermore, emissions pricing policies encourage reduction of emissions whose marginal abatement cost is lower than the tax/allowance price, so they have limited impact on emissions with higher abatement costs such as industrial process emissions (Bataille et al. 2018a; Davis et al. 2018). EU ETS emission reductions have been achieved mainly through implementation of low cost measures such as energy efficiency and fuel switching rather than more costly industrial process emissions.

Estimating the overall effectiveness of mitigation policies is difficult because of the need to identify which observed changes in emissions and their drivers are attributable to policy effort and which to other factors. Cross-Chapter Box 10 in Chapter 14 brings together several lines of evidence to indicate that mitigation policies have had a discernible impact on mitigation for specific countries, sectors and technologies and led to avoided global emissions to date by several billion tonnes CO_2-eq annually *(medium evidence, medium agreement)*.

13.6.2 Evaluation criteria

Policy evaluation is a "careful, retrospective assessment of merit, worth and value of the administration, output and outcomes of government interventions" (Vedung 2005). The inherent complexity of climate mitigation policies calls for the application of multiple criteria, and reflexiveness of analysis with regard to governments' and societies' objectives for policies (Huitema et al. 2011).

Evaluation of climate mitigation policy tends to focus on the environmental effectiveness and economic efficiency or cost-effectiveness of GHG mitigation policies, with distributional equity sometimes as an additional criterion. In policy design and implementation there is rising interest in co-benefits and side-effects of climate policies, as well as institutional requirements for implementation and the potential of policies to have transformative effect on systems. Table 13.2 elaborates.

Not all criteria are applicable to all instruments or in all circumstances and the relative importance of different criteria depend on the objectives in the specific the context. A given policy instrument may score highly on only some assessment criteria. In practice, the empirical evidence seldom exists for assessment of a policy instrument across all criteria.

Table 13.2 Criteria for evaluation and assessment of policy instruments and packages

Criterion	Description
Environmental effectiveness	Reducing GHG emissions is the primary goal of mitigation policies and therefore a fundamental criterion in evaluation. Environmental effectiveness has temporal and spatial dimensions.
Economic effectiveness	Climate change mitigation policies usually carry economic costs, and/or bring economic benefits other than through avoided future climate change. Economic effectiveness requires minimizing costs and maximizing benefits.
Distributional effects	The costs and benefits of policies are usually distributed unequally among different groups within a society (Zachmann et al. 2018), for example between industry, consumers, taxpayers; poor and rich households; different industries; different regions and countries. Policy design affects distributional effects, and equity can be taken into account in policy design in order to achieve political support for climate policies (Baranzini et al. 2017).
Co-benefits, negative side-effects	Climate change mitigation policies can have effects on other objectives, either positive co-benefits (Mayrhofer and Gupta 2016; Karlsson et al. 2020) or negative side-effects. Conversely, impacts on emissions can arise as side-effects of other policies. There can be various interactions between climate change mitigation and the Sustainable Development Goals (Liu et al. 2019).
Institutional requirements	Effective implementation of policies requires that specific institutional prerequisites are met. These include effective monitoring of activities or emissions and enforcement, and institutional structures for the design, oversight and revision and updating of policies. Requirements differ between policy instruments. A

	separate consideration is the overall feasibility of a policy within a jurisdiction, including political feasibility (Jewell and Cherp 2020).
Transformative potential	Transformational change is a process that involves profound change resulting in fundamentally different structures (Nalau and Handmer 2015), or a substantial shift in a system's underlying structure (Hermwille et al. 2015). Climate change mitigation policies can be seen has having transformative potential if they can fundamentally change emissions trajectories, or facilitate technologies, practices or products with far lower emissions.

13.6.3 Economic instruments

Economic instruments, including carbon taxes, emissions trading systems (ETS), purchases of emission reduction credits, subsidies for energy efficiency, renewables and research and development and fossil fuel subsidy removal, provide a financial incentive to reduce emissions. Pricing instruments, especially ETS and carbon taxes, have become more prevalent in recent years (Section 13.6.1). They have proven effective in promoting implementation of the low-cost emissions reductions, and practical experience has driven progress in market mechanism design *(robust evidence, high agreement)*.

13.6.3.1 Carbon taxes

A carbon tax is a charge on carbon dioxide or other greenhouse gases imposed on specified emitters or products. In practice features such as exemptions and multiple rates can lead to debate as to whether a specific tax is a carbon tax (Haites 2018). While other taxes can also reduce emissions by increasing the price of GHG emitting products, the result may be inefficient unless the tax rate is proportional to the emissions intensity. A tax on value of fossil fuels, for example, could raise the price on natural gas more than the price of coal, and hence increase emissions if the resulting substitution towards coal were to outweigh reductions in energy use.

As of April 2021, 27 carbon taxes had been implemented by national governments, mostly in Europe (World Bank 2021a). Most of the taxes apply to fossil fuels used for transportation and heating and cover between 3% and 79% of the jurisdiction's emissions. Several countries also tax F-gases. Tax rates vary widely from less than USD1 to over USD137 per tCO_2-eq. A few jurisdictions lowered existing fuel taxes when they implemented the carbon tax, thus reducing the effective tax rate (OECD 2021a). How the tax revenue is used varies widely by jurisdiction.

Carbon taxes tend to garner the least public support among possible mitigation policy options (Rhodes et al. 2017; Rabe 2018; Maestre-Andrés et al. 2019; Criqui et al. 2019) although some regulations also meet with opposition (Attari et al. 2009). Policymakers sometimes use the revenue to build support for the tax, allocating some to address regressivity, to address competitiveness claims by industry, to reduce the economic cost by lowering existing taxes, and to fund environmental projects (Gavard et al. 2018; Klenert et al. 2018; Levi et al. 2020).

Carbon tax rates can be adjusted for inflation, increases in income, the effects of technological change, changing policy ambition, or the addition or subtraction of other policies. In practice numerous jurisdictions have not increased their tax rates annually and some scheduled tax increases have not been implemented (Haites et al. 2018). Predictability of future tax rates helps improve economic performance (Bosetti and Victor 2011; Brunner et al. 2012). Uncertainty about the future existence of a carbon price can hinder investment (Jotzo et al. 2012) and uncertainty about future price levels can increase the resource costs of carbon pricing (Aldy and Armitage 2020).

13.6.3.2 Emission trading systems

The most common ETS design – cap-and-trade – sets a limit on aggregate GHG emissions by specified sources, distributes tradable allowances approximately equal to the limit, and requires regulated emitters to submit allowances equal to their verified emissions. The price of allowances is determined by the market, except in cases where government determined price floors or ceilings apply.

ETSs for GHGs were in place in 38 countries as of April 2021 (World Bank 2021a). The EU ETS, which covers 30 countries, was recently displaced by China's national ETS as the largest. ETSs tend to cover emissions by large industrial and electricity generating facilities.[3] Allowance prices as of April 1, 2021 ranged from just over USD1 to USD50, and coverage between 9 and 80% of the jurisdiction's emissions.

Multiple regional pilot ETSs with different designs have been implemented in China since 2013 to provide input to the design of a national system that is to become the world's largest ETS (Jotzo et al. 2018; Qian et al. 2018; Stoerk et al. 2019). Assessments have identified potential improvements to emissions reporting procedures (Zhang et al. 2019) and the pilot ETS designs (Deng et al. 2018). China's national ETS covering over 2,200 heat and power plants with annual emissions of about 4 billion tCO_2 took effect in 2021 (World Bank 2021a).

All of the ETSs for which data are available have accumulated surplus allowances which reduces their effectiveness (Haites 2018). Surplus allowances indicate that the caps set earlier were not stringent relative to emissions trends. Most of those ETSs have implemented measures to reduce the surplus including removal/cancellation of allowances and more rapid reduction of the cap. Several ETSs have adopted mechanisms to remove excess allowances from the market when supply is abundant and release additional allowances into the market when the supply is limited, such as the EU "market stability reserve" (Hepburn et al. 2016; Bruninx et al. 2020). Initial indications are that this mechanism is at least partially successful in stabilizing prices in response to short term disruptions such as the COVID-19 economic shock (Gerlagh et al. 2020; Bocklet et al. 2019).

Some ETS also include provisions to limit the range of market prices, making them 'hybrids' (Pizer 2002). A price floor assures a minimum level of policy effect if demand for allowances is low relative to the ETS emissions cap. It is usually implemented through a minimum price at auction, as for example in California's ETS (Borenstein et al. 2019). A price ceiling allows the government to issue unlimited additional allowances at a pre-determined price to limit the maximum cost of mitigation. Price ceilings have not been activated to date.

13.6.3.3 Evaluation of carbon pricing experience

A carbon tax or GHG ETS increases the prices of emissions intensive goods thus creating incentives to reduce emissions (see (Stavins 2019) for a comparison of a tax and ETS). The principal advantage of a pricing policy is that it promotes implementation of low cost reductions; for a carbon tax, reductions whose cost per tCO_2-eq reduced is lower than the tax and for an ETS the lowest cost (per tCO_2-eq) reductions sufficient to meet the cap. Both a tax and an ETS can be designed to limit adverse economic impacts on regulated sources and emissions leakage.

The corresponding limitations of pricing policies are that they have limited impact on adoption of mitigation measures when decisions are not sensitive to prices and do not encourage adoption of higher cost mitigation measures. Their effectiveness in influencing long-term investments depends on the expectation that the policy will continue and expectations related to future tax rates or allowance prices (Brunner et al. 2012). Other policies can be used in combination with carbon pricing to address these limitations.

FOOTNOTE [3] The UK was a member of the EU ETS until December 31, 2020. A UK Emissions Trading Scheme (UK ETS) came into effect on January 1, 2021.

The number of pricing policies has increased steadily and covered 21.5% of global GHG emissions in 2020 (World Bank 2021a). Effective coverage is lower because virtually all jurisdictions with a pricing policy have other policies that affect some of the same emissions. For example, a few jurisdictions reduced existing fuel taxes when they introduced their carbon tax thus reducing the effective tax rate, and many jurisdictions have two or more pricing policies

Environmental effectiveness and co-benefits

There is abundant evidence that carbon pricing policies reduce emissions. Statistical studies of emissions trends in jurisdictions with and without carbon pricing find a significant impact after controlling for other policies and structural factors (Best et al. 2020; Rafaty et al. 2020). Numerous assessments of specific policies, especially the EU ETS and the British Columbia carbon tax, conclude that most have reduced emissions (Narassimhan et al. 2018; FSR Climate 2019; Haites et al. 2018; Metcalf and Stock 2020; Rafaty et al. 2020; Green 2021; Aydin and Esen 2018; Pretis 2019; Andersson 2019; Arimura and Abe 2021; Bayer and Aklin 2020; Diaz et al. 2020) *(robust evidence, high agreement)*.

Estimating the emission reductions due to a specific policy is difficult due to the effects of overlapping policies and exogenous factors such as fossil fuel price changes and economic conditions. Studies that attempt to attribute a share of the reductions achieved to the EU ETS place its contribution at 3-25% (FSR Climate 2019; Bayer and Aklin 2020; Chèze et al. 2020). The relationship between a carbon tax and the resulting emission reductions is complex and is influenced by changes in fossil fuel prices, changes in fossil fuel taxes, and other mitigation policies (Aydin and Esen 2018). But the effectiveness of a carbon tax generally is higher in countries where it constitutes a large part of the fossil fuel price (Andersson 2019).

Few of the world's carbon prices are at a level consistent with various estimates of the carbon price needed to meet the Paris Agreement goals. In modelling of mitigation pathways likely to limit warming to 2°C (Chapter 3, 3.6.1) marginal abatement costs of carbon in 2030 are about 60 to 120 USD2015/tCO2, and about 170 to 290 USD2015/tCO2 in pathways that limit warming to 1.5°C with no or limited overshoot (3.6). One synthesis study estimates necessary prices at USD40–80 per tCO_2 by 2020 (High-Level Commission on Carbon Prices 2017). Only a small minority of carbon pricing schemes in 2021 had prices above USD40 per tCO_2, and all of these were in European jurisdictions (World Bank 2021a). Most carbon pricing systems apply only to some share of the total emissions in a jurisdiction, so the headline carbon price is higher than the average carbon price that applies across an economy (World Bank 2021a).

Where ETS or carbon taxes exist, they apply to different proportions of the jurisdiction's greenhouse gas emissions. The share of emissions covered by ETSs in 2020 varied widely, ranged from 9% (Canada) to 80% (California) while the share of emissions covered by carbon taxes ranged from 3% (Latvia and Spain) to 80% (South Africa) (World Bank 2021a).Where carbon pricing policies are effective in reducing GHG emissions, they usually also generate co-benefits including better air quality. For example, a Chinese study of air quality benefits from lower fossil fuel use under carbon pricing suggests that prospective health co-benefits would partially or fully offset the cost of the carbon policy (Li et al. 2018). Depending upon the jurisdiction (for example, if there are fossil fuel subsidies) carbon pricing could also reduce the economic distortions of fossil fuel subsidies, improve energy security through greater reliance on local energy sources and reduce exposure to fossil fuel market volatility. Substantial carbon prices would be in the domestic self-interest of many countries if co-benefits were fully factored in (Parry et al. 2015).

Economic effectiveness

Economic theory suggests that carbon pricing policies are on the whole more cost effective than regulations or subsidies at reducing emissions (Gugler et al. 2021). Any mitigation policy imposes costs on the regulated entities. In some cases entities may be able to recover some or all of the costs through higher prices (Neuhoff and Ritz 2019; Cludius et al. 2020). International competition from less stringently regulated firms limits the ability of emissions-intensive, trade-exposed (EITE) firms to raise their prices. Thus a unilateral mitigation policy creates a risk of adverse economic impacts, including loss of sales, employment, profits, for such firms and associated emissions leakage (see Section 13.6.6.1).

Pricing policies can be designed to minimize these risks; free allowances can be issued to EITE participants in an ETS and taxes can provide exemptions or rebates. An extensive ex post literature finds no statistically significant adverse impacts on competitiveness or leakage (13.6.6.1).

An ex post analysis of European carbon taxes finds no robust evidence of a negative effect on employment or GDP growth (Metcalf and Stock 2020). The British Columbia carbon tax led to a small net increase in employment (Yamazaki 2017) with no significant negative impacts on GDP possibly due to full recycling of the tax revenue (Bernard and Kichian 2021). Few carbon taxes apply to EITE sources (Timilsina 2018), so competitiveness impacts usually are not a particular concern.

Government revenue generated by carbon pricing policies globally was approximately USD53 billion in 2020 split almost evenly between carbon taxes and ETS allowance sales (World Bank 2021). Revenue raised though carbon pricing is generally considered a relatively efficient form of taxation and a large share of revenue enters general government budgets (Postic and Fetet 2020). Some of the revenue is returned to emitters or earmarked for environmental purposes. Allowance allocation and revenue spending measures have been used to create public support for many carbon pricing policies including at every major reform stage of the EU ETS (Dorsch et al. 2020; Klenert et al. 2018; see also Box 5.11).

Distributional effects

The most commonly studied distributional impact is the direct impact of a carbon tax on household income. Typically it is regressive; the tax induced increase in energy expenditures represents a larger share of household income for lower income households (Grainger and Kolstad 2010; Timilsina 2018; Dorband et al. 2019; Ohlendorf et al. 2021). Governments can rebate part or all of the revenue to low income households, or implement other changes to taxation and transfer systems to achieve desired distributional outcomes (Jacobs and van der Ploeg 2019; Saelim 2019; Sallee 2019) (see also Box 5.11). The full impact of the tax – after any distribution of tax revenue to households and typically adverse effects on investors – generally is less regressive or progressive (Williams III et al. 2015; Goulder et al. 2019). Where the tax revenue is treated as general revenue the government relies on existing income redistribution policies (such as income taxes) and social safety net programs to address the distributional impacts.

Carbon taxes on fossil fuels have effects similar to the removal of fossil fuel subsidies (Ohlendorf et al. 2021) (see also Section 13.6.3.6). Even if a carbon tax is progressive it increases prices for fuels, electricity, transport, food and other goods and services that adversely affect the most economically vulnerable. Redistribution of tax revenue is critical to address the adverse impacts on low income groups (Dorband et al. 2019) (see also Box 5.11). In countries with a limited capacity to collect taxes and distribute revenues to low income households, such as some developing countries, carbon taxes may have greater distributional consequences.

Distributional effects have generally not been a significant issue for ETSs. Equity for industrial participants typically is addressed through free allocation of allowances. Impacts on household incomes, with the exception of electricity prices, are too small or indirect to be a concern. Some systems are designed to limit electricity price increases (Petek 2020) or use some revenue for bill assistance to low-income households (RGGI 2019).

Technological change

Carbon pricing, especially an ETS that covers industrial sources, stimulates technological change by participants and others (Calel and Dechezleprêtre 2016; FSR Climate 2019; van den Bergh and Savin 2021) (see also Section 13.6.6.3 and Chapter 16). The purpose of pricing policies is to encourage implementation of the lowest cost mitigation measures. Pricing policies therefore are more likely to stimulate quick, low cost innovation such as fuel switching and energy efficiency, rather than long-term, costly technology development such as renewable energy or industrial process technologies (Calel 2020; Lilliestam et al. 2021). To encourage long-term technology development carbon pricing policies need to be complemented by other mitigation and R&D policies.

13.6.3.4 Offset credits

Offset credits are voluntary GHG emission reductions for which tradable credits are issued by a supervisory body (Michaelowa et al. 2019b). A buyer can use purchased credits to offset an equal quantity of its emissions. In a voluntary market governments, firms and individuals purchase credits to offset emissions generated by their actions, such as air travel. A compliance market allows specified offset credits to be used for compliance with mitigation policies, especially ETSs, carbon taxes and low carbon fuel standards. (Newell et al. 2013; Bento et al. 2016; Michaelowa et al. 2019a).

When used for compliance, governments typically specify a maximum quantity of offset credits that can be used, as well as the types of emission reduction actions, the project start dates and the geographic regions eligible credits. Initially, the EU ETS, Swiss ETS and New Zealand ETS accepted credits issued under the Kyoto Protocol (Chapter 14), but they terminated or severely constrained the quantity of international credits allowed for compliance use after 2014 (Shishlov et al. 2016)(see 13.6.6).

A key question for any offset credit is whether the emission reductions are 'additional': reductions that only happen because of the offset credit payment (Millard-Ball and Ortolano 2010; van Benthem and Kerr 2013; Burke 2016; Bento et al. 2016; Greiner and Michaelowa 2003). To assess additionality and to determine the quantity of credits to be issued, regulators develop methodologies to estimate baseline (business-as-usual) emissions in the absence of offset payments (Newell et al. 2013; Bento et al. 2016). Credits are issued for the difference between the baseline and actual emissions with adjustments for possible emissions increases outside the project boundary (Rosendahl and Strand 2011). Some research suggests that procedural and measurement advances can significantly reduce the risk of severe non-additionality (Mason and Plantinga 2013; Bento et al. 2016; Michaelowa et al. 2019a).

13.6.3.5 Subsidies for mitigation

Subsidies for mitigation encourage individuals and firms to invest in assets that reduce emissions, changes in processes or innovation. Subsidies have been used to improve energy efficiency, encourage the uptake of renewable energy and other sector-specific emissions saving options (Chapters 6 to 11), and to promote innovation. Targeted subsidies can achieve specific mitigation goals yet have intrinsically narrower coverage than more broad-based pricing instruments. Subsidies are often used not only to achieve emissions reductions but to address market imperfections or to achieve distributional or strategic objectives. Subsidies are often used alongside or in combination with other policy instruments, and are provided at widely differing cost per unit of emissions reduced.

Governments routinely provide direct funding for basic research, subsidies for R&D to private companies, and co-funding of research and deployment with industry (Dzonzi-Undi and Li 2016). Research subsidies have been found to be positively correlated with green product innovation in a study in Germany, Switzerland and Austria (Stucki et al. 2018). Government subsidies for R&D have been found to greatly increase the green innovation performance of energy intensive firms in China (Bai et al. 2019). For more detail see Chapter 16.

Subsidies of different forms are often provided for emissions savings investments to businesses and for the retrofit of buildings for energy efficiency. Emissions reductions from energy efficiencies can often be achieved at low cost, but evidence for some schemes suggests lower effectiveness in emissions reductions than expected ex ante (Fowlie et al. 2018; Valentová et al. 2019). Tax credits can be used to encourage firms to produce or invest in low-carbon emission energy and low-emission equipment. Investment subsidies have been found to be more effective in reducing costs and uncertainties in solar energy technologies than production subsidies (Flowers et al. 2016).

Subsidies have been provided extensively and in many countries for the deployment of household rooftop solar systems, and increasingly also for commercial scale renewable energy projects, typically using 'feed-in tariffs' that provide a payment for electricity generated above the market price (Pyrgou et al. 2016). Such schemes have proven effective in deploying renewable energy, but lock in subsidies for long periods of time. In some cases they provide subsidies at higher levels than would be required to motivate deployment (del Río and Linares 2014). High levels of net subsidies have been shown to diminish incentives for optimal siting of renewable energy installations (Penasco et al. 2019).

A variant of subsidies for deployment of renewable energy are auctioned feed-in tariffs or auctioned contracts-for-difference, where commercial providers bid in a competitive process. Auctions typically lead to lower price premiums (Eberhard and Kåberger 2016; Roberts 2020) but efficient outcomes depend on auction design and market structure (Grashof et al. 2020), although an emergent literature also questions whether spread of auctions is due to performance or the dynamics of the policy formulation process (Fitch-Roy et al. 2019b; Grashof et al. 2020; Grashof 2021). The prequalification requirements or the assessment criteria in the auctions sometimes also include local co-benefits such as local economic diversification (Buckman et al. 2019; White et al. 2021).

Support for rollout clean technologies at high prices can be economically beneficial in the long run if costs are reduced greatly as a function of deployment (Newbery 2018). Deployment support, much of it in the form of feed-in tariffs in Germany, enabled the scaling up of the global solar photovoltaic industry and attendant large reductions in production costs that by 2020 made solar power cost competitive with fossil fuels (Buchholz et al. 2019). There is also evidence for increased innovation activity as a result of solar feed-in tariffs (Böhringer et al. 2017b).

Many governments have also provided subsidies for the purchase of electric vehicles, including with strong effect in China (Ma et al. 2017), Norway (Baldursson et al. 2021) and other countries, and sometimes at relatively high rates (Kong and Hardman 2019).

13.6.3.6 Removal of fossil fuel subsidies

Many governments subsidize fossil fuel consumption and/or production through a variety of mechanisms (Burniaux and Chateau 2014) (see Figure 13.5). Different approaches exist to defining the scope and estimating the magnitude of fossil fuel subsidies (Koplow 2018), and all involve estimates, so the magnitudes are uncertain. Rationalizing inefficient fossil fuel subsidies is one of the indicators to measure progress toward Sustainable Development Goal 12 -- Ensure sustainable consumption and production patterns (UNEP 2019a).

Consumption subsidies represent approximately 70% of the total. Most of the subsidies go to petroleum, which accounts for roughly 50% of the consumption subsidies and 75% of the production subsidies (IEA 2020; OECD 2020). Much of the variation in the consumption subsidies is due to fluctuations in the world price of oil which is used as the reference price.

Reducing fossil fuel subsidies would lower CO_2 emissions, increase government revenues (Dennis 2016; Gass and Echeverria 2017; Rentschler and Bazilian 2017; Monasterolo and Raberto 2019; Jakob et al. 2015), improve macroeconomic performance (Monasterolo and Raberto 2019), and yield other environmental and sustainable development benefits (Solarin 2020; Rentschler and Bazilian 2017; Jakob et al. 2015) *(robust evidence, medium agreement)*. The benefits of gasoline subsidies in developing countries accrue mainly to higher income groups, so subsidy reduction usually will reduce inequality (Coady et al. 2015; Dennis 2016; Monasterolo and Raberto 2019; Labeaga et al. 2021). Some subsidies, like tiered electricity rates, benefit low income groups. Reductions of broad subsidies lead to price increases for fuels, electricity, transport, food and other goods and services that adversely affect the most economically vulnerable (Coady et al. 2015; Zeng and Chen 2016; Rentschler and Bazilian 2017). Distributing some of the revenue saved can mitigate the adverse economic impacts on low income groups (Dennis 2016; Zeng and Chen 2016; Labeaga et al. 2021; Schaffitzel et al. 2020).

The emissions reduction that could be achieved from fossil fuel subsidy removal depends on the specific context such as magnitude and nature of subsidies, energy prices and demand elasticities, and how the fiscal savings from reduced subsidies are used. Modelling studies of global fossil fuel subsidy removal result in projected emission reductions of between 1 and 10 per cent by 2030 (Delpiazzo et al. 2015; IEA 2015; Jewell et al. 2018; IISD 2019) and between 6.4 and 8.2 per cent by 2050 (Schwanitz et al. 2014; Burniaux and Chateau 2014).

An extensive literature documents the difficulties of phasing out fossil fuel subsidies (Schmidt et al. 2017; Skovgaard and van Asselt 2018; Kyle 2018; Perry 2020; Gass and Echeverria 2017; Gençsü et al. 2020). Fossil fuel industries lobby to maintain producer subsidies and consumers protest if they are adversely affected by subsidy reductions (Fouquet 2016; Coxhead and Grainger 2018). Yemen (2005 and 2014), Cameroon (2008), Bolivia (2010), Nigeria (2012), Ecuador (2019) all abandoned subsidy reform attempts following public protests (Mahdavi et al. 2020; Rentschler and Bazilian 2017). Indonesia is an example where fossil fuel subsidy removal was successful, helped by social assistance programs and a communication effort about the benefits of reform (Chelminski 2018; Burke and Kurniawati 2018). To-date instances of fossil fuel subsidy reform or removal have been driven largely by national fiscal and economic considerations (Skovgaard and van Asselt 2019).

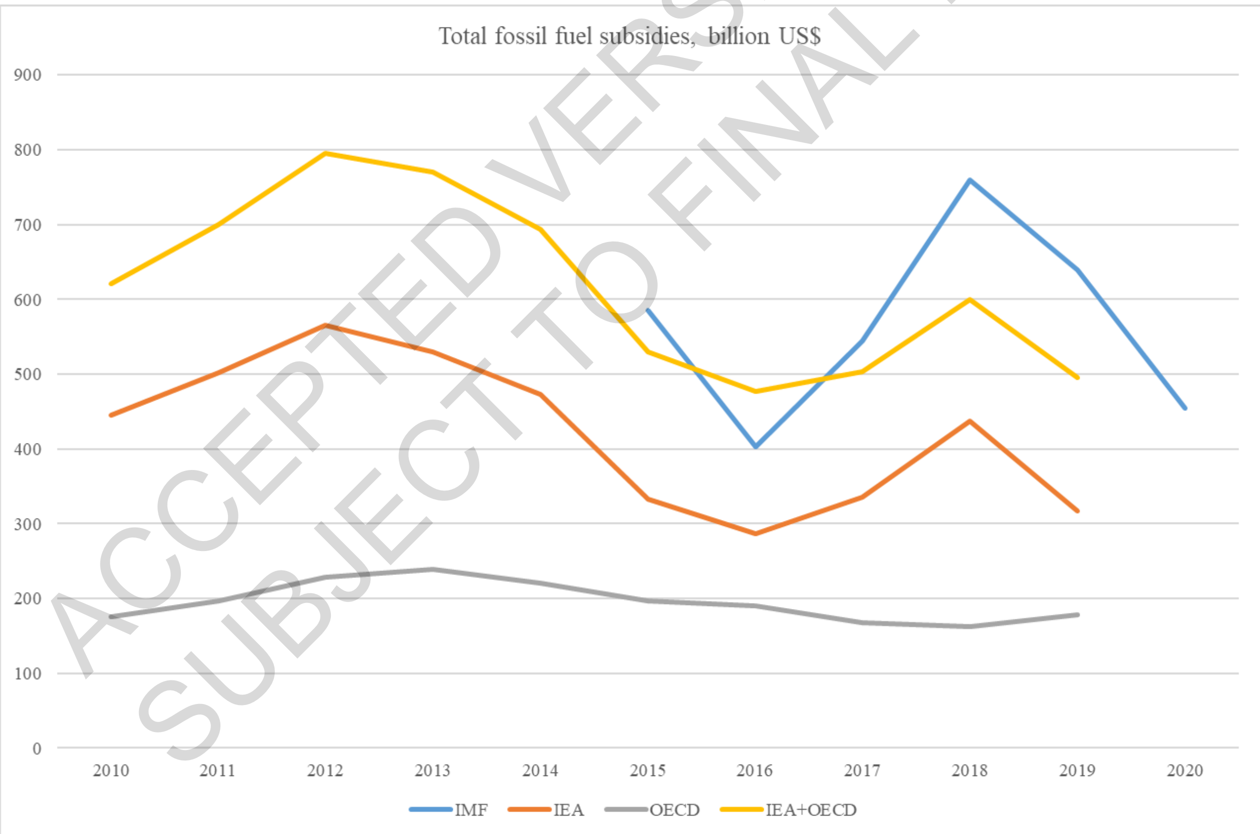

Figure 13.5 Total fossil fuel subsidies, 2010-19, in USD billion (USD2021 for IMF, USD2019 for others).

Source: OECD (2020) (43 countries, mainly production subsidies), IEA (2020) (40 countries, mainly consumption subsidies), IMF ((Parry et al. 2021); explicit subsidies for all countries).

13.6.4 Regulatory instruments

Regulatory instruments are applied by governments to cause the adoption of desired processes, technologies, products (including energy products) or outcomes (including emission levels). Failure to comply incurs financial penalties and/or legal sanctions. Regulatory instruments range from performance standards, which prescribe compliance outcomes – and in some cases allow flexibility to achieve compliance, including the trading of credits – to more prescriptive technology-specific standards, also known as command-and-control regulation. Regulatory instruments play an important role to achieve specific mitigation outcomes in sectoral applications *(robust evidence, high agreement)*. Mitigation by regulation often enjoys greater political support but tends to be more economically costly than mitigation by pricing instruments *(robust evidence, medium agreement)*.

13.6.4.1 Performance standards, including tradable credits

Performance standards grant regulated entities freedom to choose the technologies and methods to reach a general objective, such as a minimum market share of zero-emission vehicles or of renewable electricity, or a maximum emissions intensity of electricity generated. Tradable performance standards allow regulated entities to trade compliance achievement credits; under-performers can buy surplus credits from over-performers thereby reducing the aggregate cost of compliance (Fischer 2008).

Tradable performance standards have been applied to numerous sectors including electricity generation, personal vehicles, building energy efficiency, appliances, and large industry. An important application is Renewable Portfolio Standards (RPS) for electricity supply, which require that a minimum percentage of electricity is generated from specified renewable sources sometimes including nuclear and fossil fuels with CCS when referred to as a clean electricity standard (Young and Bistline 2018)(see also Chapter 6). This creates a price incentive to invest in renewable generation capacity. Such incentives can equivalently be created through feed-in tariffs, a form of subsidy (Section13.6.3) and some jurisdictions have had both instruments (Matsumoto et al. 2017). RPS can differ in features and stringency are in operation in many countries and sub-national jurisdictions, including a majority of US States (Carley et al. 2018).

Vehicle emissions standards are a common form of performance standard with flexibility (Chapter 9). A corporate fuel efficiency standard specifies an average energy use and/or GHG emissions per kilometre travelled for vehicles sold by a manufacturer. Another version of this policy, the zero-emission vehicle (ZEV) standard, requires vehicle sellers to achieve minimum requirements for sales of zero-emission vehicles (Bhardwaj et al. 2020). Both instruments allow manufacturers to use tradable credits to achieve compliance.

Low carbon fuel standards (LCFS), which set an average life-cycle carbon intensity for energy that declines over time, are another example. LCFS are in place in many different jurisdictions (Chapter 9) and have been applied to petroleum products, natural gas, hydrogen and electricity (Yeh et al. 2016). An LCFS allows regulated entities to trade credits creating the potential for high carbon intensity fuel suppliers to cross-subsidize low carbon intensity transport energy providers including low-carbon biofuels, hydrogen and electricity (Axsen et al. 2020).

Trading and other flexibility mechanisms improve the economic efficiency of standards by harmonizing the marginal abatement costs among companies or installations subject to the standard. Nevertheless tradable performance standards are less economically efficient in achieving emissions reductions than carbon pricing, sometimes by a significant amount (Giraudet and Quirion 2008; Chen et al. 2014; Holland et al. 2015; Fox et al. 2017; Zhang et al. 2018).

13.6.4.2 Technology standards

Technology standards take a more prescriptive approach by requiring a specific technology, process or product. They typically take one of three forms: requirements for specific pollution abatement technologies; requirements for specific production methods; or requirements for specific goods such as energy efficient appliances. They can also take the form of phase-out mandates, as applied for example to planned bans of internal combustion engines for road transport (Bhagavathy and McCulloch 2020), coal use (e.g. Germany's decisions to phase out coal (Oei et al. 2020)), and some industry processes and products (e.g. HFCs and use of SF6 in some products (see Box 13.10 on Non-CO_2 gases). Technology standards are also referred to as command-and-control standards, prescriptive standards, or design standards.

Technology standards are a common climate policy particularly at the sector level (Chapters 6-11). Technology standards tend to score lower in terms of economic efficiency than carbon pricing and performance standards (Besanko 1987). But they may be the best instrument for situations where decisions are not very responsive to price signals such as consumer choices related to energy efficiency and recycling and decisions relating to urban land use and infrastructure choices.

By mandating specific compliance pathways, technology standards risk locking-in a high-cost pathway when lower cost options are available or may emerge through market incentives and innovation (Raff and Walter 2020). Furthermore, standards may require high-cost GHG reductions in one sector while missing low-cost options in another sector. Technology standards can also stifle innovation by blocking alternative technologies from entering the market (Sachs 2012). Benefits of technology standards include their potential to achieve emission reductions in a relatively short timeframe and that their effectiveness can be estimated with some confidence (Montgomery et al. 2019).

13.6.4.3 Performance of regulatory instruments

Regulatory policy instruments tend to be more economically costly than pricing instruments, as explained above. However, regulatory policies may be preferred for other reasons.

In some cases, regulatory policy can elicit greater political support than pricing policy (Tobler et al. 2012; Lam 2015; Drews and van den Bergh 2016). For example, U.S. citizens have expressed more support for flexible regulation like the RPS than for carbon taxes (Rabe 2018). And a survey in British Columbia a few years after the simultaneous implementation of a carbon tax and two regulations – the LCFS and a clean electricity standard – found much less strong opposition to the regulations, even after being informed that they were costlier to consumers (Rhodes et al. 2017). The degree of public support for regulations depends, however, on the type of regulation, as outright technology prohibitions can be unpopular (Attari et al. 2009; Cherry et al. 2012).

In comparison to economic instruments, regulatory policies tend to cause greater cost of living increases in percentage terms for lower income consumers – called policy regressivity (Levinson 2019; Davis and Knittel 2019). And unlike carbon taxes, regulations do not generate revenues that can be used to compensate lower income groups.

A renewable energy procurement obligation in South Africa successfully required local hiring with perceived positive results (Walwyn and Brent 2015; Pahle et al. 2016), a clean energy regulation in Korea was perceived to provide greater employment opportunities (Lee 2017), and a UK obligation on energy companies to provide energy retrofits to low-income households improved energy affordability according to participants (Elsharkawy and Rutherford 2018).

From an energy system transformation perspective, technology standards, including phase-out mandates, have particular promise to achieve profound change in specific sectors and technologies (Tvinnereim and Mehling 2018). As such policies change the technologies available in the market, then economic instruments can also have a greater effect (Pahle et al. 2018).

START BOX 13.10 HERE

Box 13.10 Policies to limit emissions of Non-CO_2 Gases

Non-CO_2 gases weighted by their 100 year GWPs represent approximately 25% of global GHG emissions, of which methane (CH_4) accounts for 18%, nitrous oxide (N2O) – 4%, and fluorinated gases (HFCs, PFCs, SF6 and NF3) – 2% (Minx et al. 2021). Only a small share of these emissions are subject to mitigation policies.

Methane. Anthropogenic sources include agriculture, mainly livestock and rice paddies, fossil fuel extraction and processing, fuel combustion, some industrial processes, landfills, and wastewater treatment (US EPA 2019). Atmospheric measurements indicate that methane emissions from fossil fuel production are larger than shown in emissions inventories (Schwietzke et al. 2016). Only a small fraction of global CH_4 emissions is regulated. Mitigation policies focus on landfills, coal mines, and oil and gas operations.

Regulations and incentives to capture and utilize methane from coal seams came into effect in China in 2010 (Tan 2018; Tao et al. 2019). Inventory data suggest that emissions peaked and began a slow decline after 2010 (Gao et al. 2020) though satellite data indicate that China's methane emissions, largely attributable to coal mining, continued to rise in line with pre-2010 trends (Miller et al. 2019). Methane emissions from sources including agriculture, waste and industry are included in some offset credit schemes, including the CDM and at national level in Australia's Emissions Reductions Fund (Australian Climate Change Authority 2017) and the Chinese Certified Emission Reduction (CCER) scheme (Lo and Cong 2017).

Nitrous Oxide. N_2O emissions are produced by agricultural soil management, livestock waste management, fossil fuel combustion, and adipic acid and nitric acid production (US EPA 2019). Most N_2O emissions are not regulated and global emissions have been increasing. N_2O emissions by adipic and nitric acid plants in the EU are covered by the ETS (Winiwarter et al. 2018). N_2O emissions are included in some offset schemes. China, the United States, Singapore, Egypt, and Russia produce 86% of industrial N_2O emissions offering the potential for targeted mitigation action (US EPA 2019).

HFCs. Most HFCs are used as substitutes for ozone depleting substances. The Kigali Amendment (KA) to the Montreal Protocol will reduce HFC use by 85% by 2047 (UN Environment 2018). To help meet their KA commitments developed country parties have been implementing regulations to limit imports, production and exports of HFCs and to limit specific uses of HFCs.

The EU, for example, issues tradable quota for imports, production and exports of HFCs. Prices of HFCs have increased as expected (Kleinschmidt 2020) which has led to smuggling of HFCs into the EU (European Commission 2019b). HFC use has been slightly (1 to 6%) below the limit each year from 2015 through 2018 (EEA 2019). China and India released national cooling action plans in 2019, laying out detailed, cross-sectoral plans to provide sustainable, climate friendly, safe and affordable cooling (Dean et al. 2020).

PFCs, SF_6 and NF_3. With the exception of SF_6, these gases are emitted by industrial activities located in the European Economic Area (EEA) and a limited number (fewer than 30) of other countries. Regulations in Europe, Japan and the US focus on leak reduction as well as collection and reuse of SF_6 from electrical equipment. Other uses of SF_6 are banned in Europe (European Union 2014).

PFCs are generated during the aluminium smelting process if the alumina level in the electrolytic bath falls below critical levels (US EPA 2019). In Europe these emissions are covered by the EU ETS. The industry is eliminating the emissions through improved process control and a shift to different production processes.

The semiconductor industry uses HFCs, PFCs, SF_6 and NF_3 for etching and deposition chamber cleaning (US EPA 2019) and has a voluntary target of reducing GHG emissions 30% from 2010 by 2020 (World Semiconductor Council 2017). Europe regulates production, import, export, destruction and feedstock use of PFCs and SF_6, but not NF_3 (EEA 2019). In addition, fluorinated gases are taxed in Denmark, Norway, Slovenia and Spain.

<<END BOX 13.10 HERE>>

In some jurisdictions, the analysis of regulatory instruments is subject to an assessment on the basis of a shadow cost of carbon, which can influence the choice and design of regulations that affect GHG emissions (Box 13.11).

START BOX 13.11 HERE

Box 13.11 Shadow cost of carbon in regulatory analysis

In some jurisdictions, public administrations are required to apply a shadow cost of carbon to regulatory analysis

Traditionally, for example in widespread application in the United States, the shadow cost of carbon is calibrated to an estimate of the social cost of carbon as an approximation of expected future cumulative economic damage from a unit of greenhouse gas emissions (Metcalf and Stock 2017). Social cost of carbon is usually estimated using integrated assessment models and is subject to fundamental uncertainties (Pezzey 2019). An alternative approach, used for example in regulatory analysis in the United Kingdom since 2009, is to define a carbon price that is thought to be consistent with a particular targeted emissions outcome. This approach also requires a number of assumptions, including about future marginal costs of mitigation (Aldy et al. 2021).

END BOX 13.11 HERE

13.6.5 Other policy instruments

A range of other mitigation policy instruments are in use, often playing a complementary role to pricing and standards.

13.6.5.1 Transition support policies

Effective climate change mitigation can cause economic and social disruption where there is transformative change, such as changes in energy systems away from fossil fuels (See 13.9). Transitional assistance policies can be aimed to ameliorate effects on consumers, workers, communities, corporations or countries (Green and Gambhir 2020) in order to create broad coalitions of supporters or to limit opposition (Vogt-Schilb and Hallegatte 2017).

13.6.5.2 Information programs

Information programs, including energy efficiency labels, energy audits, certification, carbon labelling and information disclosure, are in wide use in particular for energy consumption. They can reduce GHG emissions by promoting voluntary technology choices and behavioural changes by firms and households.

Energy efficiency labelling is in widespread use, including for buildings, and for end users products including cars and appliances. Carbon labelling is used for example for food (Camilleri et al. 2019) and tourism (Gössling and Buckley 2016). Information measures also include specific information systems such as smart electricity meters (Zangheri et al. 2019). Chapters 5 and 9 provide detail.

Information programs can correct for a range of market failures related to imperfect information and consumer perceptions (Allcott 2016). Alongside mandatory standards (13.6.4), information programmes can nudge firms and consumers to focus on often overlooked operating cost reductions (Carroll et al. 2022). For example, consumers who are shown energy efficiency labels on average buy more energy efficient appliances than those who are not (Stadelmann and Schubert 2018). Information policies can also support the changing of social norms about consumption choices, which have been shown to raise public support for pricing and regulatory policy instruments (Gössling et al. 2020).

Energy audits provide tailored information about potential energy savings and benchmarking of best practices through a network of peers. Typical examples include the United States Better Buildings Challenge that has provided energy audits to support US commercial and industrial building owners, energy savings have been estimated at 18% to 30% (Asensio and Delmas 2017); and Germany's energy audit scheme for SMEs achieving reductions in energy consumption of 5 to 70 percent (Kluczek and Olszewski 2017).

Consumption-oriented policy instruments seek to reduce GHG emissions by changing consumer behaviour directly, via retailers or via the supply chain. Aspects that hold promise are technology lists, supply chain procurement by leading retailers or business associations, a carbon-intensive materials charge and selected infrastructure improvements (Grubb et al. 2020).

The information provided to consumers in labelling programs is often not detailed enough to yield best possible results (Davis and Metcalf 2016). Providing information about running costs tends to be more effective than providing data on energy use (Damigos et al. 2020). Sound implementation of labelling programs requires appropriate calculation methodology and tools, training and public awareness (Liang Wong and Krüger 2017). In systems where manufacturers self-report performance of their products, there tends to be misreporting and skewed energy efficiency labelling (Goeschl 2019).

A new form of information programs are financial accounting standards as frameworks to encourage or require companies to disclose how the transition risks from shifting to a low carbon economy and physical climate change impacts may affect their business or asset values (Chapter 15). The most prominent such standard was issued in 2017 by the Financial Stability Board's Task Force on Climate-related Financial Disclosures. It has found rapid uptake among regulators and investors (O'Dwyer and Unerman 2020).

Traditionally, corporate reporting has treated climate risks in a highly varied and often minimal way (Foerster et al. 2017). Disclosure of climate related risks creates incentives for companies to improve their carbon and climate change exposure, and ultimately regulatory standards for climate risk (Eccles and Krzus 2018). Disclosure can also reinforce calls for divestment in fossil fuel assets predominantly promoted by civil society organisations (Ayling and Gunningham 2017), raising moral principles and arguments about the financial risks inherent in fossil fuel investments (Green 2018; Blondeel et al. 2019).

13.6.5.3 Public procurement and investment

National, subnational and local governments determine many aspects of infrastructure planning, fund investment in areas such as energy, transport and the built environment, and purchase goods and services, including for government administration and military provisioning.

Public procurement rules usually mandate cost effectiveness but only in some cases allow or mandate climate change consideration in public purchasing, for example in EU public purchasing guidelines (Martinez Romera and Caranta 2017). Green procurement for buildings has been undertaken in Malaysia (Bohari et al. 2017). A paper cites Taiwan's green public procurement law, which has contributed to reduced emissions intensity (Tsai 2017). In practice, awareness and knowledge of 'green' public procurement techniques and procedures is decisive for climate-friendly procurement (Testa et al. 2016). Experiences in low-carbon infrastructure procurement point to procedures being tailored to concerns about competition, transaction costs and innovation (Kadefors et al. 2020).

Infrastructure investment decisions lock in high or low emissions trajectories over long periods. Low-emissions infrastructure can enable or increase productivity of private low-carbon investments (Jaumotte et al. 2021) and is typically only a little more expensive over its lifetime, but faces additional barriers including higher upfront costs, lack of pricing of externalities, or lack of information or aversion to novel products (Granoff et al. 2016). In low-income developing countries, where infrastructure has historically lagged developed countries, some of these hurdles can be exacerbated by overall more difficult conditions for public investment (Gurara et al. 2018).

Governments can also promote low-emissions investments through public-private partnerships and government owned 'green banks' that provide loans on commercial or concessional basis for environmentally friendly private sector investments (David and Venkatachalam 2019; Ziolo et al. 2019). Public funding or financial guarantees such as contracts-for-difference can alleviate financial risk in the early stages of technology deployment, creating pathways to commercial viability (Bataille 2020).

Government provision can also play an important role in economic stimulus programs, including as implemented in response to the pandemic of 2020-21. Such programs can support low-emissions infrastructure and equipment, and industrial or business development (Elkerbout et al. 2020; Hainsch et al. 2020; Barbier 2020; Hepburn et al. 2020).

START BOX 13.12 HERE

Box 13.12 Technology and R&D policy

Private businesses tend to under-invest in R&D because of market failures (Geroski 1995), hence there is a case for governments to support research and technology development. A range of different policy instruments are used, including government funding, preferential tax treatment, intellectual property rules, and policies to support the deployment and diffusion of new technologies. Chapter 16 treats innovation policy in-depth.

END BOX 13.12 HERE

13.6.5.4 Voluntary agreements

Voluntary Agreements result from negotiations between governments and industrial sectors that commit to achieve agreed goals (Mundaca and Markandya 2016). When used as part of a broader policy framework, they can enhance the cost effectiveness of individual firms in attaining emission reductions while pricing or regulations drive participation in the agreement (Dawson and Segerson 2008).

Public voluntary programs, where a government regulator develops programs to which industries and firms may choose to participate on a voluntary basis, have been implemented in numerous countries. For example, the United States Environmental Protection Agency introduced numerous voluntary programmes with industry to offer technical support in promoting energy efficiency and emissions reductions, among other initiatives (United States Environmental Protection Agency 2017). A European example is the EU Ecolabel Award program (European Commission 2020b). Agreements for industrial energy efficiency in Europe (Cornelis 2019) and Japan (Wakabayashi and Arimura 2016) have been particularly effective in addressing information barriers and for smaller companies. The International Civil Aviation Organization's CORSIA scheme (Prussi et al. 2021) is an example of an international industry-based public voluntary program.

Voluntary agreements are often implemented in conjunction with economic or regulatory instruments, and sometimes are used to gain insights ahead of implementation of regulatory standards, as in the case of energy efficiency PVPs in South Korea (Seok et al. 2021). In some cases, industries use voluntary agreements as partial fulfilment of a regulation (Rezessy and Bertoldi 2011; Langpap 2015). For example, the Netherlands have permitted participating industries to be exempt from certain energy taxes and emissions regulations (Veum 2018).

13.6.6 International interactions of national mitigation policies

One country's mitigation policy can impact other countries in various ways including changes in their GHG emissions (leakage), creation of markets for emission reduction credits, technology development and diffusion (spillovers), and reduction in the value of their fossil fuel resources.

13.6.6.1 Leakage effects

Compliance with a mitigation policy can affect the emissions of foreign sources via several channels over different time scales (Zhang and Zhang 2017) (also see Box 13.13). The effects may interact and yield a net increase or decrease in emissions. The leakage channel that is of most concern to policymakers is adverse international competitiveness impacts from domestic climate policies.

START BOX 13.13 HERE

Box 13.13 Possible sources of leakage

Competitiveness: Mitigation policy raises the costs and product prices of regulated sources which causes production to shift to unregulated sources, increasing their emissions.

Fossil fuel channel: Regulated sources reduce their fossil fuel use, which lowers fossil fuel prices and increases consumption and associated emissions by unregulated sources.

Land use channel: Mitigation policies that change land use lead to land use and emissions changes in other jurisdictions (Bastos Lima et al. 2019).

Terms of trade effect: Price increases for the products of regulated sources shift consumption to other goods, which raises emissions due to the higher output of those goods.

Technology channel: Mitigation policy induces low carbon innovation, which reduces emissions by sources that adopt the innovations that may include unregulated sources (Gerlagh and Kuik 2007).

Abatement resource effect: Regulated sources increase use of clean inputs, which reduces inputs available to unregulated sources and so limits their output and emissions (Baylis et al. 2014).

Scale channel: Changes to the output of regulated and unregulated sources affect their emissions intensities so emissions changes are not proportional to output changes (Antweiler et al. 2001).

Intertemporal channel: Capital stocks of all sources are fixed initially but change over time affecting the costs, prices, output and emissions of regulated and unregulated products.

END BOX 13.13 HERE

In principle, implementation of a mitigation policy in one country creates an incentive to shift production of tradable goods whose costs are increased by the policy to other countries with less costly emissions limitation policies (see Section 12.6.3 in Chapter 12). Such 'leakage' could to some extent negate emissions reductions in the first country, depending on the relative emissions intensity of production in both countries.

Ex ante modelling studies typically estimate significant leakage for unilateral policies to reduce emissions due to production of emissions intensive products such as steel, aluminium, and cement (Carbone and Rivers 2017). However, the results are highly dependent on assumptions and typically do not reflect policy designs specifically aimed at minimizing or preventing leakage (Fowlie and Reguant 2018).

Numerous *ex post* analyses, mainly for the EU ETS, find no evidence of any or significant adverse competitiveness impacts and conclude that there was consequently no or insignificant leakage (Branger et al. 2016; Koch and Basse Mama 2019; Venmans et al. 2020; FSR Climate 2019; Kuusi et al. 2020; aus dem

Moore et al. 2019; Verde 2020; Borghesi et al. 2020; Haites et al. 2018) *(medium evidence, medium agreement)*. This is attributed to large allocations of free allowances to emissions-intensive, trade-exposed sources, relatively low allowance prices, the ability of firms in some sectors to pass costs on to consumers, energy's relatively low share of production costs, and small but statistically significant effects on innovation (Joltreau and Sommerfeld 2019). Few carbon taxes apply to emissions-intensive, trade-exposed sources (Timilsina 2018), so competitiveness impacts usually are not a particular concern.

Policies intended to address leakage include a border carbon adjustment (Ward et al. 2019; Ismer et al. 2020). A border carbon adjustment (BCA) imposes costs – a tax or allowance purchase obligation – on imports of carbon-intensive goods equivalent to those borne by domestic products possibly mirrored by rebates for exports (Böhringer et al. 2012; Fischer and Fox 2012; Zhang 2012; Böhringer et al. 2017c) (see also Chapter 14). A BCA faces the practical challenge of determining the carbon content of imports (Böhringer et al. 2017a) and the design needs to be consistent with WTO rules and other international agreements (Cosbey et al. 2019; Mehling et al. 2019). Model estimates indicate that a BCA reduces but does not eliminate leakage (Branger and Quirion 2014). No BCA has yet been implemented for international trade although such a measure is currently under consideration by some governments.

13.6.6.2 Market for emission reduction credits

A mitigation policy may allow the use of credits issued for emission reductions in other countries for compliance purposes (see also 13.6.3.4 on offset credits and Chapter 14 on international credit mechanisms). Creation of international markets for emission reduction credits tends to benefit other countries through financial flows in return for emissions credit sales *(medium evidence, high agreement)*.

The EU, New Zealand and Switzerland allowed participants in their emissions trading systems to use credits issued under the Kyoto Protocol mechanisms, including the Clean Development Mechanism (CDM), for compliance. From 2008 through 2014 participants used 3.76 million imported credits for compliance of which 80% were CDM credits (Haites 2016).[4] Use of imported credits has fallen to very low levels since 2014 (World Bank 2014; Shishlov et al. 2016).[5]

The Clean Development Mechanism (CDM) is the world's largest offset program (Chapter 14). From 2001 to 2019 over 7,500 projects with projected emission reductions in excess of 8,000 MtCO_2-eq were implemented in 114 developing countries using some 140 different emissions reduction methodologies (UNFCCC 2012; UNEP DTU Partnership 2020). Credits reflecting over 2,000 MtCO_2-eq of emission reductions by 3,260 projects have been issued. To address additionality and other concerns the CDM Executive Board frequently updated its approved project methodologies.

13.6.6.3 Technology spillovers

Mitigation policies stimulate low-carbon R&D by entities subject to those policies and by other domestic and foreign entities (FSR Climate 2019). Policies to support technology development and diffusion tend to have positive spillover effects between countries (see section 16.3) *(medium evidence, high agreement).*

Innovation activity in response to a mitigation policy varies by policy type (Jaffe et al. 2002) and stringency (Johnstone et al. 2012). In addition, many governments have policies to stimulate R&D, further increasing low-carbon R&D activity by domestic researchers. Emitters in other countries may adopt some of the new low-carbon technologies thus reducing emissions elsewhere. Technology development and diffusion is reviewed in Chapter 16.

FOOTNOTE [4] 2010 through 2014 for the New Zealand ETS.
FOOTNOTE [5] All three ETSs were modified after 2012 including provisions that affected compliance use of imported credits.

13.6.6.4 Value of fossil fuel resources

Fossil fuel resources are a significant source of exports, employment and government revenues for many countries. The value of these resources depends on demand for the fuel and competing supplies in the relevant international markets. Discoveries and new production technologies reduce the value of established resources. Mitigation policies that reduce the use of fossil fuels also reduce the value of these resources. A single policy in one country is unlikely to have a noticeable effect on the international price, but similar policies in multiple countries could adversely affect the value of the resources. For fossil fuel exporting countries, mitigation policies consistent with the Paris Agreement goals could result in greater costs from changes in fossil fuel prices due to lower international demand than domestic policy costs (Liu et al. 2020) *(medium evidence, high agreement)*.

The impact on the value of established resources will be mitigated, to some extent, by the reduced incentive to explore for and develop new fossil fuel supplies. Nevertheless, efforts to lower global emissions will mean substantially less demand for fossil fuels, with the majority of current coal reserves and large shares of known gas and oil reserves needing to remain unused, with great diversity in impacts between different countries (McGlade and Ekins 2015) (See also Chapters 3, 6, 15).

Estimates of the potential future loss in value differ greatly. There is uncertainty about remaining future fossil fuel use under different mitigation scenarios, as well as future fossil fuel prices depending on extraction costs, market structures and policies. Estimates of total cumulative fossil fuel revenue lost range between US 5-67 trillion dollars (Bauer et al. 2015) with an estimate of the net present value of lost profit of around US 10 trillion dollars (Bauer et al. 2016). Policies that constrain supply of fossil fuels in the context of mitigation objectives could limit financial losses to fossil fuel producers (See also Chapter 14).

13.7 Integrated policy packages for mitigation and multiple objectives

Since AR5, the literature on climate policies and policy-making has expanded in two significant directions. First, there is growing recognition that mitigation policy occurs in the context of multiple climate and development objectives (Chapter 4). Different aspects of these linkages are discussed across the WGIII report, including concepts and framings (Section 1.6.2 in Chapter 1), shifting sustainable development pathways (Section 4.3 in Chapter 4 and Cross-chapter Box 5 in Chapter 4), cross-sectoral interactions (Sections 12.6.1 and 12.6.2 in Chapter 12), evidence of co-impacts (Section 17.3 in Chapter 17), links with adaptation (Section 4.4.2 in Chapter 4) and accelerating the transition (Section 13.9 in chapter 13 and Sections 17.1.1, 17.4.5 and 17.4.6 in Chapter 17). While the concept of development pathways is salient in all countries, it may particularly resonate with policymakers in developing countries focused on providing basic needs and addressing poverty and inequality, including energy poverty (Ahmad 2009; Fuso Nerini et al. 2019; Bel and Teixidó 2020; Caetano et al. 2020; Röser et al. 2020). Consequently, some countries may frame policies predominantly in terms of accelerating mitigation, while in others a multiple objectives approach linked to development pathways may dominate, depending on their specific socio-economic contexts and priorities, governance capacities (McMeekin et al. 2019) and perceptions of historical responsibility (Winkler and Rajamani 2014; Friman and Hjerpe 2015; Pan et al. 2017; Winkler et al. 2015).

Second, since AR5 there is growing attention to enabling transitions over time. Literature on socio-technical transitions, rooted in innovation studies, highlights the need for different policy focus at different stages of a transition (Geels et al. 2017b,a; Köhler et al. 2019) (also see Section 1.7.3 in Chapter 1). Other literature examines how broad patterns of development drive both social and mitigation outcomes through shifts in policies and a re-alignment of enabling conditions (Chapter 4). Explicit efforts to shift development pathways, for example by shifting patterns of energy demand and urbanisation, therefore offer broader mitigation opportunities (Cross-Chapter Box 5 in Chapter 4). Common to both approaches is an emphasis beyond the short term, and enabling longer-term structural shifts in economies and societies.

Taking these trends into account, Figure 13.6 outlines the climate policy landscape, and how it maps to different parts of this Working Group III report. One axis of variation captures alternative framings of desired outcomes in national policy-making – mitigation versus multiple objectives, while the second captures the shift in policymaking from an initial focus on shifting incentives through largely individual policy instruments, to explicit consideration of how policies and economy-wide measures , including those that shift incentives, can combine to enable transitions. As a result, Figure 13.6 represents interconnected policy ideas, but backed by distinct strands of literature. Notably, each of these categories is salient to climate policy-making, although the balance may differ depending on country context.

		Framing of Outcome	
		Enhancing Mitigation	**Addressing Multiple Objectives of Mitigation and Development**
Approach to Policy-making	**Shifting Incentives**	"Direct Mitigation Focus" *(Sec. 13.6; 2.8)* *Objective:* Reduce GHG emissions now *Literature:* How to design and implement policy instruments, with attention to distributional and other concerns *Examples:* carbon tax, cap and trade, border carbon adjustment, disclosure policies	"Co-benefits" *(Sec. 17.3; 5.6.2; 12.4.4)* *Objective:* Synergies between mitigation and development *Literature:* Scope for and policies to realise synergies and avoid trade-offs across climate and development objectives. *Examples:* Appliance standards, fuel taxes, community forest management, sustainable dietary guidelines, green building codes, packages for air pollution, packages for public transport
	Enabling Transition	"Socio-technical transitions" *(Sec. 1.7.3; 5.5; 10.8; 6.7; Cross-Chapter Box 12 in Chapter 16)* *Objective:* Accelerate low-carbon shifts in socio-technical systems *Literature:* Understand socio-technical transition processes, integrated policies for different stages of a technology 'S curve' and explore structural, social and political elements of transitions. *Examples:* Packages for renewable energy transition and coal phase-out; diffusion of electric vehicles, process and fuel switching in key industries.	"System transitions to shift development pathways" *(Sec. 11.6.6; 7.4.5; 13.9; 17.3.3; Cross-Chapter Box 5 in Chapter 4; Cross-Chapter Box 9 in Chapter 13)* *Objective:* Accelerate system transitions and shift development pathways to expand mitigation options and meet other development goals *Literature:* Examines how structural development patterns and broad cross-sector and economy wide measures drive ability to mitigate while achieving development goals through integrated policies and aligning enabling conditions. *Examples:* Packages for sustainable urbanisation, land-energy-water nexus approaches, green industrial policy, regional just transition plans

Figure 13.6 Mapping the landscape of climate policy

This section particularly focuses on climate policymaking for transition – both socio-technical transitions and shifts in development pathways, while direct climate policies and co-benefits are addressed in other parts of the report, as indicated in Figure 13.6. This section focuses in particular on lessons for designing policy packages for transitions, and is complemented by discussion in Section 13.8 on integration between adaptation and mitigation, and Section 13.9 on economy-wide measures and the broader enabling conditions necessary to accelerate mitigation.

13.7.1 Policy packages for low carbon sustainable transitions

Since AR5 an emergent multi-disciplinary literature on policy packages, or policy mixes, has emerged that examine how policies may be combined for sustainable low-carbon transitions (Rogge and Reichardt 2016; Kern et al. 2019). This literature covers various sectors including: energy (Rogge et al. 2017); transport (Givoni et al. 2013); industry (Scordato et al. 2018); agri-food (Kalfagianni and Kuik 2017); and forestry (Scullion et al. 2016).

A central theme in the literature is that transitions require policy interventions to address system level changes, thereby going beyond addressing market failures in two ways. First, structural system changes are needed for low-carbon transitions, including building low-carbon infrastructure (or example aligning electricity grids and storage with the requirements of new low-carbon technology), and adjusting existing institutions to low-carbon solutions (for example by reforming electricity market design) (Bak et al. 2017; Patt and Lilliestam 2018). Second, explicit transformational system changes are necessary, including efforts at directing transformations, such as clear direction setting through the elaboration of shared visions, and coordination across diverse actors across different policy fields, such as climate and industrial policy, and across governance levels (Uyarra et al. 2016; Nemet et al. 2017).

There are some specific suggestions for policy packages: Van den Bergh et al. (2021) suggest that innovation support and information provision combined with a carbon tax or market, or adoption subsidy leads to both effective and efficient outcomes. Others question the viability of universally applicable policy packages, and suggest packages need to be tailored to local objectives (del Río 2014) Consequently, much of the literature focuses on broad principles for design of policy packages and mixes, as discussed below.

Comprehensiveness, balance and consistency are important criteria for policy packages or mixes (Carter et al. 2018; Santos-lacueva and González 2018; Rogge and Reichardt 2016; Scobie 2016) *(robust evidence, high agreement)*. Comprehensiveness assesses the extensiveness of policy packages, including the breadth of system and market failures it addresses (Rogge and Reichardt 2016). For example, instrument mixes that include only moderate carbon pricing, but are complemented by policies supporting new low-carbon technologies and a moratorium on coal-fired power plants may not only be politically more feasible than stringent carbon pricing alone, but may also limit efficiency losses and lower distributional impacts (Bertram et al. 2015b). Balance captures whether policy instruments are deployed in complementary ways given their different purposes, combining for example technology-push approaches such as public R&D with demand-pull approaches such as an energy tax. A combination of technology-push and demand-pull approaches has been shown to support innovation in energy efficient technologies in OECD countries (Costantini et al. 2017). Consistency addresses the alignment of policy instruments among each other and with the policy strategy, which may have multiple and not always consistent objectives (Rogge 2019). Consistency of policy mixes has been identified as an important driver of low-carbon transformation, particularly for renewable energy (Lieu et al. 2018; Rogge and Schleich 2018). Box 13.14 summarises the economics literature on how policies interact, to inform design of packages.

START BOX 13.14 HERE

Box 13.14 Policy interactions of carbon pricing and other instruments

The economics literature provides insights on policy interactions among the multiple overlapping policies that directly or indirectly affect GHG emissions, including when different levels of government are involved. Multiple mitigation policies can be theoretically justified if there are multiple objectives or market failures or to achieve distributional objectives and increase policy effectiveness (Stiglitz 2019). Examples include the coexistence of the EU ETS with vehicle emission standards and energy efficiency standards (Rey et al. 2013), and the fact that 85% of the emissions covered by California's ETS are also subject to other policies (Bang et al. 2017; Mazmanian et al. 2020). Policy interactions are also widespread among energy efficiency policies (Wiese et al. 2018).

Interactive effects can influence the costs of policy outcomes. With multiple overlapping and possibly non-optimal policies, the effect on total cost is not clear. A modelling study of US mitigation policy finds the costs of using heterogeneous subnational policies to achieve decarbonisation targets is 10 % higher than national uniform policies (Peng et al. 2021). When multiple policy goals are sought, such as mitigation and R&D, a portfolio of optimal policies achieves the goals at significantly lower cost (Fischer and Newell 2008). In some cases, overlapping mitigation policies can raise the cost of mitigation (Böhringer et al. 2016) while lowering the cost of achieving other goals, such as energy efficiency improvements and expansion of renewable energy (Rosenow et al. 2016; Lecuyer and Quirion 2019). It is possible that one or more of the policies is made redundant (Aune and Golombek 2021).

While overlapping policies may raise the cost of mitigation, they increase the likelihood of achieving an emission reduction goal. Policy overlap will lead to different optimal carbon prices across jurisdictions (Bataille et al. 2018b). The existence of overlapping policies will usually increase administrative and compliance costs. However, ex-post analysis shows that transaction costs of mitigation policies are low and are not a decisive factor in policy choice (Joas and Flachsland 2016).

The effectiveness, as well as economic and distributional effects, of a given mitigation policy will depend on the interactions among all the policies that affect the targeted emissions. Because a market instrument interacts with every other policy that affects the targeted emissions, interactions tend to be more complex for market instruments than for regulations that mandate specific emission reduction actions by targeted sources independent of other policies.

An ETS scheme implemented with existing mitigation policies may be subject to the 'waterbed effect' - emission reductions undertaken by some emitters may be offset by higher emissions by other ETS participants due to overlapping mitigation policies (Schatzki and Stavins 2012). This reduces the impact of the ETS and lowers carbon trading prices (Perino 2018). However *ex post* assessments find net emissions reductions. ETS design features such as a price floor and 'market stability reserve' can limit the waterbed effect (Edenhofer et al. 2017; Kollenberg and Taschini 2019; Narassimhan et al. 2018; FSR Climate 2019).

A carbon tax, unlike the allowance price, does not change in response to the effect of overlapping policies but those policies may reduce emissions by sources subject to the tax and so lower the emission reductions achieved by the tax (Goulder and Stavins 2011).

Policy interactions often occur with the introduction of new mitigation policy instruments. For example, in China several sub-national ETSs exist alongside policies to reduce emission intensity, increase energy efficiency and expand renewable energy supplies (Zhang 2015). These quantity-based ETSs interact with many other policies (Duan et al. 2017), for example price-based provincial carbon intensity targets (Qian et al. 2017). They also interact with the level of market regulation; for example, full effectiveness of emissions pricing would require electricity market reform in China (Teng et al. 2017).

END BOX 13.14 HERE

Policy packages aimed at low carbon transitions are more effective when they include elements to enhance the phase out of carbon-intensive technologies and practices – often called exnovation -- in addition to supporting low carbon niches (Kivimaa and Kern 2016; David 2017). Such policies include stringent carbon pricing; changes in regime rules such as design of electricity markets; reduced support for dominant regime technologies such as removing tax deductions for private motor transport based on internal combustion engines; and changes in the balance of representation of incumbents versus new entrants in deliberation and advisory bodies. For example, CGE modelling for China's fossil fuel subsidy reform found that integrating both creation and destabilization policies is able to reduce rebound effects and make the policy mix more effective (Li et al. 2017). Sweden's pulp and paper industry shows that destabilisation policies including deregulation of the electricity market and a carbon tax were an important complement to support policies (Scordato et al. 2018), and other studies show complementary results for Finland's building sector (Kivimaa et al. 2017b) and Norway's transport and energy sector (Ćetković and Skjærseth 2019).

Policy packages for low-carbon transitions are more successful if they take into account the potential for political contestation and resistance from incumbents who benefit from high-carbon systems (Roberts et al. 2018; Kern and Rogge 2018; Rosenbloom 2018; Geels 2014) *(medium evidence, high agreement)*. To do so, policies can be sequenced so as to address political obstacles, for example, by initially starting with policies to facilitate the entry of new firms engaged in low-carbon technologies (Pahle et al. 2018). Such policies can generate positive feedbacks by creating constituencies for continuation of those policies, but need to be designed to do so from the outset (Edmondson et al. 2019, 2020). For example, supporting renewable energies through feed-in tariffs can buttress coalitions for more ambitious climate policy, such as through carbon pricing (Meckling et al. 2015). However, negative policy feedback may also arise from ineffective policy instruments that lose public support, or create concentrated losses that arouse oppositional coalitions (Edmondson et al. 2019). Feedback loops can operate through changes in resources available to actors; changes in expectations; and changes in government capacities, (Edmondson et al. 2019).

Another promising strategy is to design short term policies which might help to provide later entry points for more ambitious climate policy (Kriegler et al. 2018) and supportive institutions. The sequencing of policies can build coalitions for climate policy, starting with green industrial policy (e.g. supporting renewable energies through feed-in tariffs) and introducing or making carbon pricing more stringent when supportive coalitions of stringent climate policy have been formed (Meckling et al. 2015). Similarly, investing in supportive institutions, with competencies compatible with low-carbon futures, are a necessary supportive element of transitions (Domorenok et al. 2021; Rosenbloom et al. 2019; Pahle et al. 2018).

13.7.2 Policy integration for multiple objectives and shifting development pathways

This sub-section assesses policy integration and packages required to enable shifts in development pathways, with a particular focus on sectoral scale transitions. However, because shifting development pathways requires broad transformative change, it complements discussion on broader shifts in policy-making such as fiscal, educational, and infrastructure policies (Cross-Chapter Box 5 in Chapter 4) and to the alignment of a wide range of enabling conditions required for system transitions (Section 13.9).

In many countries, and particularly when climate policy occurs in the context of sustainable development, policymakers seek to address climate mitigation in the context of multiple economic and social policy objectives (Halsnæs et al. 2014; Campagnolo and Davide 2019; Cohen et al. 2019) *(medium evidence, robust agreement)*. Studies suggest that co-benefits of climate policies are substantial, especially in relation to air quality, and can yield better mitigation and overall welfare, yet these are commonly overlooked in policy-making (Nemet et al. 2010; Ürge-Vorsatz et al. 2014; von Stechow et al. 2015; Mayrhofer and Gupta 2016; Roy et al. 2018; Karlsson et al. 2020; Bhardwaj et al. 2019) *(robust evidence, robust agreement)*. Other studies have shown the existence of strong complementarities between the SDGs and realisation of NDC pledges by countries (McCollum et al. 2018). An explicit attention to development pathways can enhance the scope for mitigation, by paying explicit attention to development choices that lock-in or lock-out opportunities for mitigation, such as around land use and infrastructure choices (Cross-Chapter Box 5 in Chapter 4). While the pay-offs are considerable to an approach to mitigation that takes into account linkages to multiple objectives and the opportunity to shift development pathways, there are also associated challenges with implementing this approach to policymaking.

First, spanning policy arenas and addressing multiple objectives places considerable requirements of coordination on the policy-making process (Howlett and del Rio 2015; Obersteiner et al. 2016). Climate policy integration suggests several steps should precede actual policy-formulation, beginning with a clear articulation of the policy frame or problem statement (Adelle and Russel 2013; Candel and Biesbroek 2016). For example, a greenhouse gas limitation framework versus a co-benefits framing would likely yield different policy approaches. It is then useful to identify the range of actors and institutions involved in climate governance – the policy subsystem, the goals articulated, the level at which goals are articulated and the links with other related policy goals such as energy security or energy access (Candel and Biesbroek 2016). The adoption of specific packages of policy instruments should ideally follow these prior steps that define the scope of the problem, actors and goals.

In practice, integration has to occur in the context of an already existing policy structure, which suggests the need for finding windows of opportunity to bring about integration, which can be created by international events, alignments with domestic institutional procedures, and openings created by policy entrepreneurs (Garcia Hernandez and Bolwig 2020). Integration also has to occur in the context of existing organisational routines and cultures, which can pose a barrier to integration (Uittenbroek 2016). Experience from the EU suggests that disagreements at the level of policy instruments are amenable to resolution by deliberation, while normative disagreements at the level of objectives require a hierarchical decision structure (Skovgaard 2018). As this discussion suggests, the challenge of integration operates in two dimensions: horizontal -- between sectoral authorities such as ministries or policy domains such as forestry -- or vertical -- either between constitutional levels of power or within the internal mandates and interactions of a sector (Howlett and del Rio 2015; Di Gregorio et al. 2017). There are also important temporal dimensions to policy goals, as policy and benchmarks have to address not just immediate success but also indications of future transformation (Dupont and Oberthür 2012; Dupont 2015).

Second policy-making for shifting development pathways has to account for inherent uncertainties in future development paths (Moallemi and Malekpour 2018; Castrejon-Campos et al. 2020). These uncertainties may be greater in developing countries that are growing rapidly and where structural features of the economy including infrastructure and urbanisation patterns are fluid. For example, reviews of modelling studies of Chinese (Grubb et al. 2015) and Indian emissions futures (Spencer and Dubash 2021) find that differences in projections can substantially be accounted for by alternative assumptions about future economic structural shifts. Consequently, an important design consideration is that policy packages should be robust, that is, perform satisfactorily for all key objectives under a broad range of plausible futures (Castrejon-Campos et al. 2020; Kwakkel et al. 2016; Maier et al. 2016). Such an approach to decision making can be contrasted with one that tries to design an optimal policy package for the "best guess" future scenario (Maier et al. 2016). Moreover, policy packages can usefully be adapted dynamically to changing circumstances as part of the policy process (Haasnoot et al. 2013; Maier et al. 2016; Hamarat et al. 2014) including by using exploratory modelling techniques that allow comparison of trade-offs across alternative future scenarios (Hamarat et al. 2014). Another approach is to link quantitative models with a participatory process that enables decision-makers to test the implications of alternative interventions (Moallemi and Malekpour 2018). Rosenbloom et al. (2019) suggest that because policy mixes should adapt to changing circumstances, instead of stability of a particular mix, transitions require embedding policies within a long-term orientation toward a low-carbon economy, including a transition agenda, social legitimacy for this agenda, and an appropriate ecosystem of institutions.

Third, achieving changes in development pathways requires engaging with place-specific context. It requires attention to existing policies, political interests that may gain or lose from a transition, and locally specific governance enablers and disablers. As a result, while there may be approaches that carry over from one context to another, implementation requires careful tailoring of transition approaches to specific policy and governance contexts. Cross-Chapter Box 9 in this chapter summarises case studies of sectoral transitions from other chapters in this report (Chapters 5-12) to illustrate this complexity. Broader macro-economic transformative shifts are discussed in more detail in Section 13.9.

Common to all the sectoral cases in Cross-Chapter Box 9 is a future-oriented vision of sectoral transition often focused on multiple objectives, such as designing tram-based public transport systems in Bulawayo, Zimbabwe to simultaneously stimulate urban centers, create jobs and enable low carbon transportation. Sectoral transitions are enabled by policy mixes that bring together different combinations of instruments – including regulations, financial incentives, convening, education and outreach, voluntary agreements, procurement and creation of new institutions – to work together in a complementary manner. The effectiveness of a policy mix depends on conditions beyond design considerations and also rests on the larger governance context within which sector transitions occur, which can include enabling and disabling elements. Enabling factors illustrated in Cross-Chapter Box 9 include strong high level political support, for example to address deforestation in Brazil despite powerful logging and farmer interests, or policy design to win over existing private interests, for example, by harnessing distribution networks of kerosene providers to new LPG technology in Indonesia. Disabling conditions include local institutional contexts, such as the lack of tree and land tenure in Ghana, which, along with the monopoly of the state marketing board, posed obstacles to Ghana's low carbon cocoa transition. These examples emphasize the importance of attention to local context if policy integration and the design of policy mixes are to effectively lead to transitions guided by multiple climate and development objectives.

START CROSS-CHAPTER BOX 9 HERE

Cross-Chapter Box 9: Case studies of integrated policymaking for sector transitions

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Real world sectoral transitions reinforce critical lessons on policy integration: a high-level strategic goal (Column A), the need for a clear sector outcome framing (column B), a carefully coordinated mix of policy instruments and governance actions (column C), and the importance of context-specific governance factors (column D). Illustrative examples, drawn from sectors, help elucidate the complexity of policymaking in driving sectoral transitions.

Cross-Chapter Box 9, Table 1 Case studies of integrated policymaking for sector transitions

A. Illustrative Case	B. Objective	C. Policy mix	D. Governance Context	
			Enablers	**Barriers**
Shift in mobility service provision in Kolkata, India *[Box 5.8]*	- Improve system efficiency, sustainability and comfort - Shift public perceptions of public transport	- Strengthen co-ordination between modes - Formalize and green auto-rickshaws - Procure fuel efficient, comfortable low floor AC buses - Ban cycling on busy roads - Deploy policy actors as change-agents, mediating between interest groups	- Cultural norms around informal transport sharing, linked to high levels of social trust - Historically crucial role of buses in transit - App-cab companies shifting norms and formalizing mobility sharing - Digitalization and safety on board	- Complexity: multiple modes with separate networks and meanings - Pushback from equity-focused social movements against 'premium' fares, cycling ban
LPG Subsidy ("Zero Kero") Program, Indonesia *[Box 6.3]*	Decrease fiscal expenditures on kerosene subsidies for cooking	- Subsidize provision of Liquefied Petroleum Gas (LPG) cylinders and initial equipment - Convert existing kerosene suppliers to LPG suppliers	- Provincial Government and industry support in targeting beneficiaries and implementation - Synergies in kerosene and LPG distribution infrastructures	- Continued user preference for traditional solid fuels - Reduced GHG benefits as subsidy shifted between fossil fuels
Action Plan for Prevention and Control of Deforestation in the Legal Amazon, Brazil *[Box 7.9]*	Control deforestation and promote sustainable development	- Expand protected areas; homologation of indigenous lands - Improve inspections, satellite-based monitoring - Restrict public credit for enterprises and municipalities with high deforestation rates - Set up a REDD+ mechanism (Amazon Fund)	- Participatory agenda-setting process - Cross-sectoral consultations on conservation guidelines -Mainstreaming of deforestation in government programs and projects	- Political polarization leading to erosion of environmental governance - Reduced representation & independence of civil society in decision-making bodies - Lack of clarity around land ownership
Climate smart cocoa (CSC) production, Ghana *[Box 7.12]*	- Promote sustainable intensification of cocoa production - Reduce deforestation - Enhance incomes & adaptive capacities	- Distribute shade tree seedlings - Provide access to agronomic information and agro-chemical inputs - Design a multi-stakeholder program including MNCs, farmers and NGOs	- Local resource governance mechanisms ensuring voice for smallholders - Community governance allowed adapting to local context - Private sector role in popularising CSC	- Lack of secure tenure (tree rights) - Bureaucratic & legal hurdles to register trees - State monopoly on cocoa marketing, export

Coordination mechanism for joining fragmented urban policymaking in Shanghai, China *[Box 8.3]*	Integrate policymaking across objectives, towards low-carbon urban development	- Combine central targets and evaluation with local flexibility for initiating varied policy experiments - Establish a local leadership team for coordinating cross-sectoral policies involving multiple institutions - Create a direct program fund for implementation and capacity-building	- Strong vertical linkages between Central and local levels - Mandate for policy learning to inform national policy - Experience with mainstreaming mitigation in related areas (e.g. air pollution)	- Challenging starting point - low share of RE, high dependency on fossil fuels - Continued need for high investments in a developing context
Policy package for building energy efficiency, EU *[Box SM 9.1]*	Reduce energy consumption, integrating RE and mitigating GHG emissions from buildings	- Energy performance standards, set at nearly zero energy for new buildings - Energy performance standards for appliances - Energy performance certificates shown during sale - Long Term Renovation Strategies	- Binding EU-level targets, directives and sectoral effort sharing regulations - Supportive urban policies, coordinated through city partnerships - Funds raised from allowances auctioned under ETS	- Inadequate local technical capacity to implement multiple instruments - Complex governance structure leading to uneven stringency
African Electromobility-Trackless trams with solar in Bulawayo and e-motorbikes in Kampala *[Box 10.4]*	- Leapfrog into a decarbonized transport future - Achieve multiple social benefits beyond mobility provision	- Develop urban centres with solar at station precincts - Public-private partnerships for financing - Sanction demonstration projects for new electric transit and new electric motorbikes (for freight)	- 'Achieving SDGs' was an enabling policy framing - Multi-objective policy process for mobility, mitigation and manufacturing - Potential for funding through climate finance - Co-benefits such as local employment generation	- Economic decline in the first decade of the 21st century - Limited fiscal capacity for public funding of infrastructure - Inadequate charging infrastructure for e-motorbikes
Initiative for a climate-friendly industry in North Rhine Westphalia (NRW), Germany *[Box 11.3]*	- Collaboratively develop innovative strategies towards a net zero industrial sector, while securing competitiveness	- Build platform to bring together industry, scientists and government in self-organized innovation teams - Intensive cross-branch cooperation to articulate policy/infrastructure needs	- NRW is Germany's industrial heartland, with an export-oriented industrial base - Established govt.-industry ties - Active discourse between industry and public	- Compliance rules preventing in-depth co-operation
Food2030 Strategy, Finland *[Box 12.2]*	- Local, organic and climate friendly food production - Responsible and healthy food consumption - A competitive food supply chain	- Target funding and knowledge support for innovations - Apply administrative means (legislation, guidance) to increase organic food production and procurement - Use education and information instruments to shift behaviour (media campaigns, websites)	- Year-long deliberative stakeholder engagement process across sectors - Institutional structures for agenda-setting, guiding policy implementation and reflexive discussions	- Weak role of integrated impact assessments to inform agenda-setting - Monitoring and evaluation close to ministry in charge - Lack of standardized indicators of food system sustainability

END CROSS-CHAPTER BOX 9 HERE

13.8 Integrating adaptation, mitigation and sustainable development

There is growing consensus that integration of adaptation and mitigation will advance progress towards sustainable development, and that ambitious mitigation efforts will reduce the need for adaptation in the long term (IPCC 2014a) (*robust evidence, high agreement*). There is no level of mitigation, however, that will completely erase the need for adaptation to climate change (Mauritsen and Pincus 2017) (*robust evidence, high agreement*). It is therefore urgent to design and implement a multi-objective policy framework for mitigation, adaptation, and sustainable development that considers issues of equity and long-term developmental pathways across regions (Jordan et al. 2018a; Mills-Novoa and Liverman 2019; Wang and Chen 2019) (*robust evidence, high agreement*). This section explores the logic behind the integration of adaptation and mitigation in practice (Section 13.8.1), the approaches to this integration including climate-resilient pathways, ecosystem-based solutions, and a nexus approach (Section 13.8.2); examples of the adaption and mitigation relationships and linkages (Section 13.8.3); and enabling and disabling factors for governance of mitigation and adaption.

13.8.1 Synergies between adaptation and mitigation

Integrated climate-development actions require a context-specific understanding of synergies and trade-offs with other policy priorities (see Figure 13.6) with the aim of implementing mitigation/adaptation policies that reduce GHG emissions while simultaneously strengthening resilience and reducing vulnerability (Klein et al. 2005; IPCC 2007; Mills-Novoa and Liverman 2019; Solecki et al. 2019; Zhao et al. 2018) (*robust evidence, high agreement*). Efficient, equitable and inclusive policies which also acknowledge and contribute directly to other pressing priorities such reducing poverty, improving health, providing access to clean water, and fostering sustainable consumption and production practices are helpful for mitigation/adaptation goals (Landauer et al. 2019; Grafakos et al. 2020) (*robust evidence, high agreement*).

Adaptation and mitigation are deeply linked in practice – at the local level, for instance, asset managers address integrated low-carbon resilience to climate change impacts and urban planners do the same (Ürge-Vorsatz et al. 2018; Grafakos et al. 2020) (see Table 13.3 for details). Similarly, ecosystem-based (or nature-based) solutions, may generate co-benefits by simultaneously sinking carbon, cooling urban areas through shading, purifying water, improving biodiversity, and offering recreational opportunities that improve public health (Raymond et al. 2017). Accurately identifying and qualitatively or quantitatively assessing these co-benefits (Leiter and Pringle 2018; Leiter et al. 2019; Stadelmann et al. 2014)– is central to an integrated adaptation and mitigation policy evaluation.

Some studies press the need to consider the complex ways that power and interests influence how collective decisions are made, and who benefits from and pays for these decisions, of climate policy and to be aware of unintended consequences, especially for vulnerable people living under poor conditions (Mayrhofer and Gupta 2016; De Oliveira Silva et al. 2018). The specific adaptation and mitigation linkages will differ by country and region, as illustrated by Box 13.15.

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Box 13.15 Adaptation and mitigation synergies in Africa

Synergies between mitigation and adaptation actions and sustainable development that can enhance the quality and pace of development in Africa exist at both sectoral and national levels. Available data on NDCs show the top mitigation priorities in African countries include energy, forestry, transport and agriculture and waste, and adaptation priorities focus on agriculture, water, energy and forestry. The energy sector dominates in mitigation actions and the agricultural sector is the main focus of adaptation measures, with the latter sector being a slightly larger source of greenhouse gases than the former (Mbeva et al. 2015; African Development Bank 2019; Nyiwul 2019).

Renewable energy development can support synergies between mitigation and adaptation by stimulating local and national economies through microenterprise development; providing off-grid affordable and accessible solutions; and contributing to poverty reduction through increased locally available resource use and employment and increased technical skills (Dal Maso et al. 2020; Nyiwul 2019). The Paris Agreement's technology transfer and funding mechanisms could reduce renewable energy costs and providing scale economics to local economies.

Barriers to achieving these synergies include the absence of suitable macro-and micro- level policy environments for adaptation and mitigation actions; coherent climate change policy frameworks and governance structures to support adaptation; institutional and capacity deficiencies in climate and policy research such as on data integration and technical analysis; and the high financial needs associated with the cost of mitigation and adaptation (African Development Bank 2019; Nyiwul 2019). Strengthening of national institutions and policies can support maximising synergies and co-benefits between adaptation and mitigation to reduce silos and redundant overlaps, increase knowledge exchange at the country and regional levels, and support engagement with bilateral and multilateral partners and mobilising finance through the mechanisms available (African Development Bank 2019).

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13.8.2 Frameworks that enable the integration of adaption and mitigation

The 5th Assessment report of the IPCC emphasised the importance of climate-resilient pathways -- development trajectories that combine adaptation and mitigation through specific actions to achieve the sustainable development goals (Prasad et al. 2009; Lewison et al. 2015; Fankhauser and McDermott 2016; Romero-Lankao et al. 2016; Solecki et al. 2019) -- from the household to the state level, since risks and opportunities vary by location and the specific local development context (IPCC 2014b; Denton et al. 2015) (*robust evidence, high agreement*).

Synergies between adaptation and mitigation are included in many of the NDCs submitted to the UNFCCC, as part of overall low-emissions climate-resilient development strategies (UNFCCC Secretariat 2016). A majority of developing countries have agreed to develop National Adaptation Plans (NAPs) in which many initiatives contribute simultaneously to the SDGs (Schipper et al. 2020) as well to mitigation efforts (Hönle et al. 2019; Atteridge et al. 2020). For example, developing countries recognize that adaptation actions in sectors such as agriculture, forestry and land use management can reduce GHGs. Nevertheless, other more complex trade-offs also exist between bioenergy production or reforestation and the land needed for agricultural adaptation and food security (African Development Bank 2019; Hönle et al. 2019; Nyiwul 2019, see Chapter 7). For some of the Small Islands Development States (SIDS), forestry and coastal management, including mangrove planting, saltmarsh and seagrass are sectors that intertwine both mitigation and adaptation (Atteridge et al. 2020; Duarte et al. 2013). Integrated efforts also occur at the city level, such as the Climate Change Action Plan of Wellington City, which includes enhancing forest sinks to increase carbon sequestration while at the same time protecting biodiversity and reducing groundwater runoff as rainfall increases (Grafakos et al. 2019).

To fully maximise their potential co-benefits and trade-offs of integrating adaptation and mitigation, these should be explicitly sought, rather than accidentally discovered (Spencer et al. 2017; Berry et al. 2015), and policies designed to account for both (Caetano et al. 2020) (*robust evidence, high agreement)*. For example, the REDD$^+$ initiative focus on mitigation by carbon sequestration was set up to provide co-benefits such as: nature protection, political inclusion, monetary income, economic opportunities. However, some unintended trade-offs may have occurred such as physical displacement, loss of livelihoods, increased human–wildlife conflicts, property claims, food security concerns, and an unequal distribution of benefits to local population groups (Bushley 2014; Duguma et al. 2014a; Gebara et al. 2014; Anderson et al. 2016; Di Gregorio et al. 2016, 2017; Kongsager and Corbera 2015). Ultimately, ecosystem (or nature-based) strategies, such as the use of wetlands to create accessible recreational areas that improve public health while improving biodiversity, sinking carbon and protecting neighbourhoods from extreme flooding events, may lead to more efficient and cost-effective policies (Locatelli et al. 2011; Klein et al. 2005; Mills-Novoa and Liverman 2019; Kongsager et al. 2016).

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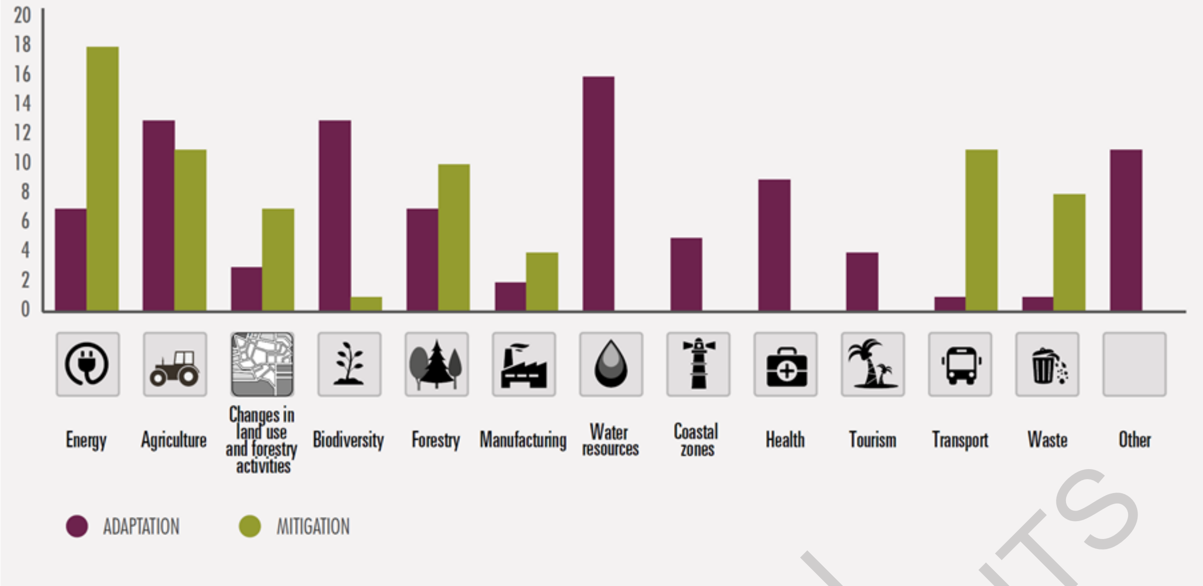
Box 13.16 Latin America region adaptation linking mitigation: REDD+ lessons

Thirty-three countries in the Latin American region have submitted their NDCs, and 70% of their initiatives have included mitigation and adaptation options focusing on sustainable development (Bárcena et al. 2018; Kissinger et al. 2019). However, most of these policies are disconnected across sectors (Loaiza et al. 2017; Locatelli et al. 2017). National governments have identified their relevant sectors as: energy, agriculture, forestry, land-use change, biodiversity, and water resources (see Figure 1 below). The region houses 57% of the primary forest of the planet. REDD+ aims to reduce GHG while provide ecosystems services to vulnerable communities (Bárcena et al. 2018). Lessons from successful REDD+ programs include the benefits of a multilevel structure from international to national down to strong community organization, as well as secure resources funding, with most of the projects relying on external sources of funding (Kissinger et al. 2019; Loaiza et al. 2017) (*medium evidence, high agreement*). However, there is limited evidence of effective adaptation co-benefits, which may be related to the lack of provision of forest standards; a disproportionate focus on mitigation and lack of attention to the well-being of the population in rural and agricultural areas (Kongsager and Corbera 2015).

Conflicts have emerged over political views, government priorities of resources (oil, bioenergy, hydropower), and weak governance among national and local authorities, indigenous groups and other stakeholders such as NGOs which play a critical role in the technological and financial support for the REDD+ initiative (Reed 2011; Kashwan 2015; Gebara et al. 2014; Locatelli et al. 2011, 2017). A more holistic approach which recognises these social, environmental and political drivers would appear to have benefits but assessment is needed to allow evidence based actionable policy statements.



Box 13.16, Figure 1 **Latin America and the Caribbean: High priority sectors for mitigation and adaptation. Number of countries that name the following sector in their national climate change plans and/or communications. The purple and green bars represent adaptation and mitigation respectively.**

Source: Reproduced from Bárcena et al. 2018

END BOX 13.16 HERE

The 'nexus' approach is another widely used framework that describes the linkages between water, energy, food, health and other socio-economic factors in some integrated assessment approaches (Rasul and Sharma 2016). The Food-Energy-Water (FEW) nexus, for example, considers how water is required for energy production and supply (and thus tied to mitigation), how energy is needed to treat and transport water, and how both are critical to adaptable and resilient food production systems (Mohtar and Daher 2014; Biggs et al. 2015). Climate change impacts all these dimensions in the form of multi-hazard risk (Froese and Schilling 2019). Although integrative, the FEW nexus faces many challenges including: limited knowledge integration; coordination between different institutions and levels of government; politics and power; cultural values; and ways of managing climate risk (Leck and Roberts 2015; Romero-Lankao et al. 2017; Mercure et al. 2019). More empirical assessment is needed to identify potential overlaps between sectoral portfolios, as this could help to delineate resources allocation for synergies and to avoid trade-offs.

13.8.3 Relationships between mitigation and adaptation measures

There are multiple ways that mitigation and adaptation may be integrated. Table 13.3 sets out those relationships broken down into four areas: adaptation that contributes to mitigation; mitigation that contributes to adaptation; holistic, sustainability first strategies; and trade-offs. The table shows that more holistic and sustainability-oriented policies can open up the possibility for accelerated transitions across multiple priority domains (*robust evidence, high agreement*).

Table 13.3 Relationships between adaptation and mitigation measures

Policy/action	Interrelation explained	Reference
	Adaptation that contributes to mitigation	
Coastal adaptation and blue carbon; developing strategies for conservation and restoration of blue carbon ecosystems generating resilient communities and landscapes. • **Contributes to carbon storage and sequestration.**	Conservation of habitats and ecosystems, protect communities from extreme events, increase food security, and provide ecosystem services. At the same time, restoration of mangroves, tidal marshes, and seagrasses have high rates of carbon sequestration, act as long-term carbon sinks, and are contained within clear national jurisdictions. **Example:** Conservation programs on Brazilian mangroves, Spanish seagrass meadows, the Great Barriers Reef in Australia, and Coastal Management Strategy in New Zealand	(Andresen et al. 2012; Herr and Landis 2016; Duarte 2017; Doll and Oliveira 2017; Howard et al. 2017; Gattuso et al. 2018; Cooley et al. 2019; Karani and Failler 2020; Lovelock and Reef 2020)
Nature-based Solutions (NbS); Nature-based solutions are interventions that use the natural functions of healthy ecosystems to protect the environment but also provide numerous economic and social benefits. • **Contributes to carbon storage and sequestration using individual and clustered trees.**	NbS complement and shares common elements with a wide variety of other approaches to building the resilience of social-ecological systems. Policies at national and subnational level include community-based adaptation, ecosystem-based disaster risk reduction, climate-smart agriculture, and green infrastructure, and often place emphasis on using participatory and inclusive processes and community/stakeholder engagement. **Examples:** Mexico and the United Kingdom provide support for NbS in their national biodiversity strategies and action plans some related to water management. UK launched the Green Recovery Challenge Fund to create jobs with a focus on tree planting and the rehabilitation of peatlands.	(Doswald and Osti 2011; Secretariat of the Convention on Biological Diversity 2019; Ihobe - Environmental Management Agency 2017; Zwierzchowska et al. 2019; Seddon et al. 2020; Choi et al. 2021; OECD 2021b)
Ecosystem-based Adaptation (EbA); use biodiversity and ecosystem services to help people to adapt to the adverse effects of climate change, aiming to maintain and increase the resilience and reduce the vulnerability of ecosystems and people • **Contributes to carbon storage and sequestration**	EbA involves the conservation, sustainable management and restoration of ecosystems, such as forests, grasslands, wetlands, mangroves or coral reefs to reduce the harmful impacts of climate hazards including shifting patterns or levels of rainfall, changes in maximum and minimum temperatures, stronger storms, and increasingly variable climatic conditions. **Examples:** Some NDCs include EbA and NbS harmonizing national policies (e.g.: National Adaptation Plan) with other national climate and development policy processes, such as: water resources management plan, disaster risk reduction strategies, land planning codes.	(IPBES 2019; Doswald et al. 2014; Secretariat of the Convention on Biological Diversity 2009; McAllister 2007; Colls et al. 2009; Rubio 2017; Raymond et al. 2017; Duarte 2017; Gattuso et al. 2018)
Urban Greening; urban forestry, planting in road reserves and tree planting along main streets. • **Contributes to carbon storage and sequestration** • **Energy use reduction**	Urban afforestation and reforestation produce cooling effect and water retention while helping to reducing carbon dioxide from the atmosphere. Green walls and rooftops increase energy efficiency of buildings and decrease water runoff and provide insulation for the buildings. **Examples:** Wellington City Council and other entities must comply with the New Zealand Emission Trading System regulatory framework that provides guidance and requirements of climate change planning and implementation for both M&A.	(Santamouris 2014; Sharifi and Yamagata 2016; Grafakos et al. 2018; Pasimeni et al. 2019; Anderson et al. 2016)

Climate adaptation plans at city level; Subnational policies that would lead to carbon reduction to support climate mitigation. Contribution to mitigation: • **Carbon storage and sequestration** • **Energy use reduction** • **Renewable energy**	Cities with Climate Actions Plans include urban spatial planning and capacity-building initiatives. Some cities with adaptation and mitigation combined climate change action plans are: Bangkok, Chicago, Montevideo, Wellington, Durban, Paris, Mexico City, and Melaka. And cities with A&M actions are: Los Angeles, Vancouver, Barcelona, London, Accra, Santiago de Chile, Bogota, Curitiba, and other. **Co-benefits generated by climate actions at cities**: heat stress reduction; water scarcity, stormwater and flood management; air quality improvement, human health and well being, aesthetic/ amenity, recreation / tourism, environmental justice, real estate value, food production, green jobs opportunities.	(Garcetti 2019; Horne 2020; Barcelona City Council 2018; Greater London Authority 2018; Accra Metropolitan Assembly 2020; Choi et al. 2021; Grafakos et al. 2019; Nakano et al. 2017; Peng and Bai 2018; Zen et al. 2019; Bai et al. 2018)
	Mitigation that contributes to adaptation	
Green Infrastructure; Policies to support the design and implementation of a hybrid network of natural, semi-natural, and engineered features within, around, and beyond urban areas at all scales, to provide multiple ecosystem services and benefits. • **Carbon storage and sequestration** • **Reduced energy consumption**	Adaptation benefits: flood management, heat stress reduction individually, or jointly, coastal protection, water scarcity management, groundwater resources, ecosystem resilience improvement, air quality, water supply, flood control, water quality improvement, groundwater recharge. Social co-benefits: aesthetic, recreation, environmental education, improved human health/wellbeing, social cohesion, and poverty reduction. Policy examples: National building code guidelines, flood safety standards, local land-use plans, local building codes, integrated water management for flood control,	(Atchison 2019; Conger and Chang 2019; Schoonees et al. 2019; De la Sota et al. 2019; Choi et al. 2021; Zwierzchowska et al. 2019)
REDD[+] Strategies; An incentive for developing countries to increase carbon sinks, to protect their forest resources and coastal wetlands. Mostly are national strategies led by the state with contribution of international donors. • **Contributes to carbon storage and sequestration** • **Renewable energy**	REDD+ strategies aim to generate social benefits such as poverty reduction, and ecological services such as water supply, water quality enhancement, conserves soil and water by reducing erosion. For example; indigenous communities of Socio Bosque in Ecuador have sustained livelihoods and maintaining ties to land, place, space, and *cosmovision* While in Cameroon, upfront contextual inequities with respect to technical capabilities, power, gender, level of education, and wealth have been barriers to individuals' likelihood of participating in and benefiting from the projects.	(McBurney 2021; Tegegne et al. 2021; Anderson et al. 2016; Busch et al. 2011; Bushley 2014; Dickson and Kapos 2012; Froese and Schilling 2019; Gebara et al. 2014; Pham et al. 2014; Jodoin 2017)
Household energy-efficiency and renewable energy measures; Energy policies may improve socioeconomic development. • **Energy use reduction**	Energy Efficiency (EE) emerges as a feasible and sustainable solution in Latin America, to minimise energy consumption, increase competitiveness levels and reduce carbon footprint. Achieving high levels of EE in the building sector requires new policies and strengthening their legal framework. Microenterprise development contributes to poverty reductions as renewable energy stimulate local and national economies	(Chan et al. 2017; Silvero et al. 2019; Zabaloy et al. 2019; Alves et al. 2020; Nyiwul 2019; Dal Maso et al. 2020)
	Sustainability first: Holistic approaches	
Integrated community sustainability plans.	Climate change mitigation and adaptation are embedded in a plan to improve affordability, biodiversity, public health, and other aspects of communities.	(Burch et al. 2014; Shaw et al. 2014; Stuart et al. 2016; Dale et al. 2020)

Inclusive future visioning using social-ecological systems or socio-technical systems thinking.	Participatory processes that highlight the cultural and social dimensions of climate change responses and synergies/trade-offs between priorities rather than an exclusive focus on technical aspects of solutions.	(Gillard et al. 2016; Krzywoszynska et al. 2016)
Climate Resilience Cities; integrating New Urban Agenda (NUA), SDGs, climate actions for A&M, and Disaster Risk Reduction (DRR) for local and subnational governments, and DRR within a multi-hazard approach based on Sendai Framework.	Resilient cities are including SDGs, targets, A&M options and DRR to build a resilient plan for urban planning, health, life quality and jobs creation. Climate mitigation and sustainable energy actions adopted at the local level are interconnected. For instance, cities with Sustainable Energy and Climate Action Plan, which required the establishment of a baseline emission inventory and the adoption of policy measures, are already showing a tangible achievement regarding sustainable goals.	(Barcelona City Council 2018; Garcetti 2019; Accra Metropolitan Assembly 2020; Blok 2016; Giampieri et al. 2019; Gomez Echeverri 2018; Long and Rice 2019; Pasimeni et al. 2019; Romero-Lankao et al. 2016)
Trade-offs		
Land use strategies; for mitigation or adaptation considered in isolation, may cause a conflict in land planning. • **Carbon storage and sequestration** • **Energy use reduction** • **Renewable energy**	Increasing density of land use, land use mix and transit connectivity could increase climate stress and reduce green open spaces. It may increase the urban heat island impacting human health, and expose population to coastal inundation. Some of the policies and strategies to minimise this are: land use planning, zoning, land-use permits, mobilizing private finance in the protection of watersheds, integrated coastal zone management, flood safety standards, and other. More assessment is needed prior to new land use to reduce or prevent actions which negatively alter ecosystem services and environmental justice	(O'Donnell 2019; Bush and Doyon 2019; Grafakos et al. 2019; Landauer et al. 2015; Viguié and Hallegatte 2012; Floater et al. 2016; Xu et al. 2019; Landauer et al. 2019)
Low-carbon, net zero and climate change resilient building codes that fail to account for affordability. • **Energy reduction** • **Renewable energy**	Low carbon or net zero emissions have multi-objective strategies, integrated policies, regulations, and actions at the national and sub-national levels. Trade-offs may be related to policy mechanisms that must be implemented comprehensively, not individually. However, different administrative levels and institutions may create a barrier to inter-sectoral coordination. For example: "Greening" programmes may produce positive mitigation and adaptation outcomes but may also accelerate displacement and gentrification at city level.	(Chaker et al. 2021; del Río and Cerdá 2017; Choi et al. 2021; Papadis and Tsatsaronis 2020; Wolch et al. 2014; Garcia-Lamarca et al. 2021; Haase et al. 2017; Sharifi 2020; Viguié and Hallegatte 2012; del Río 2014)

13.8.3.1 Governing the linkages between mitigation and adaptation at the local, regional, and global scales

International policy frameworks, such as the 2015 Paris Agreement, the Sendai Framework for Disaster Disk Reduction, and the New Urban Agenda for sustainable urban systems, provide an integrated approach for both adaptation and mitigation, while promoting sustainable development and climate resilience across scales (from global, regional, to local government actions (Nachmany and Setzer 2018; Duguma et al. 2014b; Heidrich et al. 2016; Di Gregorio et al. 2017; Locatelli et al. 2017; Mills-Novoa and Liverman 2019) (*robust evidence, high agreement*). Even so, the specific ways that these linkages are governed vary widely depending on institutional and jurisdictional scale, competing policy priorities, and available capacity (Landauer et al. 2019).

Supranational levels of action such as the EU climate change policy have influenced the development and implementation of Climate Change Action Plans (CCAPs) at the subnational level (Reckien et al. 2018; Villarroel Walker et al. 2017; Heidrich et al. 2016). While adaptation is gaining prominence and is increasingly included in the NDCs of EU nations, the implementation of adaptation and mitigation by EU states are at different stages (Fleig et al. 2017). Fleig et al. (2017) found that all EU states, with the exception of Hungary, have adopted a framework of laws tackling mitigation and adaptation to climate change. However, an assessment of climate legislation in Europe pointed out that there has been little coordination between mitigation and adaptation, and that implementation varies according to different national conditions (Nachmany et al. 2015). More recently, however, integrated adaptation/mitigation plans have been prepared in Europe under the Covenant of Mayors, in which synergies and trade-offs can be better revealed and assessed (Bertoldi et al. 2020).

Local governments and cities are increasingly emerging as important climate change actors (Gordon and Acuto 2015) (see also Section 13.5). While cities and local governments are developing Climate Change Action Plans (CCAPs), plans that explicitly integrate the design and implementation of adaptation and mitigation are a minor percentage, with few cities establishing inter-relationships between them (Nordic Council of Ministers 2017; Grafakos et al. 2018). Compared to national climate governance, local governments are more likely to develop and advance climate policies, generating socio-economic or environmental co-benefits, and improve communities' quality of life (Gill et al. 2007; Bowen et al. 2014; Deng et al. 2017; Hennessey et al. 2017; Mayrhofer and Gupta 2016; Duguma et al. 2014b). There may be a disconnect, however, between the responsibility that a particular jurisdiction has over mitigation and adaptation (city officials, for instance) and the scale of resources or capacities that they have available to bring to bear on the problem (regional to national provision of energy and transport) (Di Gregorio et al. 2019; Dale et al. 2020).

13.8.4 Integrated governance including equity and sustainable development

Climate policy integration carries implications for the pursuit of the SDGs, given that it is nearly impossible to achieve the desired socio-economic gains if fundamental environmental issues, such as climate change, are not addressed (Gomez-Echeverri 2018). Research on climate resilient development pathways (Roy et al. 2018), for instance, argues for long term policy planning that combines the governance of national climate and SD goals, builds institutional capacity across all sectors, jurisdictions, and actors, and enhances participation and transparency (*robust evidence, high agreement*) (also see Chapter 4 and 17).

In the Global South, climate change policies are often established in the context of sustainable development and of other pressing local priorities (e.g., air pollution, health, and food security). National climate policy in these countries tends to give prominence to adaptation based on country vulnerability, climatic risk, gender-based differences in exposur to that risk, and the importance of local/traditional and indigenous knowledge (Beg et al. 2002; Duguma et al. 2014b). Despite the evidence that integrated mitigation and adaptation policies can be effective and efficient (Klein et al. 2005) and can potentially reduce trade-offs, there is still limited evidence of how such integrated policies would specifically contribute to progress on the SDGs (Antwi-Agyei et al. 2018; De Coninck et al, 2018; Di Gregorio et al. 2017; Campagnolo and Davide 2019; Kongsager et al 2016) (*robust evidence, high agreement*).

Where mainstreaming of environmental concerns has been attempted through national plans, they have had success in some cases when backed by strong political commitments that support a vertical coordination structure rather than horizontal structures led by the focus ministry (Nunan et al. 2012). Such political commitments are therefore crucial to success but insufficient in and of themselves (Runhaar et al. 2018; Wamsler et al. 2020). Integration of the budget process is particularly important, as are aligned timeframes across different objectives (Saito 2013). Recognition of the functional interactions across policy sectors is improved by a translation of long-term policy objectives into a plan that aligns with integration goals (Corry 2012; Oels 2012; Dupont 2019).

There are important links between inequality, justice and climate change (Ikeme 2003; Bailey 2017). Many of these operate through the benefits, costs and risks of climate action (distributive justice), while others focus on differential participation and recognition of subnational actors and marginalized groups (procedural justice) (Bulkeley and Castán Broto 2013; Bulkeley et al. 2013; Hughes 2013; Romero-Lankao and Gnatz 2019; Reckien et al. 2018).

Justice principles are rarely incorporated in climate change framing and action (Sovacool and Dworkin 2015; Genus and Theobald 2016; Heikkinen et al. 2019; Romero-Lankao and Gnatz 2019). Yet, equity is salient to mitigation debates, because climate change mitigation policies can have also negative impacts (Brugnach et al. 2017; Ramos-Castillo et al. 2017; Klinsky 2018), exacerbated by poverty, inequality and corruption (Markkanen and Anger-Kraavi 2019; Reckien et al. 2018). The siting of facilities and infrastructure that advance decarbonisation (such as public transit infrastructure, renewable energy facilities etc.) may have implications for environmental justice. Integrated attention to justice in climate, environment and energy, as well as involvement of host communities in siting assessments and decision-making processes, can help to avoid such conflict (McCord et al. 2020; Hughes and Hoffmann 2020). As a result, successful policy integration goes beyond optimizing public management routines, and must resolve key trade-offs between actors and objectives (Meadowcroft 2009; Nordbeck and Steurer 2016).

The potential for transformative climate change policy that delivers both adaptation and mitigation is also shaped by a number of enabling and disabling factors tied to governance processes (Burch et al. 2014)(also see Section 13.9) (*robust evidence, high agreement*).

START BOX 13.17 HERE

Box 13.17 Enabling and disabling factors for integrated governance of mitigation and adaptation

Ensuring participatory governance and social inclusion: Interlinkages in the food-energy-water nexus highlight the importance of inclusive processes (Cook and Chu 2018; Shaw et al. 2014; Nakano et al. 2017; Romero-Lankao and Gnatz 2019). The cultivation of urban grassroots innovations and social innovation may accelerate progress (Wolfram and Frantzeskaki 2016), as may the development of carefully-designed climate and energy dialogues that enable learning among multiple stakeholders (Cashore et al. 2019).

Considering synergies and trade-offs with broader sustainable development priorities: The explicit consideration of synergies and trade-offs will enable more integrated policy making (von Stechow et al. 2015; Dang et al. 2003). Policy frameworks to do so ae just emerging, such as analysis of trade-offs between energy and water policies and agriculture (Huggel et al. 2015; Antwi-Agyei et al. 2018).

Employing a diverse set of tools to reach targets: Building codes, land use plans, public education initiatives, and nature-based solutions such as green ways may impact adaptation and mitigation simultaneously (Burch et al. 2014). Ecological restoration provides another suite of tools, for instance the Brazilian target of restoring and reforesting 0.12 million km^2 of forests by 2030, which can enhance biodiversity and ecosystem services while also sinking carbon (Bustamante et al. 2019). Mandatory retrofits to improve indoor air quality can also increase energy efficiency and resilience to climate change impacts (Friel et al. 2011; Houghton 2011).

Monitoring and evaluating key indicators, beyond only greenhouse gas emissions, such as biodiversity, water quality, and affordability: An integrated approach requires robust process for collecting data on these indicators. Challenges are related to the limited evidence-base on synergies, co-benefits, and trade-offs across sectors and jurisdictions (Di Gregorio et al. 2016; Kongsager et al, 2016; Locatelli et al. 2017; Zen et al. 2019). Moreover, adaptation policies mostly lack measurable targets or expected outcomes increasing the challenge of designing an integrated framework (OECD 2017).

Iterative and adaptive management: Adaptive management helps to address the underlying uncertainty (Kundzewicz et al. 2018) that characterizes implementation of integrated approaches to adaptation and mitigation. Policy integration needs to be considered iteratively along the process of development, implementation, and evaluation of climate policies.

Strategic partnerships that coordinate efforts: Strategic partnerships among diverse actors, therefore, bring diverse technical skills and capacities to the endeavour (Burch et al. 2016; Islam and Khan 2017). However, realising strategic approaches for joint adaptation and mitigation require adequate financial, technical and human resources.

Participatory and collaborative planning approaches can help overcome injustices and address power differentials: Participatory and collaborative planning approaches can provide multiple spaces of deliberation where marginalised voices can be heard (Blue and Medlock 2014; UN Habitat 2016; Castán Broto and Westman 2017; Waisman et al. 2019). These tools organise climate and sustainability action by addressing its democratic deficit and facilitating the recognition of multiple perspectives in environmental planning alongside material limits of development (Agyeman 2013).

END BOX 13.17 HERE

13.9 Accelerating mitigation through cross sectoral and economy wide system change

13.9.1 Introduction

Section 13.9 assesses literature related to economy wide and cross - sector systemic change as an approach to accelerate climate mitigation.

It focuses specifically on policy and institutions, as two of the six enabling conditions for economy wide system change and thus provides a third dimension of the role of policy and institutions to climate mitigation. Enabling conditions in general are discussed in Chapter 4 of the SR1.5 (IPCC 2018), as well as Chapter 4 of this report. This section follows on from Section 13.6 (single policy instruments) and 13.7 (policy packages). Section 13.9 literature follows closely on from Section 13.7 literature on policy packages, which discusses change within one system, although there remains an overlap.

Section 13.9.2 provides a brief introduction to policy and institutions as 2 of the 6 dimensions of enabling conditions, and the importance of enabling conditions to systemic change and climate mitigation. Section 13.9.3 briefly introduces actions for transformative justice, which seek to restructure the underlying system framework that produces mitigation inequalities. Section 13.9.4 provides a brief overview of Net Zero policies and targets (often no more than aspirational), which imply economy wide measures and system change. Section 13.9.5 assesses the literature arguing for a system restructuring approach to climate mitigation, based on systemic restructuring. Section 13.9.6 assesses the literature on stimulus packages and green new deals which aim for systemic change, sometimes with value for climate mitigation. And finally, Section 13.9.7 assesses emerging literatures which argues that there are existing challenges to accelerating climate mitigation that may be overcome by systemic change and targeted actions.

13.9.2 Enabling acceleration

IPCC AR6 WG3, particularly Chapter 4, following on from the IPCC WG3 SR1.5 (IPCC 2018), has highlighted the importance of enabling conditions for delivering successful climate mitigation actions. The AR6 Glossary term for enabling conditions is: 'enabling conditions include *finance*, *technological innovation*, strengthening policy instruments, *institutional capacity*, *multi-level governance*, and changes in *human behaviour* and lifestyles (See Glossary) (*medium evidence, high agreement*). The IPCC SR1.5 report adds to these 6 dimensions saying enabling conditions also includes 'inclusive processes, attention to power asymmetries and unequal opportunities for development and reconsideration of values' (IPCC 2018) (*medium evidence, high agreement*). Not only is the presence of enabling conditions necessary for delivering the successful implementation of single policy instruments and policy packages, but also for delivering systemic change (de Coninck et al. 2018; IPCC 2018; Waisman et al. 2019) (*medium evidence, high agreement*). The feasibility of 1.5°C compatible pathways is contingent upon enabling conditions for systemic change (de Coninck et al. 2018; Waisman et al. 2019) (*medium evidence, high agreement*).

At the same time, again following on from SR1.5 report, Section 1.8.1 explains that there are six feasibility dimensions of successful delivery of climate goals. These feasibility dimensions include geophysical; environmental & ecological; technological; economic; behaviour and lifestyles and institutional dimensions. The presence or absence of enabling conditions would affect the feasibility of mitigation as well as adaptation pathways and can reduce trade-offs whilst amplifying synergies between options (Waisman et al. 2019). Policies and institutions, which are two of the six enabling conditions, are therefore central to accelerated mitigation and systemic change. Identifying, and ensuring, the presence of all the enabling conditions for any given goal, including systemic transformation and acceleration of climate mitigation, is an important first step (Roberts et al. 2018; Le Treut et al. 2021; Singh and Chudasama 2021) (*medium evidence, medium agreement*).

13.9.3 Transformative justice action and climate mitigation

Chapter 4 is the lead chapter of this Report for justice and climate mitigation issues, and includes an overview of institutions which have been set up to ensure a Just climate transition (see Section 4.5 in Chapter 4). Chapter 13 has sought to integrate justice issues in Section 13.2 in reference to procedural justice and the impact of inequalities on sub-national institutions, 13.6 in regard to distribution, and 13.8 in relation to integrating mitigation and adaptation policies.

This sub-section introduces the concept of transformative justice as part of measures intending to accelerate mitigation. Fair and effective climate policymaking requires institutional practices to: consider the distributional impacts of climate policy in the design and implementation of every policy (Agyeman 2013; Castán Broto and Westman 2017); align mitigation with other objectives such as inclusion and poverty reduction (Hughes and Hoffmann 2020; Rice et al. 2020; Hess and McKane 2021); represent a variety of voices, especially those of the most vulnerable (Bullard et al. 2008; Temper et al. 2018); and rely on open processes of participation (Anguelovski et al. 2016; Bouzarovski et al. 2018; Rice et al. 2020) (*robust evidence, high agreement*).

Distributive approaches to climate justice address injustices related to access to resources and protection from impacts. There is an important difference between affirmative and transformative justice action (Agyeman et al. 2016; Castán Broto and Westman 2019; Fraser 1995): Affirmative action includes policies and strategies that seek to correct inequitable outcomes without disturbing the underlying political framework while transformative action seeks to correct inequitable outcomes by restructuring the underlying framework that produces inequalities.

Transformative action that responds to distributive justice concerns include economy wide actions via stimulus packages (such as the European Green Deal and the New Green Deal in the US (see Section 13.9.5)). Other examples are the increasing number of climate litigation suits that are transforming the way distributive dimensions of climate justice are understood (Section 13.4.2).

13.9.4 Net zero emissions targets

The last few years have seen a proliferation of net zero emission targets set by national and regional governments, cities as well as companies and institutions (NewClimate Institute and Data Driven EnviroLab 2020; Black et al. 2021; Rogelj et al. 2021) (see also Cross-Chapter Box 3 in Chapter 3). Meeting these targets implies economy wide systemic change (*medium evidence, high agreement*).

The Energy & Climate Intelligence Unit (ECIU) Net Zero Tracker divides countries in to those which have net zero emissions achieved, have it in law, have proposed legislation, have it in policy documents or have emission reduction targets under discussion in some form. A recent study estimated that 131 countries have either adopted, announced or are discussing net zero GHG emissions targets, covering 72% of global emissions (Höhne et al. 2021). Out of those, as of 1st October 2021, the ECIU Net Zero Tracker states that Germany, Sweden, the European Union, Japan, United Kingdom, France, Canada, South Korea, Spain, Denmark, New Zealand, Hungary and Luxembourg have net zero targets set in law (ECIU 2021).

Some have argued that the expansion of these emission reduction targets marks an important increase in climate mitigation momentum since the Paris Agreement of 2015 and the 2018 IPCC Special Report on Global Warming of 1.5°C (Black et al. 2021; Höhne et al. 2021). On the other hand net zero emission targets in their current state vary enormously in scope, quality and transparency – with many countries at the discussion stage - and this makes scrutiny and comparison difficult (NewClimate Institute and Data Driven EnviroLab 2020; Black et al. 2021; Rogelj et al. 2021).

In order to realise the mitigation potential of net zero emission targets some areas within the targets might need to be changed. For example, this includes clearer definitions; well defined timeframes and scopes; focusing on direct emission reductions within their own territory; minimal reliance on offsets; scrutiny of use and risks of CO_2 removal; attention to equity, near-term action coupled with long-term intent setting; and ongoing monitoring and review (Levin et al. 2020; NewClimate Institute and Data Driven EnviroLab 2020; Black et al. 2021; Höhne et al. 2021; Rogelj et al. 2021; World Bank 2021b) (*medium evidence, high agreement*).

13.9.5 Systemic responses for climate mitigation

There is now a significant body of work which explicitly states, or implicitly accepts, that systemic change may be necessary to deliver successful climate mitigation, including net zero targets. Newell phrases this as the difference between 'plug and play' mitigation applications where one aspect of a system is changed while everything in the system remains the same compared to systemic change, with change affecting all the system (Newell 2021a,b). This section highlights an emergent, multi-disciplinary literature since IPCC AR5, which suggests that acceleration to decarbonised systems via a sustainable development pathway may be better achieved by moving from a single policy instrument or mix of policies approach to a systemic economy wide approach (see Figure 13.6).

The complexity and multi-facetted challenges of rapidly decarbonising our current interconnected systems (such as energy, food, health) in a just way has led Michaelowa et al. (2018) to conclude that implementation of strong mitigation policy packages that are needed requires a systemic change in policymaking.

Multiple modelling assessments of different development and mitigation pathways are available. Most of these analyses which lead to significant climate mitigation assume significant systemic change across social, technological, and economic aspects of a country (for example, India (Gupta et al. 2020); Japan (Sugiyama et al. 2021)) and the globe (Rogelj et al. 2015; Dejuán et al. 2020).

UNEP (2020) argued that major, long term sectoral transformation across multiple systems is needed to reach net zero GHG emissions. Bernstein and Hoffmann (2019) and Rockström et al. (2017) argue that the presence of multi-level, multi-sectoral lock-ins of overlapping and interdependent political, economic, technological and cultural forces mean that a new approach of co-ordinated, cross-economy, systemic climate mitigation is necessary. Creutzig et al. (2018) propose a resetting of the approach to consumption and use of resources to that of demand side solutions, which would have ongoing economy-wide systemic implications.

Others focus more on single system reconfigurations, such as the energy system (Matthes 2017; Tozer 2020); urban systems (Holtz et al. 2018); or the political system (Somerville 2020; Newell and Simms 2020). Becken (2019) argues that only systemic changes at a large scale will be sufficient to break or disrupt existing arrangements and routines in the tourism industry

Others argue for thinking about mitigation in even wider ways. O'Brien (2018) posits that sector-focused, or a silo approach, to mitigation may need to give way to decisions and policies which reach across sectoral, geographic and political boundaries and involve a broad set of interrelated processes – practical, political and personal. Gillard et al. (Gillard et al. 2016) argue that a response to climate change has to move beyond incremental responses, aiming instead for a society wide transformation which goes beyond a system perspective to include learning from social theory; while Eyre et al. (2018) argue that moving beyond incremental emissions reductions will require expanding the focus of efforts beyond the technical to include people, and their behaviour and attitudes. Stoddard et al. (2021) argue that 'more sustainable and just futures require a radical reconfiguration of long-run socio-cultural and political economic norms and institutions'. They focus on nine themes: international climate governance, the vested interests of the fossil fuel industry, geopolitics and militarism, economics and financialisation, mitigation modelling, energy supply systems, inequity, high carbon lifestyles and social imaginaries.

13.9.6 Economy-wide measures

Economy wide stimulus packages which have occurred post COVID-19, and in some cases in response to environmental concerns, have the ability to undermine or aid climate mitigation (*medium evidence, high agreement*). Attention in the early efforts of their development and design can contribute to shifting sustainable development pathways and net zero outcomes, whilst meeting short term economic goals (Hepburn et al. 2020; Hanna et al. 2020) (*medium evidence, high agreement*)

Economy-wide packages, as a way to stimulate and/or restructure domestic economies to deliver particular, desired outcomes is a widely accepted tool of government (for example the Roosevelt's New Deal packages in the US between 1933 and 1939). A number of country-level stimulus package were put in place after the 2008 Global Recession, and there was support for a Global Green New Deal from UNEP (Steiner 2009; Barbier 2010). Cross-economy structural change packages may provide opportunities for another approach to accelerate climate mitigation.

This approach has already been taken up to some degree by a number of countries / blocs. For example, California as well as Germany, through the German *Energiewende*, are early examples of a US state and a country which have tried to link their economies to a sustainable future through energy-wide efforts of structural change (Morris and Jungjohann 2016; Burger et al. 2020a).

In addition to these economy wide measures, there have since been cross-economy Green New Deals implemented such as the European Green Deal (Elkerbout et al. 2020; Hainsch et al. 2020; UNEP 2020)(see also Box 13.1) with calls for other New Deals (e.g. a Blue New Deal (Dundas et al. 2020)) or deals to bring together climate and justice goals (Hathaway 2020; MacArthur et al. 2020).

The COVID-19 Pandemic has resulted in global economic recession, which many Governments have responded to with economic stimulus programs. See also Cross-Chapter Box 1 in Chapter 1 on COVID-19. It has also led to more analysis of the potential of cross-economy stimulus packages to benefit climate goals, including what lessons can be learned from the stimulus packages put in place as a result of the 2008-9 Global Recession.

The United Nations Environment Programme (UNEP) reviewed the green stimulus plans of the G20 following the 2008-9 recession to examine what worked; what did not; and the lessons which could be learnt (Barbier 2010). This work was updated (Barbier 2020) and concluded that the constituents of successful green stimulus frameworks were long term commitments in public spending; pricing reform; ensuring concerns about affordability were overcome; and minimising unwanted distributional impacts. Others argue that post 2008 recession stimulus package outcomes benefited both environmental and industrial objectives and that a long-term policy commitment to the transition to a sustainable, low carbon economy makes sense from both an environmental and industrial strategy point of view (Fankhauser et al. 2013).

With the outbreak of the COVID-19 Pandemic in 2020, past stimulus packages have been further investigated. One study interviewed 231 central bank officials and identified 5 key policies for both economic multipliers and climate impacts metrics (Hepburn et al. 2020). These were expenditure on clean physical infrastructure; building energy efficiency retrofits; investment in education and training; natural capital investment; and clean R and D. However, the mix of effective policies may differ in lower and middle income countries: rural support spending was more relevant, while clean R and D was less so. The study illuminated that there were different phases to recovery packages: the initial 'rescue' spending but then a second 'recovery' phase that can be more fairly rated green or not green. Recovery phase policies can deliver both economic and climate goals -- co-benefits can be captured (i.e. support for EV infrastructure can also reduce local air pollution etc.) -- but package design is important (Hepburn et al. 2020).

Others provide a framework which allows a systematic evaluation of options, given objectives and indicators, for COVID-19 stimulus packages (e.g. (Dupont et al. 2020; Jotzo et al. 2020; OECD 2021c)). Jotzo et al. (2020) conclude that the programmes that most closely match green stimulus are afforestation and ecosystem restoration programmes, energy efficiency upgrades and RE projects. These type of policies provide short term goals of COVID-19 whilst also making progress on longer terms objectives (Jotzo et al. 2020). The IMF concluded that a comprehensive mitigation policy package combining carbon pricing and government green infrastructure spending (that is partly debt financed) can reduce emissions substantially while boosting economic activity, supporting the recovery from the COVID-19 pandemic (Jaumotte et al. 2020).

Conversely, other short term fiscal or recovery measures in stimulus packages may perpetuate high carbon and environmental damaging systems. These include fossil fuel based infrastructure investment; fiscal incentives for high carbon technologies or projects; waivers or roll-backs of environmental regulation; bailouts of fossil fuel intensive companies without conditions for low carbon transitions or environmental sustainability (UNEP 2020; O'Callaghan and Murdock 2021; Vivid Economics 2021).

Of the USD17.2 trillion so far spent on stimulus packages, USD4.8 trillion (28% of the total as of July 2021) is linked to environmental outcomes (Vivid Economics 2021). This study relates to 30 countries: the G20 and 10 others. The packages in EU, Denmark, Canada, France, Spain, the UK, Sweden, Finland and Germany (German Federal Ministry of Finance 2020; Vivid Economics 2021) result in net benefits for the environment. A number of studies provide differing conclusions with respect to net benefits or otherwise for the environment for a number of countries (Climate Action Tracker 2020; UNEP 2020; Vivid Economics 2021). An OECD database found that, as of mid-July 2021, 21% of economic recovery spending in OECD, EU and Key Partners is allocated to environmentally positive measures (OECD 2021c). O'Callaghan and Murdock (2021) reviewed the 50 countries with the greatest stimulus spend in 2020 and find that 13% of the spend is directed to long term recovery type measures, of which 18% is spent on green recovery. This is a total of 2.5% of total spend or USD368bn on green initiatives.

13.9.7 Steps for acceleration

The multi-disciplinary literature exploring how to accelerate climate mitigation and transition to low GHG economies and systems has grown rapidly over the last few years. Acceleration is also confirmed as an important sub-theme of the more specific transition literature (Köhler et al. 2019). While literature focusing on how to accelerate the impact of climate mitigation is derived from empirical evidence, there is very little *ex post* evidence of directed acceleration approaches.

The overlapping discussions of how to accelerate climate mitigation; transition to low carbon economies; and shift development pathways depends heavily on country specific dynamics in political coalitions, material endowments, industry strategy, cultural discourses, and civil society pressures (Sections 13.2, 13.3, 13.4, 13.7, and 13.8). Ambition for acceleration at different scales and stringency (whether for cities, country climate policies, country industrial strategies, or national economic restructuring) increase governance challenges, including coordination across stakeholders, institutions, and scales. 'There is therefore no "one-size-fits-all" blueprint for accelerating low-carbon transitions' (Geels et al. 2017a; Roberts et al. 2018) (*medium evidence, high agreement*).

Markard et al. (2020) describe the key challenges to accelerating climate mitigation and sustainability transitions as:

1. the ability for low carbon innovations to emerge in whole systems. Two critical issues need to occur to overcome this challenge a) complementary interactions between different elements. For example, in an electricity system, the integration of renewable energy requires complementary storage technologies etc. and b) changes in system architecture. Thus in the accelerating phase, policy has to shift from stimulating singular innovations towards managing wider system transformation.
2. the need for greater interactions between adjacent systems: interactions between multiple systems increases the complexity of the transition. Policies are linked to institutions or government departments, and they are often compartmentalised into different policy areas (eg energy policy and transport policy). Increasing and coordinating that interaction adds complexity.
3. the resistance from declining industries; acceleration of sustainability transitions will involve the phase out of unsustainable technologies. As a result acceleration towards a sustainability transition may be resisted – whether business models, or where jobs are involved. Political struggles and conflicts are an inherent part of accelerating transitions, one strategy to deal with this resistance is to accomplish wide societal support for long term transition targets and to form broad constituencies of actors in favour of those transitions.
4. the need for changes in consumer practices and routines; this challenge relates to changes in social practices that may be required for mainstreaming of sustainable technologies. For example, electric vehicles require changes in trip planning and refuelling practices. Reducing levels or types of consumption is also desirable.
5. coordination challenges in policy and governance. There is an increasing complexity of governance which can be overcome by stronger vertical and horizontal policy coordination across systems.

The acceleration literature links two over-arching actions: first, a strategic targeting approach to overcoming the challenges to acceleration by a parallel focus on undermining high carbon systems whilst simultaneously encouraging low carbon systems; and second, focusing on a coordinated, cross-economy systemic response, including harnessing enabling conditions (Geels et al. 2017b; Rosenbloom and Rinscheid 2020; Hvelplund and Djørup 2017; Gomez Echeverri 2018; Markard 2018; Tvinnereim and Mehling 2018; European Environment Agency 2019; Newell and Simms 2020; Otto et al. 2020; Rogelj et al. 2015; Strauch 2020;

O'Brien 2018; Roberts et al. 2018; Hess 2019; Kotilainen et al. 2019; Victor et al. 2019; Burger et al. 2020a; Hsu et al. 2020b; Rosenbloom et al. 2020) (*robust evidence, high agreement*).

Strategic targeting, or the identifying of specific intervention points (Kanger et al. 2020), points of leverage (Abson et al. 2017), or upward cascading tipping points (Sharpe and Lenton 2021), broadly means choosing particular actions which will lead to a greater acceleration of climate mitigation across systems. For example, Dorninger et al (2020) provide a quantitative systematic review of empirical research addressing sustainability interventions. They take 'leverage points' – places in complex systems where relatively small changes can lead to potentially transformative systemic changes – to classify different interventions according to their potential for system wide transformative change. They argue that 'deep leverage points' – the goals of a system, its intent, and rules – need to be addressed more directly, and they provide analysis of the food and energy systems.

The strategic choosing of policies and points of intervention is linked to the importance of choosing self-reinforcing actions for acceleration (for example, (Rosenbloom et al. 2018; Butler-Sloss et al. 2021; Sharpe and Lenton 2021; Jordan and Moore 2020; Bang 2021). Butler-Sloss et al. (2021) explains the types of self-reinforcing actions (or feedback loops) which can encourage or undermine rapid transformation of energy systems.

An example of this first overarching action, the strategic targeting of the challenges to acceleration, is the focus on undermining carbon- intensive systems, thereby reducing opposition to more generalised acceleration policies, including the encouragement of low carbon systems (Rosenbloom 2018; Roberts and Geels 2019; Hvelplund and Djørup 2017; Victor et al. 2019; Rosenbloom et al. 2020; Rosenbloom and Rinscheid 2020) (*robust evidence, high agreement*). Undermining high carbon systems includes deliberately phasing out unsustainable technologies and systems (Kivimaa and Kern 2016; David 2017; Johnsson et al. 2019; UNEP 2019b; Carter and McKenzie 2020; European Environment Agency 2019; Newell and Simms 2020); confronting the issues of incumbent resistance (Roberts et al. 2018); and avoiding future emissions and energy excess by reducing demand (Rogelj et al. 2015; UNEP 2019b; Victor et al. 2019).

Other strategic goals include tackling the equity and justice issues of 'stranded regions' (Spencer et al. 2018); paying greater attention to system architecture to enable increased acceleration to low carbon electricity supply, in this case in the wind industry (McMeekin et al. 2019); and the importance of maintaining global ecosystem of low carbon supply chains (Goldthau and Hughes 2020).

Other strategic goals combine national and global action. For example, global NGO coalitions have formed around strategic policy outcomes such as the 'Keep it in the Ground' movement (Carter and McKenzie 2020), and are supported via coordinated networks, such as the Powering Past Coal Alliance (Jewell et al. 2019), and with knowledge dissemination, for example, the 'Fossil Fuel Cuts Database' (Gaulin and Le Billon 2020).

The second overarching point highlighted by the literature is the benefits of focusing on a coordinated, cross-economy systemic response. Coordination is central to this. For example, coordination of actions and coherent narratives across sectors and cross economy, including within and between all governance levels and scales of actions, is beneficial for acceleration (Zürn and Faude 2013; Hawkey and Webb 2014; Huttunen et al. 2014; Magro et al. 2014; Warren et al. 2016; Köhler et al. 2019; Kotilainen et al. 2019; McMeekin et al. 2019; Victor et al. 2019; Hsu et al. 2020b) (*robust evidence, high agreement*). Victor et al. (2019) provide a framework of how to prioritise the most urgent actions for climate mitigation and they give practical case studies of how to improve coordination to accelerate reconfiguration of systems for economy wide climate mitigation in sectors such as power; cars; shipping; aviation; buildings; cement; and plastics.

However, coordination is a necessary but insufficient condition of acceleration. All enabling conditions are required to deliver systemic transformation (Section 13.9.2).

Other disciplines argue that social transformation is likely to be as important as the technical challenges in a coordinated, cross-economy approach to acceleration. For example, some argue for social tipping interventions (STI) alongside other technical and political interventions so that they can 'activate contagious processes of rapidly spreading technologies, behaviours, social norms, and structural reorganisation' (Otto et al. 2020). They argue that these STIs are *inter alia*: removing fossil fuel subsidies and incentivising decentralised energy generation; building carbon neutral cities; divesting from assets linked to fossil fuels; revealing the moral implications of fossil fuels; strengthening climate education and engagement; and disclosing information of GHG emissions (Otto et al. 2020). Others illuminate the importance of narratives and framings in the take-up (or not) of acceleration actions (Sovacool et al. 2020). Others are optimistic about the possibilities of transformation but also highlight the importance of political economy for rapid and just transitions (Newell and Simms 2020; Newell 2021).

In summary, a synthesis of the multi-disciplinary, acceleration literature suggests that climate mitigation is a multifaceted problem which spans cross-economy and society issues, and that solutions to acceleration may lie in coordinated systemic approaches to change and strategic targeting of leverage points. Broadly, this literature agrees on a dual approach of non-incremental systemic change and a targeting of specific acceleration challenges, with tailored actions drawing on enabling conditions. The underlying argument of this is that there is a strategic logic to focusing on actions which undermine high carbon systems at the same time as encouraging low carbon systems. If high carbon systems are weakened then this may reduce the opposition to policies and actions aimed at accelerating climate mitigation, enabling more support for low carbon systems. In addition, targeting of actions which may create 'tipping point cascades' which increase the rate of decarbonisation may also be beneficial. Finally, new modes of governance may be better suited to this approach in the context of transformative change.

13.10 Further research

Research has expanded in a number of areas relevant to climate mitigation, yet there is considerable scope to add to knowledge. Key areas for research exist in climate institutions and governance, politics, policies and acceleration of action. In each area there is an overarching need for more *ex post* analysis of impact, more cases from the developing world, and understanding how institutions and policies work in combination with each other.

13.10.1 Climate institutions, governance and actors

- The different approaches to framework legislation, how it can be tailored to country context and evolve over time, how it diffuses across countries, and *ex post* analysis of its impact.
- Approaches to mainstreaming climate governance across sectors and at different scales, and developing governmental and non-governmental capacity to bring about long-term low-carbon transformations and associated capacity needs.
- The drivers of subnational climate action, the scope for coordination or leakage with other scales of action, and the effect, in practice on GHG outcomes.
- Comparative research on how countries develop NDCs, and whether and how that shapes national policy processes.

13.10.2 Climate politics

- The full range of approaches that governments and non-governmental actors may take to overcome lock-in to carbon-intensive activities including through addressing material endowments, cultural values, institutional settings and behaviours.
- The factors that influence emergence of popular movements for and against climate actions, and their direct and indirect impacts.
- The role of civic organizations in climate governance, including religious organisations, consumer groups, indigenous communities, labour unions, and development aid organizations.
- The relationship between climate governance approaches and differing political systems, including the role of corruption on climate governance.
- The impacts of media – traditional and social – on climate mitigation, including the role of disinformation.
- The role of corporate actors in climate governance across a broad range of industries.
- Systematic comparative research on the differing role of climate litigation across various juridical systems.

13.10.3 Climate policies

- Greater *ex post* empirical studies of mitigation policy outcomes, their design features, the impacts of policy instruments under different conditions of implementation, especially in developing countries. Such research needs to assess the effectiveness, economic and distributional effects, co-benefits and side effects, and transformational potential of mitigation policies.
- Understand how packages of policies are designed and implemented, including with attention to local context and trade-offs.
- Policy design and institutional needs for the explicit purpose of net zero transitions.
- Greater understanding of the differences between, and benefits of, policy packages and economy wide measures for in-system and cross-system structural change.
- Policies and packages for emissions sources that are unregulated or under-regulated, including industrial and non-CO_2 emissions.
- The existence and extent of carbon leakage across countries, the relative impact of different channels of leakage, and the implications of policy instruments designed to address leakage.

13.10.4 Coordination and acceleration of climate action

- How to ensure a just transition that gains wide popular support through research on actual and perceived distributional effects across countries and contexts.
- How to coordinate and integrate for climate mitigation, between what actors, sectors, governance scale and goals, and how to evaluate.
- Knowledge on the political and policy related links between adaptation and mitigation across sectors and countries.

- Further theoretical and empirical research on the necessary institutional, cultural, social and political conditions to accelerate climate mitigation.
- How to transform developed and developing economies and societies for acceleration, including by shifting development pathways.
- The approaches to, and value of, coordinated, cross economy structural change, including Green New Deal approaches, as a way to accelerate GHG reduction.

Frequently Asked Questions (FAQs)

FAQ 13.1 What roles do national play in climate mitigation, and how can they be effective?

Institutions and governance underpin mitigation. Climate laws provide the legal basis for action, organisations through which policies are developed and implemented, and frameworks through which diverse actors interact. Specific organisations, such as expert committees, can inform emission reduction targets, inform the creation of policies and packages, and strengthen accountability. Institutions enable strategic thinking, building consensus among stakeholders and enhanced coordination.

Climate governance is constrained and enabled by countries' political systems, material endowments and their ideas, values and belief systems, which leads to a variety of country specific approaches to climate mitigation.

Countries follow diverse approaches. Some countries focus on greenhouse gases emissions by adopting comprehensive climate laws and creating dedicated ministries and institutions focused on climate change. Others consider climate change among broader scope of policy objectives, such as poverty alleviation, energy security, economic development and co-benefits of climate actions, with the involvement of existing agencies and ministries. See also FAQ 13.3 on subnational climate mitigation.

FAQ 13.2 What policies and strategies can be applied to combat climate change?

Institutions can enable creation of mitigation and sectoral policy instruments; policy packages for low-carbon system transition, and economy wide measures for systemic restructuring. Policy instruments to reduce greenhouses gas emissions include economic instruments, regulatory instruments and other approaches.

Economic policy instruments directly influence prices to achieve emission reductions through taxes, permit trading, offset systems, subsidies, and border tax adjustments, and are effective in promoting implementation of low-cost emissions reductions. Regulatory instruments help achieve specific mitigation outcomes particularly in sectoral applications, by establishing technology or performance requirements. Other instruments includes information programs, government provision of goods, services and infrastructure, divestment strategies, and voluntary agreements between governments and private firms.

Climate policy instruments can be sector-specific or economy-wide and could be applied at national, regional, or local levels. Policymakers may directly target GHG emission reduction or seek to achieve multiple objectives, such as urbanization or energy security, with the effect of reducing emissions. In practice, climate mitigation policy instruments operate in combination with other policy tools, and require attention to the interaction effects between instruments. At all levels of governance, coverage, stringency and design of climate policies define their efficiency in reducing greenhouse gases emissions.

Policy packages, when designed with attention to interactive effects, local governance context, and harnessed to a clear vision for change, are better able to support socio-technical transitions and shifts in development pathways toward low carbon futures than individual policies. See also Chapter 14 on international climate governance.

FAQ 13.3 How can actions at the sub-national level contribute to climate mitigation?

Sub-national actors (e.g. individuals, organizations, jurisdictions and networks at regional, local and city levels) often have a remit over areas salient to climate mitigation, such as land use planning, waste management, infrastructure, housing, and community development. Despite constraints on legal authority and dependence on national policy priorities in many countries, subnational climate change policies exist in more than 120 countries. However, they often lack national support, funding, and capacity, and adequate coordination with other scales. Sub-national climate action in support of specific goals is more likely to succeed when linked to local issues such as travel congestion alleviation, air pollution control.

The main drivers of climate actions at sub-national levels include high levels of citizen concern, jurisdictional authority and funding, institutional capacity, national level support and effective linkage to development objectives. Subnational governments often initiate and implement policy experiments that could be scaled to other levels of governance.

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Chapter 14: International cooperation

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Date of Draft: 1/11/2021

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Executive summary

International cooperation is having positive and measurable results (*high confidence*). The Kyoto Protocol led to measurable and substantial avoided emissions, including in 20 countries with Kyoto first commitment period targets that have experienced a decade of declining absolute emissions. It also built national capacity for GHG accounting, catalysed the creation of GHG markets, and increased investments in low-carbon technologies (medium confidence). Other international agreements and institutions have led to avoided CO_2 emissions from land-use practices, as well as avoided emissions of some non-CO_2 greenhouse gases (*medium confidence*). {14.3, 14.5, 14.6}

New forms of international cooperation have emerged since AR5 in line with an evolving understanding of effective mitigation policies, processes, and institutions. Both new and pre-existing forms of co-operation are vital for achieving climate mitigation goals in the context of sustainable development (*high confidence*). While previous IPCC assessments have noted important synergies between the outcomes of climate mitigation and achieving sustainable development objectives, there now appear to be synergies between the two processes themselves (*medium confidence*). Since AR5, international cooperation has shifted towards facilitating national level mitigation action through numerous channels. Now including both processes established under the UNFCCC regime and through regional and sectoral agreements and organisations. {14.2, 14.3, 14.5, 14.6}

Participation in international agreements and transboundary networks is associated with the adoption of climate policies at the national and sub-national levels, as well as by non-state actors (*high confidence*). International cooperation helps countries achieve long-term mitigation targets when it supports development and diffusion of low-carbon technologies, often at the level of individual sectors, which can simultaneously lead to significant benefits in the areas of sustainable development and equity (*medium confidence*). {14.2, 14.3, 14.5, 14.6}

International cooperation under the UN climate regime has taken an important new direction with the entry into force of the 2015 Paris Agreement, which strengthened the objective of the UN climate regime, including its long-term temperature goal, while adopting a different architecture to that of the Kyoto Protocol to achieve it (*high confidence*). The core national commitments under the Kyoto Protocol have been legally binding quantified emission targets for developed countries tied to well-defined mechanisms for monitoring and enforcement. By contrast, the commitments under the Paris Agreement are primarily procedural, extend to all parties, and are designed to trigger domestic policies and measures, enhance transparency, and stimulate climate investments, particularly in developing countries, and to lead iteratively to rising levels of ambition across all countries (*high confidence*). Issues of equity remain of central importance in the UN climate regime, notwithstanding shifts in the operationalisation of 'common but differentiated responsibilities and respective capabilities' from Kyoto to Paris (*high confidence*). {14.3}

There are conflicting views on whether the Paris Agreement's commitments and mechanisms will lead to the attainment of its stated goals. Arguments in support of the Paris Agreement are that the processes it initiates and supports will in multiple ways lead, and indeed have already led, to rising levels of ambition over time. The recent proliferation of national mid-century net-zero GHG targets can be attributed in part to the Paris Agreement (*medium confidence*). Moreover, its processes and commitments will enhance countries' abilities to achieve their stated level of ambition, particularly among developing countries (*medium confidence*). Arguments against the Paris Agreement are that it lacks a mechanism to review the adequacy of individual Parties' nationally determined contributions (NDCs), that collectively current NDCs are inconsistent in their level of ambition with achieving the Paris Agreement's temperature goal, that its processes will not lead to sufficiently rising levels of ambition in the NDCs, and that NDCs will not be achieved because the targets, policies and measures they contain are not legally binding at the international level (*medium confidence*). To some extent, arguments on both sides are aligned with different analytic frameworks, including assumptions about the main barriers to mitigation that international cooperation can help overcome (*medium confidence*). The extent to which countries increase the ambition of their NDCs and ensure they are effectively implemented will depend in part on the successful implementation of the support mechanisms in the Paris Agreement, and in turn will determine whether the goals of the Paris Agreement are met (*high confidence*). {14.2, 14.3, 14.4}

International cooperation outside the UNFCCC processes and agreements provides critical support for mitigation in particular regions, sectors and industries, for particular types of emissions, and at the sub- and trans-national levels (*high confidence*). Agreements addressing ozone depletion, transboundary air pollution, and release of mercury are all leading to reductions in the emissions of specific greenhouse gases (*high confidence*). Cooperation is occurring at multiple governance levels including cities. Transnational partnerships and alliances involving non-state and sub-national actors are also playing a growing role in stimulating low-carbon technology diffusion and emissions reductions (*medium confidence*). Such transnational efforts include those focused on climate litigation; the impacts of these are unclear but promising. Climate change is being addressed in a growing number of international agreements operating at sectoral levels, as well as within the practices of many multilateral organisations and institutions (*high confidence*). Sub-global and regional cooperation, often described as climate clubs, can play an important role in accelerating mitigation, including the potential for reducing mitigation costs through linking national carbon markets, although actual examples of these remain limited (*high confidence*). {14.2, 14.4, 14.5, 14.6}

International cooperation will need to be strengthened in several key respects in order to support mitigation action consistent with limiting temperature rise to well below 2°C in the context of sustainable development and equity *(high confidence)*. Many developing countries' NDCs have components or additional actions that are conditional on receiving assistance with respect to finance, technology development and transfer, and capacity building, greater than what has been provided to date (*high confidence*). Sectoral and sub-global cooperation is providing critical support, and yet there is room for further progress. In some cases, notably with respect to aviation and shipping, sectoral agreements have adopted climate mitigation goals that fall far short of what would be required to achieve the temperature goal of the Paris Agreement (*high confidence*). Moreover, there are cases where international cooperation may be hindering mitigation efforts, namely evidence that trade and investment agreements, as well as agreements within the energy sector, impede national mitigation efforts (*medium confidence*). International cooperation is emerging but so far fails to fully address transboundary issues associated with solar radiation modification and carbon dioxide removal (*high confidence*) {14.2, 14.3, 14.4, 14.5, 14.6}

14.1 Introduction

This chapter assesses the role and effectiveness of international cooperation in mitigating climate change. Such cooperation includes multilateral global cooperative agreements among nation states such as the 1992 United Nations Framework Convention on Climate Change (UNFCCC), and its related legal instruments, the 1997 Kyoto Protocol and the 2015 Paris Agreement, but also plurilateral agreements involving fewer states, as well as those focused on particular economic and policy sectors, such as components of the energy system. Moreover, this chapter assesses the role of transnational agreements and cooperative arrangements between non-state and sub-national actors, including municipal governments, private-sector firms and industry consortia, and civil society organisations. This chapter does not assess international cooperation within the European Union, as this is covered in Chapter 13 of this report.

Past IPCC assessment reports have discussed the theoretical literature, providing insights into the rationale for international cooperation, as well as guidance as to its structure and implementation. This chapter limits such theoretical discussion primarily to the new developments since AR5. Important developments in this respect include attention to climate clubs (groups of countries and potentially non-state actors that can work together to achieve particular objectives), and the effects of framing the global climate change mitigation challenge as one of accelerating a socio-technical transition or transformation, shifting development pathways accordingly, in addition to (or rather than) solving a global commons problem. This chapter draws from theory to identify a set of criteria by which to assess the effectiveness of existing forms of international cooperation.

The rest of this chapter describes existing cooperative international agreements, institutions, and initiatives with a view to clarifying how they operate, what effects they have, and ultimately, whether they work. At the heart of this international institutional architecture lies the Paris Agreement, which sets the overall approach for international cooperation under the UNFCCC at the global level. In many ways, the Paris Agreement reshapes the structure of such cooperation, from one oriented primarily towards target setting, monitoring, and enforcement, to one that is oriented towards supporting and enabling nationally determined actions (including targets), monitoring as well as catalysing non-state and sub-national actions at multiple levels of governance. In addition to the Paris Agreement, many forms of cooperation have taken shape in parallel: those designed to address other environmental problems that have a significant impact on climate mitigation; those operating at the sub-global or sectoral level; and, those where the main participants are non-state actors. The chapter ends with an overall assessment of the effectiveness of current international cooperation and identifies areas that would benefit from improved and enhanced action.

14.1.1 Key findings from AR5

AR5 found that two characteristics of climate change make international cooperation essential: that it is a global commons problem that needs to be addressed in a coordinated fashion at the global scale; and that given the global diversity with respect to opportunities for and cost of mitigation, there are economic efficiencies associated with cooperative solutions (13.2.1.1). Consequently, AR5 found evidence to suggest that climate policies that are implemented across geographical regions would be more effective in terms of both their environmental consequences and their economic costs (13.13, 13.6, 14.4). AR5 also suggested that regional cooperation could offer opportunities beyond what countries may be able to achieve by themselves. These opportunities are due to geographic proximity, shared infrastructure and policy frameworks, trade, and cross-border investments, and examples included renewable energy pools across borders, networks of energy infrastructure and coordinated forestry policies (1.2, 6.6,15.2, 14.2). AR5 also suggested that policy linkages exist across regional, national, and sub-national scales (13.3.1, 13.5.1.3). For these reasons, AR5 suggested that although the UNFCCC remains the primary international forum for climate negotiations, many other institutions engaged at the global, regional, and local levels do and should play an active role (1.3.3.1,13.4.1.4,13.5). AR5 also noted that the inclusion of climate change issues across a variety of forums often creates institutional linkages between mitigation and adaptation (13.3,13.4.13.5). In addition to centralised cooperation and governance, with a primary focus on the UNFCCC and its associated institutions, AR5 noted the emergence of new transnational climate-related institutions of decentralised authority such as public-private sector partnerships, private sector governance initiatives, transnational NGO programs, and city-led initiatives (13.2,13.3.1,13.12). It noted that these have resulted in a multiplicity of cooperative efforts in the form of multilateral agreements, harmonised national policies and decentralised but coordinated national and regional policies (13.4.1, 13.3.2, 14.4). Finally, it suggested that international cooperation may also have a role in promoting active engagement of the private sector in technological innovation and cooperative efforts leading to technology transfer and the development of new technologies (13.3, 13.9, 13.12).

14.1.2 Developments since AR5

14.1.2.1 Negotiation of the Paris Agreement

The key development since AR5 has been the negotiation and adoption of the Paris Agreement, which, building on the UNFCCC, introduces a new approach to global climate governance. This new approach, as discussed below (Section 14.3.1.1), is driven by the need to engage developing countries in emissions reductions beyond those they had taken on voluntarily under the Cancun Agreements, extend mitigation commitments to those developed countries that had rejected or withdrawn from the Kyoto Protocol, and to respond to the rapidly changing geopolitical context (Section 14.3.1.2).

14.1.2.2 2030 Agenda for Sustainable Development and the Sustainable Development Goals

It has long been clear that a failure to mitigate climate change would exacerbate existing poverty, accentuate vulnerability and worsen inequality (IPCC 2014), but there is an emerging attempt to harmonise mitigation actions with those oriented towards social and economic development. A key development since AR5 is the adoption in 2015 of the 2030 Agenda for Sustainable Development, which contains 17 Sustainable Development Goals (SDGs). This Agenda offers an aspirational narrative, coherent framework and actionable agenda for addressing diverse issues of development through goals that balance the economic, social and environmental dimensions of sustainable development as well as issues of governance and institutions (ICSU ISSC 2015). Scholars have noted that these dimensions of sustainable development are inter-dependent (Nilsson et al. 2016), and, as such it is difficult if not impossible to achieve economic and social gains while neglecting environmental concerns, including climate change (Le Blanc 2015). The SDGs are closely linked to the Paris Agreement, adopted a few weeks later. There is a growing body of literature that examines the interlinkages between SDGs, including SDG 13 (taking urgent action to combat climate change) and others, concluding that without a proper response to climate change, success in many of the other SDGs would be difficult if not impossible (Weitz et al. 2018; ICSU ISSC 2015; Le Blanc 2015; Nilsson et al. 2016). Likewise, failure to achieve the SDGs will have a detrimental effect on the ability to limit climate change to manageable levels. Initiatives such as The World in 2050 (TWI2050 2018), a large research initiative by a global consortium of research and policy institutions, work on the premise that pursuing climate action and sustainable development in an integrated and coherent way, based on a sound understanding of development pathways and dynamics, is the strongest approach to enable countries to achieve their objectives in both agreements.

14.1.2.3 IPCC Special Reports

Further key developments since AR5 include the release of three IPCC special reports. The first of these assessed the differential impacts of limiting climate change to 1.5°C global average warming compared to 2°C warming, indicated the emissions reductions necessary and enabling conditions to stay within this limit (IPCC 2018a). While the events that have unfolded since the report are not yet comprehensively documented in literature, arguably the report has led to a renewed perception of the urgency of climate mitigation (Wolf et al. 2019). In particular, the report appears to have crystalised media coverage in some parts of the world around a need to reduce emissions to net zero by 2050 (whether of GHGs or CO_2), rather than delaying such reductions until the latter half of the century, as had been previously understood and indicated in the Paris Agreement. Its release is hence one factor explaining the rise in transnational climate mobilisation efforts (Boykoff and Pearman 2019). It has also played a role, in addition to the Paris Agreement (Geden 2016a), in the numerous announcements, pledges and indications by governments, including by all G-7 countries, of their adoption of net zero GHG targets for 2050. The other two special reports focused on ocean and the cryosphere (IPCC 2019), and the potential of land-related responses to contribute to adaptation and mitigation (IPCC 2020). There has been no literature directly tying the publication of these latter two reports to changes in international cooperation. However, the 25th UNFCCC Conference of Parties in Madrid in 2019 convened a dialogue on ocean and climate change to consider how to strengthen mitigation and adaptation action in this context (UNFCCC 2019a, para 31).

14.2 Evaluating international cooperation

This section describes recent insights from social-science theory that can shed light on the need for and ideal structure of international cooperation. This section starts by describing developments in framing the underlying problem, move towards a body of theory describing the benefits of multilateral sub-global action, and ends with a theory-based articulation of criteria to assess the effectiveness of international cooperation.

14.2.1 Framing concepts for assessment of the Paris Agreement

Previous IPCC reports have framed international climate cooperation, and indeed climate mitigation more generally, primarily as addressing a global commons problem (Stavins et al. 2014). In this report, by contrast, multiple framings are considered. Chapter 1 introduces four analytic frameworks: aggregated economic approaches such as cost-benefit analysis, which maps onto the global commons framing; ethical approaches; analysis of transitions and transformations; and psychology and politics of changing course. Here, we highlight some of the findings that are of relevance to international cooperation.

When applied to the international context, the public good (or global commons) framing stresses that the incentives for mitigation at the global level are greater than they are for any single country, since the latter does not enjoy the benefits of its own mitigation efforts that accrue outside its own borders (Patt 2017; Stavins et al. 2014). This framing does not preclude countries engaging in mitigation, even ambitious mitigation, but it suggests that these countries' level of ambition and speed of abatement would be greater if they were part of a cooperative agreement.

Theoretical economists have shown that reaching such a global agreement is difficult, due to countries' incentives to freeride, namely benefit from other countries' abatement efforts while failing to abate themselves (Barrett 1994; Gollier and Tirole 2015). Numerical models that integrate game theoretic concepts, whether based on optimal control theory or on dynamic programming, consistently confirm this insight, at least in the absence of transfers (Germain et al. 2003; Lessmann et al. 2015; Chander 2017). Recent contributions suggest that regional or sectoral agreements, or agreements focused on a particular subset of GHGs, can be seen as building blocks towards a global approach (Asheim et al.

2006; Froyn and Hovi 2008; Sabel and Victor 2017; Stewart et al. 2017). In a dynamic context, this gradual approach through building blocks can alleviate the free-riding problem and ultimately lead to global cooperation (Caparrós and Péreau 2017). Much of this literature is subsumed under the concept of "climate clubs," described in the next section. Other developments based on dynamic game theory suggest that the free-riding problem can be mitigated if the treaties do not prescribe countries' levels of green investment and the duration of the agreement, as countries can credibly threaten potential free-riders with a short-term agreement where green investments will be insufficient due to the hold-up problem (Battaglini and Harstad 2016). Finally, thresholds and potential climate catastrophes have also been shown, theoretically and numerically, to reduce free-riding incentives, especially for countries that may become pivotal in failing to avoid the threshold (Barrett 2013; Emmerling et al. 2020).

In addition to mitigation in the form of emissions abatement, innovation in green technologies also has public good features, leading for the same reasons to less innovation than would be globally ideal (Jaffe et al. 2005). Here as well, theory suggests that there are benefits from cooperation on technology development at the regional or sectoral levels, but also that cooperation on technology, especially for breakthrough technologies, may prove to be easier than for abatement (El-Sayed and Rubio 2014; Rubio 2017). In a dynamic context, the combination of infrastructure lock-in, network effects with high switching cost, and dynamic market failures suggests that deployment and adoption of clean technologies is path dependent (Acemoglu et al. 2012; Aghion et al. 2014), with a multiplicity of possible equilibria. This implies that no outcome is guaranteed, although the most likely pathway will depend on economic expectations and initial conditions of the innovation process (Krugman 1991). Therefore, the government has a role to play, either by shifting expectations (e.g. credibly committing to climate policy), or by changing initial conditions (e.g. investing in green infrastructure or subsidising clean energy research) (Acemoglu et al. 2012; Aghion et al. 2014). This result is exacerbated by the irreversibility of energy investments and the extremely long periods of operation of the typical energy investment (Caparrós et al. 2015; Baldwin et al. 2020).

While the public goods and global commons framing concentrates on free-riding incentives as the primary barrier to mitigation taking place at a pace that would be globally optimal, other factors arise across the four analytic frameworks. For example, within the political framework, Beiser-McGrath and Bernauer (2021) highlight that not just the incentive to free-ride, but also the knowledge that another major emitter is free-riding, could lessen a country's political incentive to mitigate. Aklin and Mildenberger (2020) present evidence to suggest that distributive conflict within countries, rather than free riding across countries, is the primary barrier to ambitious national level action. Another barrier could be a lack of understanding and experience with particular policy approaches; there is evidence that participation in cooperative agreements could facilitate information exchange across borders and lead to enhanced mitigation policy adoption (Rashidi and Patt 2018).

The analytic approach focusing on transitions and transformation focuses on path dependent processes as an impediment to the shift to low-carbon technologies and systems. Cross-chapter box 12 on Transition Dynamics (Chapter 16) summarizes the key points of this literature. This chapter describes how the two framings focus on different indicators of progress, and potentially different types of cooperative action within the international context. This chapter highlights in later sections conflicting views on whether the Paris Agreement is likely to prove effective (section 14.3.3.2). To some extent, the dichotomy of views aligns with the two framings: analysis implicitly aligned with the global commons framing is negative about the Paris architecture, whereas that aligned with the transitions framing is more positive (Kern and Rogge 2016; Roberts et al. 2018; Patt 2017).

Within the global commons framing, the primary indicator of progress is the actual level of GHG emissions, and the effectiveness of policies can be measured in terms of whether such emissions rise or fall (Patt 2017; Hanna and Victor 2021). The fact that the sum of all countries' emissions has continued to grow (IPCC 2018a), even as there has been a global recognition that they should decline, is seen as being consistent with the absence of a strong global agreement. Within this framing, there is traditionally an emphasis on treaties' containing self-enforcing agreements (Olmstead and Stavins 2012), ideally through binding commitments, as a way of dealing with the overarching problem of free-ridership (Barrett 1994; Finus and Caparrós 2015; Tulkens 2019). However, as discussed above, the emphasis has now shifted to a gradual cooperation approach, either regional or sectoral, as an alternative way of dealing with free-riding incentives (Caparrós and Péreau 2017; Sabel and Victor 2017; Stewart et al. 2017). The gradual linkage of emission trading systems (discussed in Section 14.4.4), goes in the same direction. There is also literature suggesting that the diversity of the countries involved may in fact be an asset to reduce the free-rider incentive (Pavlova and De Zeeuw 2013; Finus and McGinty 2019), which argues in favour of a system where all countries, irrespectively of their income levels, are fully involved in mitigation, unlike the Kyoto Protocol and in line with the Paris Agreement. Finally, recent efforts have discussed potential synergies between mitigation and adaptation efforts in a strategic context (Bayramoglu et al. 2018) (see Section 14.5.1.2) In general, current efforts go beyond considering climate policy as a mitigation-only issue, much in line with the discussion about linkages between climate change and sustainable development policies described in detail in Chapters 1 and 4 of this report.

In the transitions framing, by contrast, global emissions levels are viewed as the end (and often greatly delayed) result of a large number of transformative processes. International cooperation may be effective at stimulating such processes, even if a change in global emissions is not yet evident, implying that short-term changes in emissions levels may be a misleading indicator of progress towards long-term goals (Patt 2017). Hanna and Victor (2021) suggest a particular focus on technical advances and deployment patterns in niche low carbon technologies, such as wind and solar power, and electric vehicles. However, this is one among many suggestions: the literature does not identify a single clear indicator to use, and there are many metrics of technological progress and transformation, described in Chapter 16, Section 16.3.3 of this report. These can include national level emissions among countries participating in particular forms of cooperation, as well as leading indicators of such emissions such as changes in low-carbon technology deployment and cost.

Just as the transition framing highlights indicators of progress other than global emissions, it de-emphasises the importance of achieving cost-effectiveness with respect to global emissions. Hence, this strand of the literature does not generally support the use of international carbon markets, suggesting that these can delay transformative processes within countries that are key drivers of technological change (Cullenward and Victor 2020). For similar reasons, achieving cross-sectoral cost-effectiveness, a goal of many carbon markets, is not seen as a high priority. Instead, within the transitions framing the emphasis with respect to treaty design is often on providing mechanisms to support parties' voluntary actions, such as with financial and capacity-building support for new technologies and technology regimes (Geels et al. 2019). The transitions literature also highlights impediments to transformation as being sector specific, and hence the importance of international cooperation addressing sector-specific issues (Geels et al. 2019). While such attention often starts with promoting innovation and diffusion of low-carbon technologies that are critical to a sector's functioning, it often ends with policies aimed at phasing out the high-carbon technologies once they are no longer needed (Markard 2018). In line with this, many scholars have suggested value in supply-side international agreements, aimed at phasing out the production and use of fossil fuels (Collier and Venables 2014; Piggot et al. 2018; Asheim et al. 2019; Newell and Simms 2020).

Analytic approaches centred on equity and development figure prominently within this report, with many of the key concepts addressed in Chapter 4. Primarily the focus is on aligning climate policy at the international level with efforts to shift development pathways towards improved quality of life and greater sustainability (see cross chapter box 5 on shifting sustainable development pathways, Chapter 4). There are also overlaps between the equity framework and the others. Within the global commons framing, the emphasis is on international carbon markets to reduce the costs from climate policies, and as way of generating financial flows to developing countries (Michaelowa et al. 2019a). The transitions framing, while focused empirically primarily on industrialized countries, nevertheless aligns with an understanding of climate mitigation taking place within a wider development agenda; in many cases it is a lack of development that creates a barrier to rapid system transformation, which international cooperation can address (Delina and Sovacool 2018)(see also Cross-chapter Box 12).

14.2.2 Climate clubs and building blocks

A recent development in the literature on international climate governance has been increased attention to the potential for climate clubs (Victor 2011). Hovi et al. (2016) define these "as any international actor group that (1) starts with fewer members than the UNFCCC has and (2) aims to cooperate on one or more climate change-related activities, notably mitigation, adaptation, climate engineering or climate compensation." While providing public goods (such as mitigation), they also offer member-only benefits (such as preferential tariff rates) to entice membership. In practice, climate clubs are sub-global arrangements, and formal agreement by interstate treaty is not a prerequisite. Actors do not have to be states, although in the literature on climate clubs states have hitherto dominated. The literature has an essentially static dimension that focuses on the incentives for actors to join such a club, and a dynamic one, which focuses on the "building blocks" for global cooperative agreements.

The literature focusing on the static aspects of clubs highlight that they represent "coalitions of the willing" (Falkner 2016a; Gampfer 2016; Falkner et al. 2021), which offer a package of benefits, part of which are pure public goods (available also to non-club members), and others are club benefits that are only available to members (Hovi et al. 2016). The members-only or excludable part can be a system of transfers within the club to compensate the countries with higher costs. For example, the benefit from participating in the club can be to have access to a common emissions trading system, which in general is more attractive the larger the diversity of the countries involved, although this is not a general result as discussed in detail in Doda and Taschini (2017). However, as costs and effort sharing agreements are unsuccessful in a static context (Barrett 1994), mainly due to free-rider incentives, several studies have proposed using tariffs on trade or other forms of sanctions to reduce incentives for free-riding (Helm and Sprinz 2000; Eyland and Zaccour 2012; Anouliès 2015; Nordhaus 2015; Al Khourdajie and Finus 2020). For example, Nordhaus (2015) uses a coalition formation game model to show that a uniform percentage tariff on the imports of nonparticipants into the club region (at a relatively low tariff rate of about 2%) can induce high participation within a range of carbon price values. More recently, Al Khourdajie and Finus (2020) show that border carbon adjustments and an open membership policy can lead to a large stable climate agreement, including full participation. Table 14.1 presents a number of key results related to climate clubs from a static context.

Table 14.1 Key climate club static modelling results

	Aakre et al. (2018)	(Nordhaus 2015)	(Hovi et al. 2017; Sprinz et al. 2018)	(Sælen et al. 2020; Sælen 2020)
Scope	Transboundary black carbon and methane in the Arctic	Global emissions	Global emissions	Global emissions
Modelling method	TM5-FASST model ("reduced-form air quality and impact evaluation tool")	C-DICE (coalition formation game based on a static version of the multiregional	Agent-based model	Agent-based model

		DICE-RICE optimisation model)		
Border tax adjustment	No	Yes	No	No
Key results	Black carbon can be more easily controlled than methane, based on self-interest; inclusion of non-Arctic Council major polluters desirable to control pollutants	For non-participants in mitigation efforts, modest tariffs on trade are advised to stabilize coalition formation for emission reductions	Climate clubs can substantially reduce GHG emissions, provided club goods are present. The (potential) departure of a single major actor (e.g., USA) reduces emissions coverage, yet is rarely fatal to the existence of the club	The architecture of the Paris Agreement will achieve the 2°C goal only under a very fortunate constellation of parameters. Potential (e.g., US) withdrawal further reduces these chances considerably

In a dynamic context, the literature on climate clubs highlights the co-called 'building blocks' approach (Stewart et al. 2013a,b, 2017). This is a bottom-up strategy designed to create an array of smaller-scale, specialised initiatives for transnational cooperation in particular sectors and/or geographic areas with a wide range of participants. As part of this literature, Potoski and Prakash (2013) provide a conceptual overview of voluntary environmental clubs, showing that many climate clubs do not require demanding obligations for membership and that a substantial segment thereof are mostly informational (Weischer et al. 2012; Andresen 2014). Also crafted onto the building blocks approach, Potoski (2017) demonstrates the theoretical potential for green certification and green technology clubs. Green (2017) further highlights the potential of "pseudo-clubs" with fluid membership and limited member benefits to promote the diffusion and uptake of mitigation standards. Falkner et al. (2021) suggest a typology of normative, bargaining, and transformational clubs. Before the adoption of the Paris Agreement, some literature suggested that the emergence of climate clubs in parallel to the multilateral climate regime would lead to "forum shopping", with states choosing the governance arrangement that best suits their interests (McGee and Taplin 2006; van Asselt 2007; Biermann et al. 2009; Oh and Matsuoka 2017). However, more recent literature suggests that climate clubs complement rather than challenge the international regime established by the UNFCCC (van Asselt and Zelli 2014; Draguljić 2019; Falkner 2016a).

In this dynamic context, one question is whether to negotiate a single global agreement or to start with smaller agreements in the hope that they will eventually evolve into a larger agreement. It has been debated extensively in the context of free trade whether a multilateral (global) negotiating approach is preferable to a regional approach, seen as a building block towards global free trade. Aghion et al. (2007) analysed this issue formally for trade, showing that a leader would always choose to move directly to a global agreement. In the case of climate change, it appears that even the mildest form of club discussed above (an efforts and costs sharing agreement, as in the case of the linkage of emissions trading systems) can yield global cooperation following a building-blocks approach, and that the sequential path relying on building-blocks may be the only way to reach global cooperation over time (Caparrós and Péreau 2017). While the existence of a nearly universal agreement such as the Paris

Agreement may arguably have rendered this discussion less relevant, the Paris Agreement co-exists, and will likely continue to do so, with a multitude of sectoral and regional agreements, meaning that this discussion is still relevant for the evolution of these complementary regimes.

Results based on an agent-based model suggest that climate clubs results in major emission reductions if there is a sufficiently high provision of the club good and if initial membership by several states with sufficient emissions weight materializes. Such configurations allow the club to grow over time to enable effective global action (Hovi et al. 2017). The departure of a major emitter (specifically the United States) triggered a scientific discussion on the stability of the Paris Agreement. Sprinz et al. (2018) explore whether climate clubs are stable against a leader willing to change its status, e.g., from leader to follower or even completely leaving the climate club, finding in most cases such stability to exist. Related studies on the macroeconomic incentives for climate clubs by Paroussos et al. (2019) show that climate clubs are reasonably stable, both internally and externally (i.e., no member willing to leave and no new member willing to join), and climate clubs that include obligations in line with the 2°C goal combined with financial incentives can facilitate technology diffusion. The authors also show that preferential trade arrangements for low-carbon goods can reduce the macroeconomic effects of mitigation policies. Aakre et al. (2018) show numerically that small groups of countries can limit black carbon in the Arctic, driven mainly for reasons of self-interest, yet reducing methane requires larger coalitions due to its larger geographical dispersal and require stronger cooperation.

14.2.3 Assessment criteria

This section identifies a set of criteria for assessing the effectiveness of international cooperation, which is applied later in the chapter. Lessons from the implementation of other multilateral environmental agreements (MEAs) can provide some guidance. There is considerable literature on this topic, most of which predates AR5, and which will therefore not be covered in detail. Issues include ways to enhance compliance, and the fact that a low level of compliance with an MEA does not necessarily mean that the MEA has no effect (Downs et al. 1996; Victor et al. 1998; Weiss and Jacobson 1998). Recent research examines effectiveness from the viewpoint of the extent to which an MEA influences domestic action, including the adoption of implementing legislation and policies (Brandi et al. 2019).

Many have pointed to the Montreal Protocol, addressing stratospheric ozone loss, as an example of a successful treaty because of its ultimate environmental effectiveness, and relevance for solving climate change. Scholarship emerging since AR5 emphasises that the Paris Agreement has a greater 'bottom-up' character than many other MEAs, including the Montreal or Kyoto Protocols, allowing for more decentralised 'polycentric' forms of governance that engage diverse actors at the regional, national and sub-national levels (Ostrom 2010; Jordan et al. 2015; Falkner 2016b; Victor 2016). Given the differences in architecture, lessons drawn from studies of MEA regimes need to be supplemented with assessments of the effectiveness of cooperative efforts at other governance levels and in other forums. Emerging research in this area proposes methodologies for this task (Hsu et al. 2019a). Findings highlight the persistence of similar imbalances between developed and developing countries as at the global level, as well as the need for more effective ways to incentivise private sector engagement in transnational climate governance (Chan et al. 2018).

While environmental outcomes and economic performance have been long-standing criteria for assessment of effectiveness, the other elements deserve some note. It is the case that the achievement of climate objectives, such as limiting global average warming to 1.5 – 2°C, will require the transition from high- to low-carbon technologies, and the transformation of the sectors and social environments within which those technologies operate. Such transformations are not linear processes, and hence many of the early steps taken – such as supporting early diffusion of new renewable energy technologies – will have little immediate effect on GHG emissions (Patt 2015; Geels et al. 2017). Hence, activities that contribute to transformative potential include technology transfer and financial support for low-carbon infrastructure, especially where the latter is not tied to immediate emissions reductions. Assessing the transformative potential of international cooperation takes these factors into account. Equity and distributive outcomes are of central importance to the climate change debate, and hence for evaluating the effects of policies. Equity encompasses the notion of distributive justice which refers to the distribution of goods, burdens, costs and benefits, as well as procedural-related issues (Kverndokk 2018).

Finally, the literature on the performance of other MEAs highlights the importance of institutional strength, which can include regulative quality, mechanisms to enhance transparency and accountability, and administrative capacity. Regulative quality includes guidance and signalling (Oberthür et al. 2017), as well as clear rules and standards to facilitate collective action (Oberthür and Bodle 2016). The literature is clear that legally binding obligations (which require the formal expression of state consent) and non-binding recommendations can each be appropriate, depending on the particular circumstances (Skjærseth et al. 2006), and indeed it has been argued that for climate change non-binding recommendations may better fit the capacity of global governance organisations (Victor 2011). Mechanisms to enhance transparency and accountability are essential to collect, protect, and analyse relevant data about parties' implementation of their obligations, and to identify and address challenges in implementation (Kramarz and Park 2016; Kinley et al. 2020). Administrative capacity refers to the strength of the formal bodies established to serve the parties to the regime and help ensure compliance and goal attainment (Andler and Behrle 2009; Bauer et al. 2017).

In addition to building on the social science theory just described, we recognise that it is also important to strike a balance between applying the same standards developed and applied to international cooperation in AR5, and maintaining consistency with other chapters of this report (primarily Chapters 1, 4, 13, and 15). Table 14.2 presents a set of criteria that do this, and which are then applied later in the chapter.

Table 14.2 Criteria for assessing effectiveness of international cooperation

Criterion	Description
Environmental outcomes	To what extent does international cooperation lead to identifiable environmental benefits, namely the reduction of economy-wide and sectoral emissions of greenhouse gases from pre-existing levels or 'business as usual' scenarios?
Transformative potential	To what extent does international cooperation contribute to the enabling conditions for transitioning to a zero-carbon economy and sustainable development pathways at the global, national, or sectoral levels?
Distributive outcomes	To what extent does international cooperation lead to greater equity with respect to the costs, benefits, and burdens of mitigation actions, taking into account current and historical contributions and circumstances?
Economic performance	To what extent does international cooperation promote the achievement of economically efficient and cost-effective mitigation activities?
Institutional strength	To what extent does international cooperation create the institutional framework needed for the achievement of internationally agreed-upon goals, and contribute to national, sub-national, and sectoral institutions needed for decentralised and bottom-up mitigation governance?

14.3 The UNFCCC and the Paris Agreement

14.3.1 The UN climate change regime

14.3.1.1 Instruments & Milestones

The international climate change regime, in evolution for three decades, comprises the 1992 UNFCCC, the 1997 Kyoto Protocol, and the 2015 Paris Agreement. The UNFCCC is a 'framework' convention, capturing broad convergence among states on an objective, a set of principles, and general obligations relating to mitigation, adaptation, reporting and support. The UNFCCC categorises parties into Annex I and Annex II. Annex I parties, comprising developed country parties, have a goal to return, individually or jointly, their GHG emissions to 1990 levels by 2000. Annex II parties, comprising developed country parties except for those with economies in transition, have additional obligations relating to the provision of financial and technology support. All parties, including developing country parties, characterised as non-Annex-I parties, have reporting obligations, as well as obligations to take policies and measures on mitigation and adaptation. The UNFCCC also establishes the institutional building blocks for global climate governance. Both the 1997 Kyoto Protocol and the 2015 Paris Agreement are distinct but 'related legal instruments' in that only parties to the UNFCCC can be parties to these later instruments.

The Kyoto Protocol specifies GHG emissions reduction targets for the 2008-2012 commitment period for countries listed in its Annex B (which broadly corresponds to Annex I to the UNFCCC) (UNFCCC 1997, Art. 3 and Annex B). The Kyoto Protocol entered into force in 2005. Shortly thereafter, states began negotiating a second commitment period under the Protocol for Annex B parties, as well as initiated a process under the UNFCCC to consider long-term cooperation among all parties.

At COP 13 in Bali in 2007, parties adopted the *Bali Action Plan* that launched negotiations aimed at an agreed outcome enhancing the UNFCCC's 'full, effective and sustained implementation'. The agreed outcome was to be adopted at COP 15 in Copenhagen in 2009, but negotiations failed to deliver a consensus document. The result instead was the *Copenhagen Accord*, which was taken note of by the COP. While it was a political agreement with no formal legal status under the UNFCCC, it reflected significant progress on several fronts and set in place the building blocks for the Paris Agreement, namely: setting a goal of limiting global temperature increase to below 2°C; calling on all countries to put forward mitigation pledges; establishing broad new terms for the reporting and verification of countries' actions; setting a goal of mobilising USD100 billion a year by 2020 from a wide variety of sources, public and private, bilateral and multilateral, including alternative sources of finance; and, calling for the establishment of a new Green Climate Fund and Technology Mechanism (Rogelj et al. 2010; Rajamani 2010; UNFCCC 2010a). One hundred and forty states endorsed the Copenhagen Accord, with 85 countries entering pledges to reduce their emissions or constrain their growth by 2020 (Christensen and Olhoff 2019).

At COP 16 in Cancun in 2010, parties adopted a set of decisions termed the *Cancun Agreements* that effectively formalised the core elements of the Copenhagen Accord, and the pledges states made, under the UNFCCC. The Cancun Agreements were regarded as an interim arrangement through to 2020, and parties left the door open to further negotiations, in line with negotiations launched in 2005, toward a legally binding successor to the Kyoto Protocol (Freestone 2010; Liu 2011a). Collectively the G-20 states are on track to meeting the mid-level of their Cancun pledges, although there is uncertainty about some individual pledges. However, there is significant gap between annual emissions expected under full implementation of pledges and the level consistent with the 2°C goal (Christensen and Olhoff 2019).

At the 2011 Durban climate conference, parties launched negotiations for 'a Protocol, another legal instrument or agreed outcome with legal force' with a scheduled end to the negotiations in 2015 (UNFCCC 2012, Dec. 1, para. 2). At the 2012 Doha climate conference, parties adopted a second commitment period for the Kyoto Protocol, running from 2013-2020. The Doha amendment entered into force in 31 December 2020. Given the subsequent adoption of the Paris Agreement, the Kyoto Protocol is unlikely to continue beyond 2020 (Bodansky et al. 2017a). At the end of the compliance assessment period under the Kyoto Protocol, Annex B parties were in full compliance with their targets for the first commitment period; in some cases through the use of the Protocol's flexibility mechanisms (Shishlov et al. 2016).

Although both the Kyoto Protocol and Paris Agreement are under the UNFCCC, they are generally seen as representing fundamentally different approaches to international cooperation on climate change (Held and Roger 2018; Falkner 2016b). The Paris Agreement has been characterised as a 'decisive break' from the Kyoto Protocol (Keohane and Oppenheimer 2016). Some note that the mitigation efforts under the Kyoto Protocol take the form of targets that, albeit based on national self-selection, were part of the multilateral negotiation process, whereas under the Paris Agreement parties make nationally determined contributions. The different approaches have been characterised by some as a distinction between a 'top down' and 'bottom up' approach (Bodansky and Rajamani 2016; Bodansky et al. 2016; Chan et al. 2016; Doelle 2016) but others disagree with such a characterisation pointing to continuities within the regime, for example, in terms of rules for reporting and review, and crossover and use of common institutional arrangements (Depledge 2017; Allan 2019). Some note, in any case, that the Kyoto Protocol's core obligations are substantive obligations of result, while many of the Paris Agreement's core obligations are procedural obligations, complemented by obligations of conduct (Rajamani 2016a; Mayer 2018a).

The differences between and continuities in the three treaties that comprise the UN climate regime are summarised in Table 14.3 below. The Kyoto targets apply only to Annex I parties, but the procedural obligations relating to NDCs in the Paris Agreement apply to all parties, with flexibilities in relation to some obligations for Least Developed Countries (LDCs), Small Island Developing States (SIDS), and developing countries that need it in light of their capacities. The Kyoto targets are housed in its Annex B, therefore requiring a formal process of amendment for revision, whereas the Paris NDCs are located in an online registry that is maintained by the Secretariat, but to which parties can upload their own NDCs. The Kyoto Protocol allows Annex B parties to use three market-based mechanisms – the Clean Development Mechanism (CDM), Joint Implementation and International Emissions Trading – to fulfil a part of their GHG targets. The Paris Agreement recognizes that parties may choose to cooperate voluntarily on markets, in the form of cooperative approaches under Article 6.2, and a mechanism with international oversight under Article 6.4, subject to guidance and rules that are yet to be adopted. These rules relate to integrity and accounting (La Hoz Theuer et al. 2019). Article 5 also provides explicit endorsement of REDD+. The Kyoto Protocol contains an extensive reporting and review process, backed by a compliance mechanism. This mechanism includes an enforcement branch, to ensure compliance, and sanction non-compliance (through the withdrawal of benefits such as participation in market-based mechanisms), with its national system requirements, and GHG targets. By contrast, the Paris Agreement relies on informational requirements and flows to enhance the clarity of NDCs, and to track progress in the implementation and achievement of NDCs.

Table 14.3 Continuities in and differences between the UNFCCC, Paris Agreement and the Kyoto Protocol

Feature	UNFCCC	Kyoto Protocol	Paris Agreement
Objective	To stabilize GHGs in the atmosphere at a level that would prevent	Primarily mitigation-focused (although in pursuit of the	Mitigation in line with a long-term temperature goal, adaptation and finance goals, as well as

	dangerous anthropogenic interference with the climate system, in a time frame to protect food security, enable natural ecosystem adaptability and permit economic development in a sustainable manner	UNFCCC objective)	sustainable development and equity (also, in pursuit of the UNFCCC objective)
Architecture	'Framework' agreement with agreement on principles such as CBDRRC, division of countries into Annexes, with different groups of countries with differentiated commitments.	Differentiated targets, based on national offers submitted to the multilateral negotiation process, and multilaterally negotiated common metrics	Nationally determined contributions subject to transparency, multilateral consideration of progress, common metrics in inventories and accounting.
Coverage of mitigation-related commitments	Annex I Parties with a GHG stabilization goal, all Parties to take policies and measures	UNFCCC Annex I/Kyoto Annex B parties only	All parties
Targets	GHG stabilization goal for Annex I parties ('quasi target')	Legally binding, differentiated mitigation targets inscribed in treaty	Non-binding (in terms of results) contributions incorporated in parties' NDCs, and provisions including those relating to highest possible ambition, progression and common but differentiated responsibilities and respective capabilities, in light of different national circumstances
Timetable	Aim to return to 1990 levels of GHGs by 2000	Two commitment periods (2008-2012; 2013-2020)	Initial NDCs for timeframes from 2020 running through 2025 or 2030 with new or updated NDCs every five years, and

			encouragement to submit long-term low GHG emission development strategies
Adaptation	Parties to cooperate in preparing for adaptation to the impacts of climate change	Parties to formulate and implement national adaptation measures, share of proceeds from CDM to fund adaptation	Qualitative global goal on adaptation to enhance adaptative capacity and resilience, and reduce vulnerability, parties to undertake national adaptation planning and implementation
Loss and Damage	Not covered	Not covered	Cooperation and facilitation to enhance understanding, action and support for loss and damage, including through the Warsaw International Mechanism on Loss and Damage under the UNFCCC
Transparency	National communications from parties, with differing content and set to differing timeframes for different categories of parties	Reporting and review – Annex B parties only	Enhanced transparency framework and five-yearly global stocktake for a collective assessment of progress towards goals – all parties
Support	Annex II commitments relating to provision of finance, development and transfer of technology to developing countries	Advances UNFCCC Annex II commitments relating to provision of finance, development and transfer of technology to developing countries	Enhances reporting in relation to support, expands the base of donors, and tailors support to the needs and capacities of developing countries
Implementation	National implementation, communication on implementation	Market mechanisms (international emissions trading, joint implementation, CDM)	Voluntary cooperation on mitigation (through market-based and non-market approaches); encouragement of REDD+ (guidance and rules under negotiation)

Compliance	Multilateral consultative process, never adopted	Compliance committee with facilitative and enforcement branches; sanctions for non-compliance	Committee to promote compliance and facilitate implementation; no sanctions

14.3.1.2 Negotiating Context and Dynamics

The 2015 Paris Agreement was negotiated in a starkly different geopolitical context to that of the 1992 UNFCCC and the 1997 Kyoto Protocol (Streck and Terhalle 2013; Ciplet et al. 2015). The 'rupturing binary balance of superpowers' of the 1980s had given way to a multipolar world with several distinctive trends: emerging economies began challenging US dominance (Ciplet et al. 2015); industrialised countries' emissions peaked in the 2010s and started declining, while emissions from emerging economies began to grow (Falkner 2019); the EU stretched eastwards and became increasingly supra-national (Kinley et al. 2020); disparities within the group of developing countries increased (Ciplet et al. 2015); and the role of non-state actors in mitigation efforts has grown more salient (Bäckstrand et al. 2017; Kuyper et al. 2018b; Falkner 2019). The rise of emerging powers, many of whom now have 'veto power', however, some noted, did not detract from the unequal development and inequality at the heart of global environmental politics (Hurrell and Sengupta 2012).

In this altered context, unlike in the 1990s when the main cleavages were between the EU and the US (Hurrell and Sengupta 2012), US-China 'great power politics' came to be seen as determinative of outcomes in the climate change negotiations (Terhalle and Depledge 2013). The US-China joint announcement (Whitehouse 2014), for instance, before the 2014 Lima climate conference, brokered the deal on differentiation that came to be embodied in the Paris Agreement (Ciplet and Roberts 2017; Rajamani 2016a). Others have identified, on the basis of economic standing, political influence, and emissions levels, three influential groups - the first comprising the US with Japan, Canada, and Russia, the second comprising the EU and the third comprising China, India and Brazil (Brenton 2013). The emergence of the Major Economies Fora (MEF), among other climate clubs (discussed in Section 14.2.2) reflects this development (Brenton 2013). It also represents a 'minilateral' forum, built on a recognition of power asymmetries, in which negotiating compromises are politically tested and fed into multilateral processes (Falkner 2016a).

Beyond these countries, in the decade leading up to the Paris climate negotiations, increasing differences within the group of developing countries divided the 134-strong developing country alliance of the G-77/China into several interest-based coalitions (Vihma et al. 2011; Bodansky et al. 2017b). A division emerged between the vulnerable least developed and small island states on the one side and rapidly developing economies, the BASIC (Brazil, South Africa, India and China) on the other, as the latter are 'decidedly not developed but not wholly developing' (Hochstetler and Milkoreit 2013). This 'fissure' in part led to the High Ambition Coalition in Paris between vulnerable countries and the more progressive industrialised countries (Ciplet and Roberts 2017). A division also emerged between the BASIC countries (Hurrell and Sengupta 2012), that each have distinctive identities and positions (Hochstetler and Milkoreit 2013). In the lead up to the Paris negotiations, China and India formed the Like-Minded Developing Countries (LMDCs) with OPEC and the Bolivarian Alliance for the Peoples of our Americas (ALBA) countries, to resist the erosion of differentiation in the regime. Yet, the 'complex and competing' identities of India and China, with differing capacities, challenges and self-images, have also influenced the negotiations (Rajamani 2017; Ciplet and Roberts 2017). Other developing countries' coalitions also played an important role in striking the final deal in Paris. The

Alliance of Small Island States (AOSIS), despite their lack of structural power, played a leading role, in particular in relation to the inclusion of the 1.5°C long term temperature goal in the UN climate regime (Agueda Corneloup and Mol 2014; Ourbak and Magnan 2018). The Association of the Latin American and Caribbean Countries (AILAC) that emerged in 2012 also played a decisive role in fostering ambition (Edwards et al. 2017; Watts and Depledge 2018).

Leadership is essential to reaching international agreements and overcoming collective action problems (Parker et al. 2015). The Paris negotiations were faced, as a reflection of the multipolarity that had emerged, with a 'fragmented leadership landscape' with the US, EU, and China being perceived as leaders at different points in time and to varying degrees (Parker et al. 2014; Karlsson et al. 2012). Small island states are also credited with demonstrating 'moral leadership'(Agueda Corneloup and Mol 2014), and non-state and sub-national actors are beginning to be recognised as pioneers and leaders (Wurzel et al. 2019). There is also a burgeoning literature on the emergence of diffused leadership and the salience of followers (Busby and Urpelainen 2020; Parker et al. 2014).

It is in the context of this complex, multipolar and highly differentiated world - with a heterogeneity of interests, constraints and capacities, increased contestations over shares of the carbon and development space, as well as diffused leadership - that the Paris Agreement was negotiated. This context fundamentally influenced the shape of the Paris Agreement in particular on issues relating to its architecture, 'legalisation' (Karlas 2017) and differentiation (Bodansky et al. 2017b; Kinley et al. 2020), all of which are discussed below.

14.3.2 Elements of the Paris Agreement relevant to mitigation

The 2015 Paris Agreement to the UNFCCC, which entered into force on 4 November 2016, and has 192 Parties as of date, is at the centre of international cooperative efforts for climate change mitigation and adaptation in the post-2020 period. Although its legal form was heavily disputed, especially in the initial part of its four-year negotiating process (Rajamani 2015; Maljean-Dubois and Wemaëre 2016; Klein et al. 2017; Bodansky et al. 2017b), the Paris Agreement is a treaty containing provisions of differing levels of "bindingness" (Bodansky 2016; Rajamani 2016b; Oberthür and Bodle 2016). The legal character of provisions within a treaty, and the extent to which particular provisions lend themselves to assessments of compliance or non-compliance, depends on factors such as the normative content of the provision, the precision of its terms, the language used, and the oversight mechanisms in place (Werksman 2010; Bodansky 2015; Oberthür and Bodle 2016; Rajamani 2016b). Assessed on these criteria, the Paris Agreement contains the full spectrum of provisions, from hard to soft law (Pickering et al. 2019; Rajamani 2016b) and even 'non-law', provisions that do not have standard-setting or normative content, but which play a narrative-building and context-setting role (Rajamani 2016b). The Paris Agreement, along with the UNFCCC and the Kyoto Protocol, can be interpreted in light of the customary international law principle of harm prevention according to which states must exercise due diligence in seeking to prevent activities within their jurisdiction from causing extraterritorial environmental harm (Mayer 2016a; Maljean-Dubois 2019).The key features of the Paris Agreement are set out in Box 14.1.

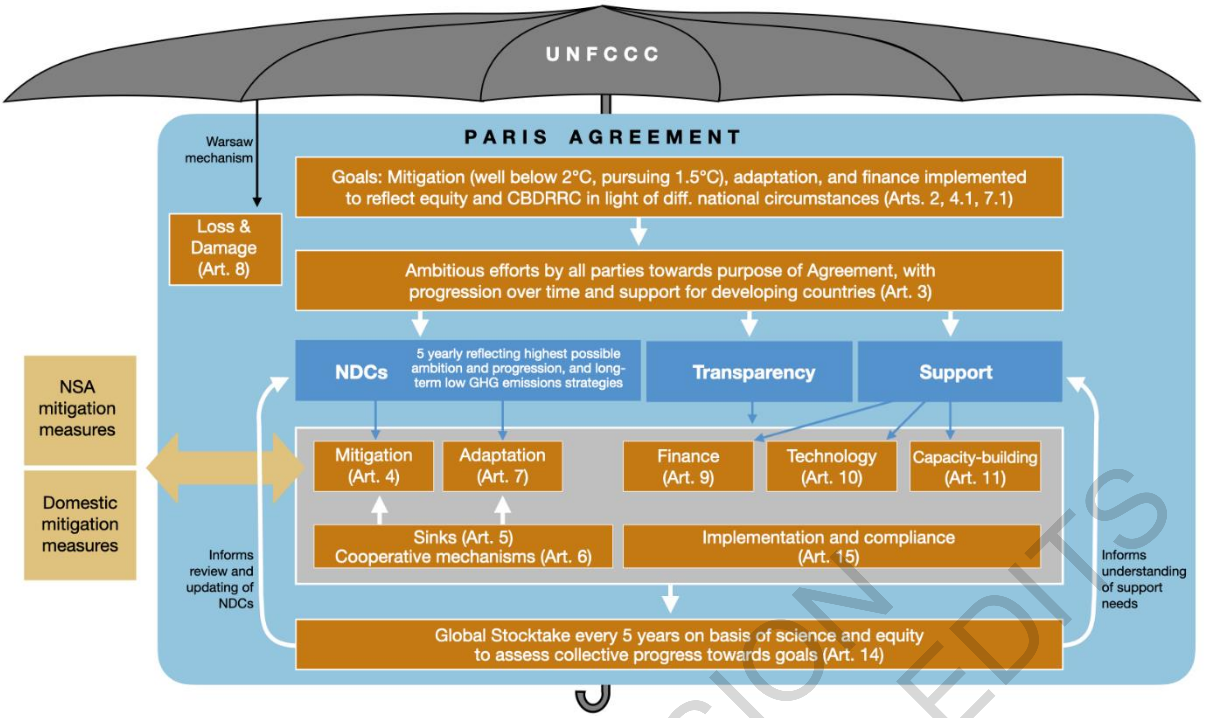

Figure 14.1 Key features of the Paris Agreement. Arrows illustrate the interrelationship between the different features of the Paris Agreement, in particular between the Agreement's goals, required actions (through NDCs, support (finance, technology and capacity-building), transparency framework and global stocktake process. The figure also represents points of interconnection with domestic mitigation measures, whether taken by state parties or by non-state actors (NSAs). This figure is illustrative rather than exhaustive of the features and interconnections.

Figure 14.1 illustrates graphically the key features of the Paris Agreement. The Paris Agreement is based on a set of binding procedural obligations requiring parties to 'prepare, communicate, and maintain' 'nationally determined contributions' (NDCs) (UNFCCC 2015a, Art. 4.2) every five years (UNFCCC 2015a, Art. 4.9). These obligations are complemented by: (1) an 'ambition cycle' that expects parties, informed by five-yearly global stocktakes (Art 14), to submit successive NDCs representing a progression on their previous NDCs (UNFCCC 2015a; Bodansky et al. 2017b), and (2) an 'enhanced transparency framework' that places extensive informational demands on parties, tailored to capacities, and establishes review processes to enable tracking of progress towards achievement of NDCs (Oberthür and Bodle 2016). In contrast to the Kyoto Protocol with its internationally inscribed targets and timetable for emissions reduction for developed countries, the Paris Agreement contains nationally determined contributions embedded in an international system of transparency and accountability for all countries (Doelle 2016; Maljean-Dubois and Wemaëre 2016) accompanied by a shared global goal, in particular in relation to a temperature limit.

14.3.2.1 Context and purpose

The preamble of the Paris Agreement lists several factors that provide the interpretative context for the Agreement (Carazo 2017; Bodansky et al. 2017b), including a reference to human rights. The human rights implications of climate impacts garnered particular attention in the lead up to Paris (Duyck 2015; Mayer 2016b). In particular, the Human Rights Council, its special procedures mechanisms, and the Office of the High Commissioner for Human Rights, through a series of resolutions, reports, and activities, advocated a rights-based approach to climate impacts, and sought to integrate this approach in the climate change regime. The Paris Agreement's preambular recital on human rights recommends that parties, 'when taking action to address human rights', take into account 'their respective obligations on human rights' (UNFCCC 2015a, preambular recital 14), a first for an environmental treaty (Knox 2016). The 'respective obligations' referred to in the Paris Agreement could potentially include those relating to the right to life (UNGA 1948, Art. 3, 1966, Art. 6), right to health (UNGA 1966b, Art. 12), right to development, right to an adequate standard of living, including the right to food (UNGA 1966b, Art. 11), which has been read to include the right to water and sanitation (CESCR 2002, 2010), the right to housing (CESCR 1991), and the right to self-determination, including as applied in the context of indigenous peoples (UNGA 1966a,b, Art. 1). In addition, climate impacts contribute to displacement and migration (Mayer and Crépeau 2016; McAdam 2016), and have disproportionate effects on women (Pearse 2017). There are differing views on the value and operational impact of the human rights recital in the Paris Agreement (Adelman 2018; Boyle 2018; Duyck et al. 2018; Rajamani 2018; Savaresi 2018; Knox 2019). Notwithstanding proposals from some parties and stakeholders to mainstream and operationalise human rights in the climate regime post-Paris (Duyck et al. 2018), and references to human rights in COP decisions, the 2018 Paris Rulebook contains limited and guarded references to human rights (Duyck 2019; Rajamani 2019) (see Section 14.5.1.2). In addition to the reference to human rights, the preamble also notes the importance of 'ensuring the integrity of all ecosystems, including oceans and the protection of biodiversity' which provides opportunities for integrating and mainstreaming other environmental protections.

The overall purpose of international cooperation through the Paris Agreement is to enhance the implementation of the UNFCCC, including its objective of stabilising atmospheric GHG concentrations 'at a level that would prevent dangerous anthropogenic interference with the climate system' (UNFCCC 1992, Art. 2). The Paris Agreement aims to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty, by inter alia '[h]olding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels' (UNFCCC 2015a, Art. 2(1)(a)). There is an ongoing structured expert dialogue under the UNFCCC in the context of the second periodic review of the long-term global goal (the first was held between 2013-2015) aimed at enhancing understanding of the long-term global goal, pathways to achieving it, and assessing the aggregate effect of steps taken by parties to achieve the goal.

Some authors interpret the Paris Agreement's temperature goal as a single goal with two inseparable elements, the well below 2°C goal pressing towards 1.5°C (Rajamani and Werksman 2018), but others interpret the goal as a unitary one of 1.5°C with minimal overshoot (Mace 2016). Yet others interpret 1.5° C as the limit within the long-term temperature goal, and that it 'signals an increase in both the margin and likelihood by which warming is to be kept below 2°C (Schleussner et al. 2016). Although having a long-term goal has clear advantages, the literature highlights the issue of credibility, given the lengthy timeframe involved (Urpelainen 2011), and stresses that future regulators may have incentives to relax current climate plans, which could have a significant effect on the achieved GHG stabilisation level (Gerlagh and Michielsen 2015).

As the risks of adverse climate impacts, even with a 'well below' 2°C increase, are substantial, the purpose of the Paris Agreement extends to increasing adaptive capacity and fostering climate resilience (UNFCCC 2015a, Art. 2(1)(b)), as well as redirecting investment and finance flows (UNFCCC 2015a, Art (2)(1)(c); Thorgeirsson 2017). The finance and adaptation goals are not quantified in the Paris Agreement itself but the temperature goal and the pathways they generate may, some argue, enable a quantitative assessment of the resources necessary to reach these goals, and the nature of the impacts requiring adaptation (Rajamani and Werksman 2018). The decision accompanying the Paris Agreement resolves to set a new collective quantified finance goal prior to 2025 (not explicitly limited to developed countries), with USD100 billion yr^{-1} as a floor (UNFCCC 2016a, para. 53; Bodansky et al. 2017b). Article 2 also references sustainable development and poverty eradication, and thus implicitly underscores the need to integrate the SDGs in the implementation of the Paris Agreement (Sindico 2016).

The Paris Agreement's purpose is accompanied by an expectation that the Agreement 'will be' implemented to 'reflect equity and the principle of common but differentiated responsibilities and respective capabilities (CBDRRC), in the light of different national circumstances' (UNFCCC 2015a, Art. 2.2). This provision generates an expectation that parties will implement the agreement to reflect CBDRRC, and is not an obligation to do so (Rajamani 2016a). Further, the inclusion of the term 'in light of different national circumstances' introduces a dynamic element into the interpretation of the CBDRRC principle. As national circumstances evolve, the application of the principle will also evolve (Rajamani 2016a). This change in the articulation of the CBDRRC principle is reflected in the shifts in the nature and extent of differentiation in the climate change regime (Maljean-Dubois 2016; Rajamani 2016a; Voigt and Ferreira 2016a), including through a shift towards 'procedurally-oriented differentiation' for developing countries (Huggins and Karim 2016).

Although NDCs are developed by individual state parties, the Paris Agreement requires that these are undertaken by parties 'with a view' to achieving the Agreement's purpose and collectively 'represent a progression over time' (UNFCCC 2015a, Art. 3). The Paris Agreement also encourages parties to align the ambition of their NDCs with the temperature goal through the Agreement's 'ambition cycle', thus imparting operational relevance to the temperature goal (Rajamani and Werksman 2018).

Article 4.1 contains a further non-binding requirement that parties 'aim' to reach global peaking of GHG 'as soon as possible' and to undertake rapid reductions thereafter to achieve net zero GHG emissions 'in the second half of the century'. Some argue this implies a need to reach net zero GHG emissions in the third quarter of the 21st century (Rogelj et al. 2015; IPCC 2018b; ch2, table 2.4; cross-chapter box 3 on net zero targets). To reach net zero CO_2 around 2050, in the short-term global net human-caused CO_2 emissions would need to fall by about 45% - 60% from 2010 levels by 2030 (IPCC 2018b). Achieving the Paris Agreement's Article 4.1 aim potentially implies imply that global warming will peak and then follow a gradually declining path, potentially to below 1.5°C warming (Rogelj et al. 2021).

Albeit non-binding, Article 4.1 has acted as a catalyst for several national net-zero GHG targets, as well net zero CO_2 and GHG targets across local governments, sectors, businesses, and other actors (Day et al. 2020). There is a wide variation in the targets that have been adopted – in terms of their legal character (policy statement, executive order or national legislation), scope (GHGs or CO_2) and coverage (sectors or economy-wide). National net-zero targets could be reflected in the long-term strategies that states are urged to submit under Article 4.19, but only a few states have submitted such strategies thus far. The Paris Rulebook, agreed at the Agreement's first meeting of the parties in 2018, further strengthens the operational relevance of the temperature goal by requiring parties to provide information when submitting their NDCs on how these contribute towards achieving the objective identified in UNFCCC Article 2, and Paris Agreement Articles 2.1 (a) and 4.1 (UNFCCC 2019b, Annex I, para. 7), Parties could in this context include information on how their short-term actions align with their long-tern net zero GHG or CO_2 targets thereby enhancing the credibility of their long-term goals.

At last count 131 countries had adopted or had net zero targets (whether of carbon or GHG) in the pipeline, covering 72% of global emissions. If these targets are fully implemented some estimate that this could bring temperature increase down to 2-2.4°C by 2100 as compared to current policies which are estimated to lead to a temperature increase of 2.9–3.2 °C, and NDCs submitted to the Paris Agreement which are estimated to lead to a temperature increase of 2.4-2.9°C (Höhne et al. 2021).

It is worth noting that Article 4.1 recognizes that 'peaking will take longer for developing countries' and that the balance between emissions and removals needs to be on the 'basis of equity, and in the context of sustainable development and efforts to eradicate poverty.' This suggests that not all countries are expected to reach net zero GHG emissions at the same time, or in the same manner. If global cost-effective 1.5 °C and 2 °C scenarios from integrated assessment models are taken, without applying an equity principle, the results suggest that domestic net zero GHG and CO_2 emissions would be reached a decade earlier than the global average in Brazil and the USA and later in India and Indonesia (van Soest et al. 2021). By contrast if equity principles are taken into account, countries like Canada and the EU would be expected to phase-out earlier than the cost-optimal scenarios indicate, and countries like China and Brazil could phase out emissions later, as well as other countries with lower per-capita emissions (van Soest et al. 2021). Some suggest that the application of such fairness considerations could bring forward the net zero GHG date for big emitting countries by up to 15 to 35 years as compared to the global least-cost scenarios (Lee et al. 2021b). In any case, reaching net-zero GHG emissions requires to some extent the use of carbon dioxide removal (CDR) methods as there are important sources of non-CO_2 GHGs, such as methane and nitrous oxide, that cannot be fully eliminated resorting to carbon dioxide removal (CDR) methods (IPCC 2018b). However, there are divergent views on different CDR methods, policy choices determine the degree to which and the type of CDR methods that are considered and there is a patchwork of applicable regulatory instruments. There are also uncertainties and governance challenges associated with CDR methods which render tracking progress against net zero GHG emissions challenging (Mace et al. 2021). Researchers have noted that given the key role of CDR in net-zero targets and 1.5 °C compatible pathways, and the fact that it presents 'significant costs to current and future generations,' it is important to consider what an equitable distribution of CDR might look like (UNFCCC 2019c; Day et al. 2020; Lee et al. 2021b).

14.3.2.2 NDCs, progression and ambition

Each party to the Paris Agreement has a procedural obligation to 'prepare, communicate and maintain' successive NDCs 'that it intends to achieve.' Parties have a further procedural obligation to 'pursue domestic mitigation measures' (UNFCCC 2015a, Art. 4.2). These procedural obligations are coupled with an obligation of conduct to make best efforts to achieve the objectives of NDCs (Rajamani 2016a; Mayer 2018b). Many states have adopted climate policies and laws, discussed in Chapter 13, and captured in databases (LSE 2020).

The framing and content of NDCs is thus largely left up to parties, although certain normative expectations apply. These include developed country leadership through these parties undertaking economy-wide absolute emissions reduction targets (UNFCCC 2015a, Art. 4.4), as well as 'progression' and 'highest possible ambition' reflecting 'common but differentiated responsibilities and respective capabilities in light of different national circumstances' (Art 4.3). There is 'a firm expectation' that for every five-year cycle a party puts forward a new or updated NDC that is 'more ambitious than their last' (Rajamani 2016a). While what represents a party's highest possible ambition and progression is not prescribed by the Agreement or elaborated in the Paris Rulebook (Rajamani and Bodansky 2019), these obligations could be read to imply a due diligence standard (Voigt and Ferreira 2016b).

In communicating their NDCs every five years (UNFCCC 2015a, Art. 4.9), all parties have an obligation to 'provide the information necessary for clarity, transparency and understanding' (UNFCCC 2015a, Art. 4.8). These requirements are further elaborated in the Paris Rulebook (Doelle 2019; UNFCCC 2019b). This includes requirements — for parties' second and subsequent NDCs — to provide quantifiable information on the reference point e.g. base year, reference indicators and target relative to the reference indicator (UNFCCC 2019b, Annex I, para 1). It also requires parties to provide information on how they consider their contribution 'fair and ambitious in light of different national circumstances', and how they address the normative expectations of developed country leadership, progression and highest possible ambition (UNFCCC 2019b, Annex I, para 6). However, parties are required to provide the enumerated information only 'as applicable' to their NDC (UNFCCC 2019b, Annex I, para 7). This allows parties to determine the informational requirements placed on them through their choice of NDC. In respect of parties' first NDCs or NDCs updated by 2020, such quantifiable information 'may' be included, 'as appropriate', signalling a softer requirement, although parties are 'strongly encouraged' to provide this information (UNFCCC 2019b, Annex I, para 9).

Parties' first NDCs submitted to the provisional registry maintained by the UNFCCC Secretariat vary in terms of target type, reference year or points, time frames, and scope and coverage of GHGs. A significant number of NDCs include adaptation, and several NDCs have conditional components, for instance, being conditional on the use of market mechanisms or on the availability of support (UNFCCC 2016b). There are wide variations across NDCs. Uncertainties are generated through interpretative ambiguities in the assumptions underlying NDCs, (Rogelj et al. 2017). According to the assessment in this report, current policies lead to median global GHG emissions of 63 $GtCO_2$-eq with a full range of 57-70 by 2030 and unconditional and conditional NDCs to 59 (55-65) and 56 (52-61) $GtCO_2$-eq, respectively (Chapter 4, Table 4.1). Many omit important mitigation sectors, provide little detail on financing implementation, and are not effective in meeting assessment and review needs (Pauw et al. 2018). Although, it is estimated that the land-use sector could contribute as much as 20% of the full mitigation potential of all the intended NDC targets (Forsell et al. 2016) , there are variations in how the land-use component is included, and the related information provided, leading to large uncertainties on whether and how these will contribute to the achievement of the NDCs (Grassi et al. 2017; Obergassel et al. 2017a; Benveniste et al. 2018; Fyson and Jeffery 2019; Forsell et al. 2016). All these variations make it challenging to aggregate the efforts of countries and compare them to each other (Carraro 2016). Although parties attempted to discipline the variation in NDCs, including whether they could be conditional, through elaborating the 'features' of NDCs in the Rulebook, no agreement was possible on this. Thus, parties continue to enjoy considerable discretion in the formulation of NDCs (Rajamani and Bodansky 2019; Weikmans et al. 2020).

There are several approaches to evaluating NDCs incorporating indicators such as CO_2 emissions, GDP, energy intensity of GDP, CO_2 per energy unit, CO_2 intensity of fossil fuels, and share of fossil fuels in total energy use (Peters et al. 2017). However, some favour approaches that use metrics beyond emissions such as infrastructure investment, energy demand, or installed power capacity (Iyer et al. 2017; Jeffery et al. 2018). One approach is to combine the comparison of aggregate NDC emissions using Integrated Assessment Model scenarios with modelling of NDC scenarios directly, and carbon budget analyses (Jeffery et al. 2018). Another approach is to engage in a comprehensive assessment of multiple indicators that reflect the different viewpoints of the parties under the UNFCCC (Aldy et al. 2017; Höhne et al. 2018). These different approaches are described in greater depth in Chapter 4, section 4.2.2.

It is clear, however, that the NDCs communicated by parties for the 2020-2030 period are insufficient to achieve the temperature goal (den Elzen et al. 2016; Rogelj et al. 2016; Schleussner et al. 2016; Robiou du Pont and Meinshausen 2018; UNEP 2018a; Alcaraz et al. 2019; UNEP 2019, 2020), and the emissions gap is larger than ever (Christensen and Olhoff 2019) (see Chapter 4). The IPCC 1.5ºC Report notes that pathways that limit global warming to 1.5°C with no or limited overshoot show up to 40-50% reduction of total GHG emissions from 2010 levels by 2030, and that current pathways reflected in the NDCs are consistent with cost-effective pathways that result in a global warming of about 3°C by 2100 ((IPCC 2018b) SPM, D.1.1). Analysis by the UNFCCC Secretariat of the second round of those NDCs submitted until into October 2021 suggests that 'total global GHG emission level, taking into account full implementation of all the latest NDCs (including their conditional elements), implies possibility of global emissions peaking before 2030'. However, such total global GHG emission level in 2030 is still expected to be 15.9% above the 2010 level. This 'implies an urgent need for either a significant increase in the level of ambition of NDCs between now and 2030 or a significant overachievement of the latest NDCs, or a combination of both.' (UNFCCC 2021a).

Many NDCs with conditional elements may not be feasible as the conditions are not clearly defined and existing promises of support are insufficient (Pauw et al. 2020). Moreover, 'leadership by conditional commitments' (when some states promise to take stronger commitments if others do so as well), and the system of pledge-and-review, may lead to decreasing rather than deeper contributions over time

(Helland et al. 2017). Some note, however, that many of the NDCs are conservative and may be overachieved, that NDCs may be strengthened over time as expected under the Paris Agreement, and there are significant non-state actions that have not been adequately captured in the NDCs (Höhne et al. 2017). Further, if all NDCs with and without conditional elements are implemented, net land use, land use change and forestry emissions will decrease in 2030 compared to 2010 levels, but large uncertainties remain on how Parties estimate, project and account for emissions and removals from this sector (Forsell et al. 2016; Fyson and Jeffery 2019). According to the estimates in Table 4.3 (Chapter 4), communicated unconditional commitments imply about a 7% reduction of world emissions by 2030, in terms of Kyoto GHGs, compared to a scenario where only current policies are in place. If conditional commitments are also included, the reduction in world emissions by 2030 would be about 12%.

In this context, it should be noted that many NDCs have been formulated with conditional elements, and such NDCs require international cooperation on finance, technology and capacity-building (Kissinger et al. 2019), potentially including through Article 6 in the form of bilateral agreements and market mechanisms (UNFCCC 2016b). More broadly, some argue that there is a 'policy inconsistency' between the facilitative, 'bottom up' architecture of the Paris Agreement, and both the setting of the long-term temperature goal, as well as expectations that it will be delivered (Geden 2016b). As Figure 14.2 shows, there is a large share of additional effort needed to reach a 1.5ºC compatible path by 2030 (and even a 2ºC compatible path). International coordination and cooperation are crucial in enhancing the ambition of current pledges, as countries will be more willing to increase their ambition if matched by other countries (coordination) and if cost-minimising agreements between developed and developing countries, through Article 6 and other means, are fully developed (cooperation) (Sælen 2020).

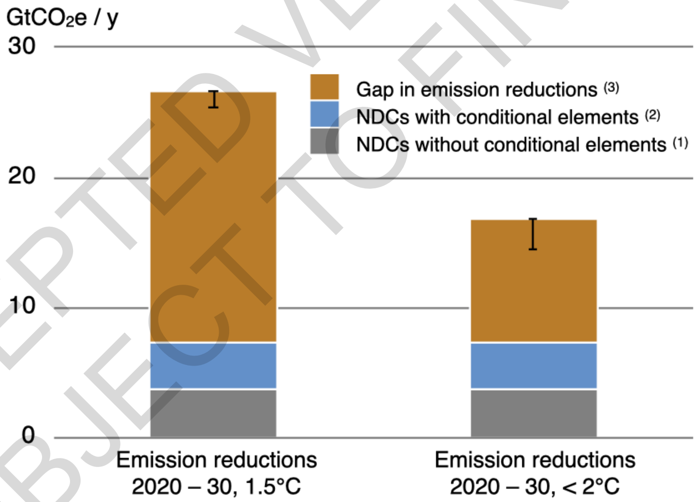

Figure 14.2 The role of international cooperation in the reductions in annual emissions by 2030 needed to follow a 1.5°C (respectively < 2°C) cost-effective path from 2020 onwards. The figure represents the additional contribution of pledges included in the NDCs over current policies at the global level, and the remaining gap in emission reductions needed to move from current policies to cost-effective long-term mitigation pathways for limiting warming to 1.5°C with low (<0.1°C) overshoot (50% chance), respectively for limiting warming to 2°C (66% chance). Median values are used, showing the confidence interval for the total effort. See Figure 1 in Cross-Chapter Box 4, and Tables 4.2 and 4.3 for details. (1) The grey share represents NDCs with abatement efforts pledged without any conditions (called "unconditional" in the literature). They are based mainly on domestic abatement actions, although countries can use international cooperation to meet their targets. (2) The blue share represents NDCS with conditional components. They require international cooperation, for example bilateral agreements under article 6, financing or monetary and/or technological transfers. (3) The remaining gap in emission reductions – the orange share – can potentially be achieved through national and international actions.

International coordination of more ambitious efforts promotes global ambition and international cooperation provides the cost-saving basis for more ambitious NDCs.

14.3.2.3 NDCs, fairness and equity

The Paris Agreement encourages Parties, while submitting their NDCs, to explain how these are 'fair and ambitious' (UNFCCC 2015a, Art. 4.8 read with UNFCCC 2016a, para. 27). The Rulebook obliges Parties to provide information on 'fairness considerations, including reflecting on equity' as applicable to their NDC (Rajamani and Bodansky 2019; UNFCCC 2019b paras 7a and 9, Annex, paras 6(a) and (b)). Although equity within nations and between communities is also important, much of the literature on fairness and equity in the context of NDCs focuses on equity between nations.

In the first round of NDCs, most Parties declared their NDCs as fair (Robiou du Pont et al. 2017). Their claims, however, were largely unsubstantiated or drawn from analysis by in-country experts (Winkler et al. 2018). At least some of the indicators Parties have identified in their NDCs as justifying the 'fairness' of their contributions, such as a 'small share of global emissions', 'cost-effectiveness' and assumptions that privilege current emissions levels ('grandfathering') are not, according to one group of scholars, in accordance with principles of international environmental law (Rajamani et al. 2021) . Moreover, the NDCs reveal long-standing institutional divisions and divergent climate priorities between Annex I and non-Annex I Parties, suggesting that equity and fairness concerns remain salient (Stephenson et al. 2019). Fairness concerns also affect the share of carbon dioxide removal (CDR) responsibilities for major emitters if they delay near-term mitigation action (Fyson et al. 2020).

It is challenging, however, to determine 'fair shares', and address fairness and equity in a world of voluntary climate contributions (Chan 2016a), in particular, since these contributions are insufficient (see above Section 14.3.2.2.). Self-differentiation in contributions has also led to fairness and equity being discussed in terms of individual nationally determined contributions rather than between categories of countries (Chan 2016a). In the climate change regime, one option is for Parties to provide more rigorous information under the Paris Agreement to assess fair shares (Winkler et al. 2018), and another is for Parties to articulate what equity principles they have adopted in determining their NDCs, how they have operationalised these principles, and explain their mitigation targets in terms of the portion of the appropriated global budget (Hales and Mackey 2018).

Equity is critical to addressing climate change, including through the Paris Agreement (Klinsky et al. 2017), however, since the political feasibility of developing equity principles within the climate change regime is low, the onus is on mechanisms and actors outside the regime to develop these (Lawrence and Reder 2019). Equity and fairness concerns are being raised in national and regional courts that are increasingly being asked to determine if the climate actions pledged by states are adequate in relation to their fair share (The Supreme Court of the Netherlands 2019; European Court of Human Rights 2020; German Constitutional Court 2021), as it is only in relation to such a 'fair share' that the adequacy of a state's contribution can be assessed in the context of a global collective action problem (see chapter 13.5.5 for a discussion of national climate litigation). Some domestic courts have stressed that as climate change is a global problem of cumulative impact, all emissions contribute to the problem regardless of their relative size and there is a clear articulation under the UNFCCC and Paris Agreement for developed countries to 'take the lead' in addressing GHG emissions (Preston 2020). Given the limited avenues for multilateral determination of fairness, several researchers have argued that the onus is on the scientific community to generate methods to assess fairness (Herrala and Goel 2016; Lawrence and Reder 2019). Peer-to-peer comparisons also potentially create pressure for ambitious NDCs (Aldy et al. 2017).

There are a range of options to assess or introduce fairness. These include: adopting differentiation in financing rather than in mitigation (Gajevic Sayegh 2017); adopting a carbon budget approach (Hales and Mackey 2018; Alcaraz et al. 2019), which may occur through the transparency processes (Hales and Mackey 2018); quantifying national emissions allocations using different equity approaches, including those reconciling finance and emissions rights distributions (Robiou du Pont et al. 2017); combining equity concepts in a bottom-up manner using different sovereign approaches (Robiou du Pont and Meinshausen 2018), using data on adopted emissions targets to find an ethical framework consistent with the observed distribution (Sheriff 2019); adopting common metrics for policy assessment (Bretschger 2017); and developing a template for organising metrics on mitigation effort - emission reductions, implicit prices, and costs - for both ex ante and ex post review (Aldy et al. 2017). The burden of agricultural mitigation can also be distributed using different approaches to effort sharing (responsibility, capability, need, equal cumulative per-capita emissions) (Richards et al. 2018). Further, there are temporal (inter-generational) and spatial (inter-regional) dimensions to the distribution of the mitigation burden, with additional emissions reductions in 2030 improving both inter-generational and inter-regional equity (Liu et al. 2016). Some of the equity approaches rely on 'grandfathering' as an allocation principle, which some argue has led to 'cascading biases' against developing countries (Kartha et al. 2018), and is morally 'perverse' (Caney 2011). While no country's NDC explicitly supports the grandfathering approach, many countries describe as 'fair and ambitious' NDCs that assume grandfathering as the starting point (Robiou du Pont et al. 2017). It is worth noting that the existence of multiple metrics associated with a range of equity approaches, has implications for how the ambition and 'fair' share of each state is arrived at, some average out multiple approaches and indicators (Hof et al. 2012; Meinshausen et al. 2015; Robiou du Pont and Meinshausen 2018), others exclude indicators and approaches that do not, in their interpretation, accord with principles of international environmental law (Rajamani et al. 2021). One group of scholars have suggested that utilitarianism offers a 'ethically minimal and conceptually parsimonious' benchmark that promotes equity, climate and development (Budolfson et al. 2021).

14.3.2.4 Transparency and accountability

Although NDCs reflect a 'bottom-up', self-differentiated approach to climate mitigation actions, the Paris Agreement couples this to an international transparency framework designed, among other things, to track progress in implementing and achieving mitigation contributions (UNFCCC 2015a, Art. 13). This transparency framework builds on the processes that already exist under the UNFCCC. The transparency framework under the Paris Agreement s applicable to all Parties, although with flexibilities for developing country Parties that need it in light of their capacities (Mayer 2019). Each Party is required to submit a national inventory report, as well as 'the information necessary to track progress in implementing and achieving' its NDC, (UNFCCC 2015a, Art. 13.7) biennially (UNFCCC 2016a, para. 90). The Paris Rulebook requires all Parties to submit their national inventory reports using the 2006 IPCC Guidelines (UNFCCC 2019b, Annex, para. 20).

In relation to the provision of information necessary to track progress towards implementation and achievement of NDCs, the Paris Rulebook allows each party to choose its own qualitative or quantitative indicators (UNFCCC 2019k, Annex, para 65), a significant concession to national sovereignty (Rajamani and Bodansky 2019). The Rulebook phases in common reporting requirements for developed and developing countries (except LDCs and SIDS) at the latest by 2024 (UNFCCC 2019k, para. 3), but offers flexibilities in 'scope, frequency, and level of detail of reporting, and in the scope of the review' for those developing countries that need it in light of their capacities (UNFCCC 2019k, Annex, para. 5). Some differentiation also remains for information on support provided to developing countries (Winkler et al. 2017), with developed country parties required to report such information biennially, while others are only 'encouraged' to do so (UNFCCC 2015a, Art. 9.7).

The information provided by Parties in biennial transparency reports and GHG inventories will undergo technical expert review, which must include assistance in identifying capacity-building needs for developing country parties that need it in light of their capacities. Each Party is also required to participate in a 'facilitative, multilateral consideration of progress' of implementation and achievement of its NDC. Although the aim of these processes is to expose each Party's actions on mitigation to international review, thus establishing a weak form of accountability for NDCs at the international level, the Rulebook circumscribes the reach of these processes (Rajamani and Bodansky 2019). The technical expert review teams are prohibited in mandatory terms from making 'political judgments' or reviewing the 'adequacy or appropriateness' of a party's NDC, domestic actions, or support provided (UNFCCC 2019k, Annex, para. 149). This, among other such provisions, has led some to argue that the scope and practice of existing transparency arrangements reflects rather than mediates ongoing disputes around responsibility, differentiation and burden sharing, and thus there is limited answerability through transparency (Gupta and van Asselt 2019). There are also limits to the extent that the enhanced transparency framework will reduce ambiguities, and associated uncertainties, for instance, in how LULUCF is incorporated into the NDCs (Fyson and Jeffery 2019) and lead to increased ambition (Weikmans et al. 2020). More broadly, there has been 'weak' translation of transparency norms into accountability (Ciplet et al. 2018). Hence, the Paris Agreement's effectiveness in ensuring NDCs are achieved will depend on additional accountability pathways at the domestic level involving political processes and civil society engagement (Jacquet and Jamieson 2016; van Asselt 2016; Campbell-Duruflé 2018a; Karlsson-Vinkhuyzen et al. 2018).

14.3.2.5 Global stocktake

The Paris Agreement's transparency framework is complemented by the global stocktake, which will take place every five years (starting in 2023) and assess the collective progress towards achieving the Agreement's purpose and long-term goals (UNFCCC 2015a, Art. 14). The scope of the global stocktake is comprehensive – covering mitigation, adaptation and means of implementation and support – and the process is to be facilitative and consultative. The Paris Rulebook outlines the scope of the global stocktake to include social and economic consequences and impacts of response measures, and loss and damage associated with the adverse effects of climate change (UNFCCC 2019f, paras. 8-10).

The global stocktake is to occur 'in the light of equity and the best available science.' While the focus of the global stocktake is on collective and not individual progress towards the goals of the Agreement, the inclusion of equity in the global stocktake enables a discussion on equitable burden sharing (Rajamani 2016a; Winkler 2020), and for equity metrics to be factored in (Robiou du Pont and Meinshausen 2018). The Paris Rulebook includes consideration of the modalities and sources of inputs for the global stocktake (UNFCCC 2019f, paras 1, 2, 13, 27, 31, 36h and 37g), which arguably will result in equity being factored into the outcome of the stocktake (Winkler 2020). The Rulebook does not, however, some argue, resolve the tension between the collective nature of the assessment that is authorised by the stocktake and the individual assessments required to determine relative 'fair share' (Rajamani and Bodansky 2019; Zahar 2019).

The global stocktake is seen as crucial to encouraging parties to increase the ambition of their NDCs (Huang 2018; Hermwille et al. 2019; Milkoreit and Haapala 2019) as its outcome 'shall inform Parties in updating and enhancing, in a nationally determined manner, their actions and support' (Art 14.3) (Rajamani 2016a; Friedrich 2017; Zahar 2019). The Rulebook provides for the stocktake to draw on a wide variety of inputs sourced from a full range of actors, including 'non-Party stakeholders' (UNFCCC 2019f, para. 37). However, the Rulebook specifies that the global stocktake will be 'a Party-driven process' (UNFCCC 2019f, para. 10), will not have an 'individual Party focus', and will include only 'non-policy prescriptive consideration of collective progress' (UNFCCC 2019f, para. 14).

14.3.2.6 Conservation of sinks and reservoirs, including forests

Article 5 of the Paris Agreement calls for parties to take action to conserve and enhance sinks and reservoirs of greenhouse gases, including biomass in terrestrial, coastal, and marine ecosystems, and encourages countries to take action to support the REDD+ framework under the Convention. The explicit inclusion of land use sector activities, including forest conservation, is potentially, while cautiously, a 'game changer' as it encourages countries to safeguard ecosystems for climate mitigation purposes (Grassi et al. 2017). Analyses of parties' NDCs shows pledged mitigation from land use, and forests in particular, provides a quarter of the emission reductions planned by parties and, if fully implemented, would result in forests becoming a net sink of carbon by 2030 (Forsell et al. 2016; Grassi et al. 2017).

A key action endorsed by Article 5 is REDD+, which refers to initiatives established under the UNFCCC for reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries. It remains an evolving concept and some identified weaknesses are being addressed, including the issues of scale (project-based vs sub-national jurisdictional approach), problems with leakage, reversal, benefit sharing, as well as safeguards against potential impacts on local and indigenous communities. Nevertheless, REDD+ shows several innovations under the climate regime with regard to international cooperation. The legal system for REDD+ manages to reconcile flexibility (creating consensus) and legal security. It shows a high standard of effectiveness (Dellaux 2017).

Article 5.2 encourages parties to implement and support the existing framework for REDD+, including through 'results-based payments' i.e. provision of financial payments for verified avoided or reduced forest carbon emissions (Turnhout et al. 2017). The existing REDD+ framework set up under decisions of the UNFCCC COP includes the Warsaw Framework for REDD+, which specifies modalities for measuring, reporting and verifying (MRV) greenhouse gas emissions and removals. This provides an essential tool for linking REDD+ activities to results-based finance (Voigt and Ferreira 2015). Appropriate finance support for REDD+ is also considered critical to move from its inclusion in many countries' NDCs to implementation on the ground (Hein et al. 2018). Since public finance for REDD+ is limited, private sector participation is expected by some to leverage REDD+ (Streck and Parker 2012; Henderson et al. 2013; Pistorius and Kiff 2015; Seymour and Busch 2016; Ehara et al. 2019). Article 5.2 also encourages parties' support for 'alternative policy approaches' to forest conservation and sustainable management such as 'joint mitigation and adaptation approaches.' It reaffirms the importance of incentivising, as appropriate, non-carbon benefits associated with such approaches (e.g. improvements in the livelihoods of forest-dependent communities, facilitating poverty reduction and sustainable development). This provision, along with the support for non-market mechanisms in Article 6 (discussed below), is seen as an avenue for cooperative joint mitigation-adaptation and non-market REDD+ activities with co-benefits for biodiversity conservation (Gupta and Dube 2018).

14.3.2.7 Cooperative approaches

Article 6 of the Paris Agreement provides for voluntary cooperative approaches. Its potential importance in terms of project-based cooperation should be viewed against the background of key lessons from the market-based mechanisms under the Kyoto Protocol, particularly the Clean Development Mechanism (CDM). The CDM has been used for implementing bilateral strategies and unilateral (non-market) actions for instance in India (Phillips and Newell 2013), hence arguably covering all the mechanisms now included in Article 6 of the Paris Agreement. As we describe in section 14.3.3.1, below, ex-post evaluation of the Kyoto market mechanisms, in particular the CDM, have been at-best mixed. However, Article 6 goes beyond the project-based approach followed by the CDM, as hinted by the emerging landscape of activities based on Article 6 (Greiner et al. 2020), such as the bilateral treaty signed under the framework of Article 6 in October 2020 by Switzerland and Peru (see section 14.4.4).

This experience from the CDM is relevant to the implementation of Article 6 (4) of the Paris Agreement. It addresses a number of specific types of cooperative approaches, including those involving the use of internationally transferred mitigation outcomes (ITMOs) towards NDCs, a 'mechanism to contribute to mitigation and support sustainable development', and a framework for non-market approaches such as many aspects of REDD+.

Article 6.1 recognises the role that cooperative approaches can play, on a voluntary basis, in implementing parties' NDCs 'in order to allow for higher ambition' in their mitigation actions and to promote sustainable development and environmental integrity. Article 6.2 indicates that ITMOs can originate from a variety of sources, and that parties using ITMOs to achieve their NDCs shall promote sustainable development, ensure environmental integrity, ensure transparency, including in governance, and apply 'robust accounting' in accordance with CMA guidance to prevent double counting. While this provision, unlike Article 17 of the Kyoto Protocol, does not create an international carbon market, it enables parties to pursue this option should they choose to do so, for example, through the linking of domestic or regional carbon markets (Marcu 2016; Müller and Michaelowa 2019). Article 6.2 could also be implemented in other ways, including direct transfers between governments, linkage of mitigation policies across two or more parties, sectoral or activity crediting mechanisms, and other forms of cooperation involving public or private entities, or both (Howard 2017).

Assessments of the potential of Article 6.2 generally find that ITMOs are likely to result in cost reductions in achieving mitigation outcomes, with the potential for such reductions to enhance ambition and accelerate parties' progression of mitigation pledges across NDC cycles (Fujimori et al. 2016; Gao et al. 2016; Mehling 2019). However, studies applying insights from the CDM highlight environmental integrity risks associated with using ITMOs under the Paris Agreement given the challenges that the diverse scope, metrics, types and timeframes of NDC targets pose for robust accounting (Schneider and La Hoz Theuer 2019) and the potential for transfers of 'hot air' as occurred under the Kyoto Protocol (La Hoz Theuer et al. 2019). These studies collectively affirm that robust governance on accounting for ITMOs, and for reporting and review, will be critical to ensuring the environmental integrity of NDCs making use of them (Mehling 2019; Müller and Michaelowa 2019).

Article 6.4 concerns the mitigation mechanism, with some similarities to the Kyoto Protocol's CDM. Unlike the CDM, there is no restriction on which parties can host mitigation projects and which parties can use the resulting emissions reductions towards their NDCs (Marcu 2016). This central mechanism will operate under the authority and guidance of the CMA, and is to be supervised by a body designated by the CMA (Marcu 2016).

The Article 6.4 central mechanism is intended to promote mitigation while fostering sustainable development. The decision adopting the Paris Agreement specifies experience with Kyoto market mechanisms as a basis for the new mitigation mechanism (UNFCCC 2016a, para. 37(f)). Compared with the CDM under the Kyoto Protocol, the central mechanism has a more balanced focus on both climate and development objectives, and a stronger political mandate to measure sustainable development impact and to verify that the impacts are 'real, measurable, and long-term' (Olsen et al. 2018). There are also opportunities to integrate human rights into the central mechanism (Obergassel et al. 2017b; Calzadilla 2018). It is further subject to the requirement that it must deliver 'an overall mitigation in global emissions,' which is framed by the general objectives of Article 6 for cooperation to enhance ambition (Kreibich 2018).

Negotiations over rules to operationalise Article 6 have thus far proven intractable, failing to deliver both at COP-24 in Katowice in 2018, where the rest of the Paris Rulebook was agreed, and in COP-25 in Madrid in 2019. Ongoing points of negotiation have included: whether to permit the carryover and use of Kyoto CDM credits and AAUs into the Article 6.4 mechanism, whether to impose a mandatory share of proceeds on Article 6.2 mechanism to fund adaptation, like for Article 6.4; and whether and how credits generated under Article 6.4 should be subject to accounting rules under Article 6.2 (Michaelowa et al. 2020a).

14.3.2.8 Finance flows

Finance is the first of three means of support specified under the Paris Agreement to accomplish its objectives relating to mitigation (and adaptation) (UNFCCC 2015a, Art. 14.1). This sub-section discusses the provision made in the Paris Agreement for international cooperation on finance. Section

14.4.1 below considers broader cooperative efforts on public and private finance flows for climate mitigation, including by multilateral development banks and through instruments such as green bonds.

As highlighted above, the objective of the Paris Agreement includes the goal of '[m]aking finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development' (UNFCCC 2015a, Art 2.1(c)). Alignment of financial flows, and in some cases provision of finance will be critical to the achievement of many parties' NDCs, particularly those that are framed in conditional terms (Zhang and Pan 2016; Kissinger et al. 2019) (see further Chapter 15 on investment and finance).

International cooperation on climate finance represents 'a complex and fragmented landscape' with a range of different mechanisms and forums involved (Pickering et al. 2017; Roberts and Weikmans 2017). These include entities set up under the international climate change regime, such as the UNFCCC financial mechanism, with the Global Environment Facility (GEF) and Green Climate Fund (GCF) as operating entities; special funds, such as the Special Climate Change Fund, the Least Developed Countries Fund (both managed by the GEF), and the Adaptation Fund established under the Kyoto Protocol; the Standing Committee on Finance, a constituted body which assists the COP in exercising its functions with respect to the UNFCCC financial mechanism; and other bodies outside of the international climate change regime, such as the Climate Investment Funds (CIF) administered through multilateral development banks (the role of these banks in climate finance is discussed further in Section 14.4.1 below).

Pursuant to decisions adopted at the Paris and Katowice conferences, parties agreed that the operating entities of the financial mechanism – GEF and GCF – as well as the Special Climate Change Fund, the Least Developed Countries Fund, the Adaptation Fund and the Standing Committee on Finance, all serve the Paris Agreement (UNFCCC 2016a, paras 58 and 63, 2019e,g). The GCF, which became operational in 2015, is the largest dedicated international climate change fund and plays a key role in channelling financial resources to developing countries (Antimiani et al. 2017; Brechin and Espinoza 2017).

Much of the current literature on climate finance and the Paris Agreement focuses on the obligations of developed countries to provide climate finance to assist the implementation of mitigation and adaptation actions by developing countries. The principal provision on finance in the Paris Agreement is the binding obligation on developed country parties to provide financial resources to assist developing country parties (UNFCCC 2015a, Art 9.1). This provision applies to both mitigation and adaptation and is in continuation of existing developed country parties' obligations under the UNFCCC. This signals that the Paris Agreement finance requirements must be interpreted in light of the UNFCCC (Yamineva 2016). The novelty introduced by the Paris Agreement is a further expansion in the potential pool of donor countries as Article 9.2 encourages 'other parties' to provide or continue to provide such support on a voluntary basis. However, 'as part of the global effort, developed countries should continue to take the lead in mobilising climate finance', with a 'significant role' for public funds, and an expectation that such mobilisation of finance 'should represent a progression beyond previous efforts' Beyond this there are no new recognised promises (Ciplet et al. 2018). In the Paris Agreement parties formalized the continuation of the existing collective mobilization goal to raise 100 billion a year through 2025 in the context of meaningful mitigation actions and transparency on implementation. The Paris Agreement decision also provided for the CMA by 2025 to set a new collective quantified goal from a floor of USD100 billion yr^{-}, taking into account the needs and priorities of developing countries (UNFCCC 2016a, para. 53). This new collective goal on finance is not explicitly limited to developed countries and could therefore encompass finance flows from developing countries' donors (Bodansky et al. 2017b). Deliberations on setting a new collective quantified goal on finance is expected to be initiated at COP26 in 2021 (UNFCCC 2019g,e; Zhang 2019).

It is widely recognised that the USD100 billion yr^{-1} figure is a fraction of the broader finance and investment needs of mitigation and adaptation embodied in the Paris Agreement (Peake and Ekins 2017). One estimate, based on a review of 160 (I)NDCs, suggests the financial demand for both mitigation and adaptation needs of developing countries could reach USD474 billion yr^{-1} by 2030 (Zhang and Pan 2016). The OECD reports that climate finance provided and mobilised by developed countries was USD79.6 billion in 2019. This finance included four components: bilateral public, multilateral public (attributed to developed countries), officially supported export credits and mobilised private finance (OECD 2021) (See also Chapter 15.3.2, and Box 15.4).

More broadly, there is recognition of the need for better accounting, transparency and reporting rules to allow evaluation of the fulfilment of finance pledges and the effectiveness of how funding is used (Xu et al. 2016; Roberts et al. 2017; Jachnik et al. 2019; Roberts et al. 2021; Gupta and van Asselt 2019). There is also a concern about climate finance being new and additional though the Paris Agreement does not make an explicit reference to it, nor is there a clear understanding of what constitutes new and additional (UNFCCC 2018; Carty et al. 2020; Mitchell et al. 2021). Some authors see the 'enhanced transparency framework' of the Paris Agreement (see Section 14.3.2.4 above), and the specific requirements for developed countries to provide, biennially, indicative quantitative and qualitative information as well as report on financial support and mobilisation efforts (Articles 9.5 and 9.7), as promising marked improvements (Weikmans and Roberts 2019), including for the fairness of effort-sharing on climate finance provision (Pickering et al. 2015). Others offer a more circumspect view of the transformative capability of these transparency systems (Ciplet et al. 2018).

The more limited literature focusing on the specific finance needs of developing countries, particularly those expressed in NDCs conditional on international climate finance, suggests that once all countries have fully costed their NDCs, the demand for (public and private) finance to support NDC implementation is likely to be orders of magnitude larger than funds available from bilateral and multilateral sources. For some sectors, such as forestry and land-use, this could leave 'NDC ambitions ... in a precarious position, unless more diversified options are pursued to reach climate goals' (Kissinger et al. 2019). In addition, there is a need for fiscal policy reform in developing countries to ensure international climate finance flows are not undercut by public and private finance supporting unsustainable activities (Kissinger et al. 2019). During the 2018 Katowice conference, UNFCCC Parties requested the Standing Committee on Finance to prepare, every four years, a report on the determination of the needs of developing country Parties related to implementing the Convention and the Paris Agreement, for consideration by parties at COP26 (UNFCCC 2019c).

14.3.2.9 Technology development and transfer

Technology development and transfer is the second of three 'means of implementation and support' specified under the Paris Agreement to accomplish its objectives relating to mitigation (and adaptation) (UNFCCC 2015a, Art. 14.1). This sub-section discusses the provision made in the Paris Agreement for international cooperation on technology development and transfer. Section 14.4.2 below considers broader cooperative efforts on technology development and transfer under the UNFCCC. Both sections complement the discussion in Chapter 16.6 on the role of international cooperation in fostering transformative change.

The importance of technology as a means of implementation for climate mitigation obligations under the Paris Agreement is evident from parties' NDCs. Of the 168 NDCs submitted as of June 2019, 109 were expressed as conditional upon support for technology development and transfer, with 70 parties requesting technological support for both mitigation and adaptation, and 37 parties for mitigation only (Pauw et al. 2020). Thirty-eight LDCs (79%) and 29 SIDS made their NDCs conditional on technology transfer, as did 50 middle-income countries (Pauw et al. 2020).

While technology is seen as a key means of implementation and support for Paris Agreement commitments, the issue of technology development and the transfer of environmentally sound technologies for climate mitigation was heavily contested between developed and developing countries in the Paris negotiations, and these differences are likely to persist as the Paris Agreement is implemented (Oh 2019). Contestations continued in negotiations for the Paris Rulebook, particularly regarding the meaning of technological innovation, which actors should be supported, and how support should be provided by the UNFCCC (Oh 2020a).

Article 10 of the Paris Agreement articulates a shared 'long-term vision on the importance of fully realising technology development and transfer in order to improve resilience to climate change and to reduce greenhouse gas emissions' (UNFCCC, 2015, Art. 10.1). All parties are required 'to strengthen cooperative action on technology development and transfer' (UNFCCC, 2015, Art. 10.2). In addition, support, including financial support, 'shall be provided' to developing country parties for the implementation of Article 10, 'including for strengthening cooperative action on technology development and transfer at different stages of the technology cycle, with a view to achieving a balance between support for mitigation and adaptation' (UNFCCC, 2015, Art. 10.6). Available information on efforts related to support on technology development and transfer for developing country parties is also one of the matters to be taken into account in the global stocktake (UNFCCC, 2015, Art. 10.6) (see Section 14.3.2.5 above).

The Paris Agreement emphasises that efforts to accelerate, encourage and enable innovation are 'critical for an effective long-term global response to climate change and promoting economic growth and sustainable development' and urges that they be supported, as appropriate, by the Technology Mechanism and Financial Mechanism of the UNFCCC (UNFCCC, 2015, Art. 10.5). This support should be directed to developing country parties 'for collaborative approaches to research and development, and facilitating access to technology, in particular for early stages of the technology cycle' (UNFCCC, 2015, Art. 10.5). Inadequate support for R&D, particularly in developing countries, has been identified in previous studies of technology interventions by international institutions as a key technology innovation gap that might be addressed by the Technology Mechanism (Coninck and Puig 2015).

To support parties' cooperative action, the Technology Mechanism, established in 2010 under the UNFCCC (see further Section 14.4.2 below), will serve the Paris Agreement, subject to guidance of a new 'technology framework' (UNFCCC, 2015, Art. 10.4). The latter was strongly advocated by the African group in the negotiations for the Paris Agreement (Oh 2020a), and was adopted in 2018 as part of the Paris Rulebook, with implementation entrusted to the component bodies of the Technology Mechanism. The guiding principles of the framework are coherence, inclusiveness, a results-oriented approach, a transformational approach and transparency. Its 'key themes' include innovation, implementation, enabling environment and capacity-building, collaboration and stakeholder engagement, and support (UNFCCC 2019e, Annex). A number of 'actions and activities' are elaborated for each thematic area. These include: enhancing engagement and collaboration with relevant stakeholders, including local communities and authorities, national planners, the private sector and civil society organisations, in the planning and implementation of Technology Mechanism activities; facilitating parties undertaking, updating and implementing technology needs assessments (TNAs) and aligning these with NDCs; and enhancing the collaboration of the Technology Mechanism with the Financial Mechanism for enhanced support for technology development and transfer. As regards TNAs, while some developing countries have already used the results of their TNA process in NDC development, other countries might benefit from following the TNA process, including its stakeholder involvement, and multi-criteria decision analysis methodology, to strengthen their NDCs (Hofman and van der Gaast 2019).

14.3.2.10 Capacity-building

Together with finance, and technology development and transfer, capacity-building is the third of 'the means of implementation and support' specified under the Paris Agreement (see UNFCCC 2015a, Art.

14.1). Capacity-building has primarily been implemented through partnerships, collaboration and different cooperative activities, inside and outside the UNFCCC. This sub-section discusses the provision made in the Paris Agreement for international cooperation on capacity-building. Section 14.4.3 below considers broader cooperative efforts on capacity-building within the UNFCCC.

In its annual synthesis report for 2018, the UNFCCC secretariat stressed the importance of capacity-building for the implementation of the Paris Agreement and NDCs, with a focus on measures already in place, regional and cooperative activities, and capacity-building needs for strengthening NDCs (UNFCCC 2019h). Of the 168 NDCs submitted as of June 2019, capacity-building was the most frequently requested type of support (113 of 136 conditional NDCs) (Pauw et al. 2020). The focus of capacity-building activities is on enabling developing countries to take effective climate change action, given that many developing countries continue to face significant capacity challenges, undermining their ability to effectively or fully carry out the climate actions they intend to pursue (Dagnet et al. 2016). Content analysis of NDCs shows that capacity-building for adaptation is prioritised over mitigation for developing countries, with the element of capacity-building most indicated in NDCs being research and technology (Khan et al. 2020). In addition, developing countries' needs for education, training and awareness-raising for climate change mitigation and adaptation feature prominently in NDCs, particularly those of LDCs (Khan et al. 2020). Differences are evident though between capacity-building needs expressed in the NDCs of LDCs (noting that Khan et al's review was limited to NDCs in English) compared with those of upper-middle income developing countries as categorised by the World Bank (World Bank 2021); the latter have more focus on mitigation with an emphasis on technology development and transfer (Khan et al. 2020).

The Paris Agreement urges all parties to cooperate to enhance the capacity of developing countries to implement the Agreement (UNFCCC 2015a, Art. 11.3), with a particular focus on LDCs and SIDS (UNFCCC 2015a, Art. 11.1). Developed country parties are specifically urged to enhance support for capacity-building actions in developing country Parties (UNFCCC 2015a, Art. 11.3). Article 12 of the Paris Agreement addresses cooperative measures to enhance climate change education, training, public awareness, public participation and public access to information, which can also be seen as elements of capacity-building (Khan et al. 2020). Under the Paris Rulebook, efforts related to the implementation of Article 12 are referred to as 'Action for Climate Empowerment' and parties are invited to develop and implement national strategies on this topic, taking into account their national circumstances (UNFCCC 2019i, para. 6). Actions to enhance climate change education, training, public awareness, public participation, public access to information, and regional and international cooperation may also be taken into account by parties in the global stocktake process under Article 14 of the Paris Agreement (UNFCCC 2019i, para. 9).

Under the Paris Agreement, capacity-building can take a range of forms, including: facilitating technology development, dissemination and deployment; access to climate finance; education, training and public awareness; and the transparent, timely and accurate communication of information (UNFCCC 2015a, Art. 11.1; see also 14.3.2.4 on 'Transparency' above). Principles guiding capacity-building support are that it should be: country-driven; based on and responsive to national needs; fostering country ownership of parties at multiple levels; guided by lessons learned; and an effective, iterative process that is participatory, cross-cutting and gender-responsive (UNFCCC 2015a, Art. 11.2). Parties undertaking capacity-building for developing country parties must 'regularly communicate on these actions or measures.' Developing countries parties have a soft requirement ('should') to communicate progress made on implementing capacity-building plans, policies, actions or measures to implement the Paris Agreement (UNFCCC 2015a, Art. 11.4).

Article 11.5 provides that capacity-building activities 'shall be enhanced through appropriate institutional arrangements to support the implementation of this Agreement, including the appropriate institutional arrangements established under the Convention that serve this Agreement'. The COP decision accompanying the Paris Agreement established the Paris Committee on Capacity-building, with the aim to 'address gaps and needs, both current and emerging, in implementing capacity-building in developing country Parties and further enhancing capacity-building efforts, including with regard to coherence and coordination in capacity-building activities under the Convention' (UNFCCC 2016a, para. 71). The activities of the Committee are discussed further in Section 14.4.3 below. The relevant COP decision also established the Capacity Building Initiative for Transparency (UNFCCC 2016a, para. 84), which is managed by the GEF and designed to support developing country parties in meeting the reporting and transparency requirements under Article 13 of the Paris Agreement (Robinson 2018).

Studies on past capacity-building support for climate mitigation offer some lessons for ensuring effectiveness of arrangements under the Paris Agreement. For example, Umemiya et al. (2020) suggest the need for a common monitoring system at the global level, and evaluation research at the project level to achieve more effective capacity building support. Khan et al. (2020) articulate 'four key pillars' of a sustainable capacity-building system for implementation of NDCs in developing countries: universities in developing countries as institutional hubs; strengthened civil society networks and partnerships; long-term programmatic finance support; and consideration of a capacity-building mechanism under the UNFCCC – paralleling the Technology Mechanism – to marshal, coordinate and monitor capacity-building activities and resources.

14.3.2.11 Implementation and compliance

The Paris Agreement establishes a mechanism to facilitate implementation and promote compliance under Article 15. This mechanism is to operate in a transparent, non-adversarial and non-punitive manner (Voigt 2016; Campbell-Duruflé 2018b; Oberthür and Northrop 2018) that distinguishes it from the more stringent compliance procedures of the Kyoto Protocol's Enforcement branch. The Paris Rulebook elaborated the modalities and procedures for the implementation and compliance mechanism, specifying the nature and composition of the compliance committee, the situations triggering its procedures, and the facilitative measures it can apply, which include a 'finding of fact' in limited situations, dialogue, assistance and recommendations (UNFCCC 2019e). The compliance committee is focused on ensuring compliance with a core set of binding procedural obligations (UNFCCC 2019j, Annex, Para. 22). This compliance committee, characterised as 'one of its kind' and an 'an important cornerstone' of the Agreement's legitimacy, effectiveness and longevity (Zihua et al. 2019), is designed to facilitate compliance rather than penalise non-compliance.

START BOX 4.1 HERE

Box 14.1 Key features of the Paris Agreement relevant to mitigation.

The Paris Agreement's overall aim is to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty. This aim is explicitly linked to enhancing implementation of the UNFCCC, including its objective in Article 2 of stabilising greenhouse gas emissions at a level that would 'prevent dangerous anthropogenic interference with the climate system'. The Agreement sets three goals:

1. *Temperature*: holding the global average temperature increase to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels.

2. *Adaptation and climate resilience:* increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development, in a manner that does not threaten food production.

3. *Finance*: making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development.

In order to achieve the long-term temperature goal, parties aim to reach global peaking of emissions as soon as possible, recognising that peaking will take longer for developing countries, and then to undertake rapid reductions in accordance with the best available science. This is designed to reach global net zero GHG emissions in the second half of the century, with the emissions reductions effort to be determined on the basis of equity and in the context of sustainable development and efforts to eradicate poverty. In addition, implementation of the Agreement as a whole is expected to reflect equity and parties' common but differentiated responsibilities and respective capabilities, in light of different national circumstances.

The core mitigation commitments of parties under the Paris Agreement centre on preparing, communicating and maintaining successive 'nationally determined contributions' (NDCs), the contents of which countries determine for themselves. All parties must have NDCs and pursue domestic mitigation measures with the aim of achieving the objectives of their NDCs, but parties NDCs are neither subject to a review of adequacy (at an individual level) nor to legally binding obligations of result. The compliance mechanism is correspondingly facilitative.

The Paris Agreement establishes a global goal on adaptation, and recognises the importance of averting, minimising and addressing loss and damage associated with the adverse effects of climate change.

The efficacy of the Paris Agreement in achieving its goals is therefore dependent upon at least three additional elements:

1. *Ratcheting of NDCs*: Parties must submit a new or updated NDC every 5 years that is in line with the Paris Agreement's expectations of progression over time and the party's highest possible ambition, reflecting common but differentiated responsibilities and respective capabilities in light of different national circumstances.

2. *Enhanced transparency framework*: Parties' actions to implement their NDCs are subject to international transparency and review requirements, which will generate information that may also be used by domestic constituencies and peers to pressure governments to increase the ambition of their NDCs.

3. *Collective global stocktake*: The global stocktake undertaken every 5 years, starting in 2023, will review the collective progress of countries in achieving the Paris Agreement's goals, in light of equity and best available science. The outcome of the global stocktake informs parties in updating and enhancing their subsequent NDCs.

These international processes establish an iterative ambition cycle for the preparation, communication, implementation and review of NDCs.

For developing countries, the Paris Agreement recognises that increasing mitigation ambition and realising long-term low-emissions development pathways can be bolstered by the provision of financial resources, capacity building, and technology development and transfer. In continuation of existing obligations under the Convention, developed countries are obliged to provide financial assistance to developing countries with respect to mitigation and adaptation. The Paris Agreement also recognizes that Parties may choose to voluntarily cooperate in the implementation of their NDCs to allow for higher ambition in their mitigation and adaptation actions and to promote sustainable development and environmental integrity.

END BOX 4.1 HERE

14.3.3 Effectiveness of the Kyoto Protocol and the Paris Agreement

14.3.3.1 Ex-post assessment of the Kyoto Protocol's effects

Previous assessment reports have assessed the Kyoto Protocol with respect to each of the criteria identified in this chapter. However, at the time of AR5, it was premature to assess the impact of Kyoto on emissions, as this data had not been entirely compiled yet. Since AR5, a number of studies have done so. Chapter 2 of this report lists 24 countries that have sustained absolute emissions reductions for at least a decade, of which 20 are countries that had Kyoto targets for the first commitment period. Most studies have concluded that Kyoto did cause emissions reductions. Such studies find a positive, statistically significant impact on emission reductions in Annex I countries (Kim et al. 2020), Annex B countries (Grunewald and Martínez-Zarzoso 2012; Kumazawa and Callaghan 2012; Grunewald and Martínez-Zarzoso 2016; Maamoun 2019), or all countries respectively (Aichele and Felbermayr 2013; Iwata and Okada 2014). Overall, countries with emission reduction obligations emit on average less CO_2 than similar countries without emission reduction obligations – with estimates ranging from 3-50% (Grunewald and Martínez-Zarzoso 2012, 2016). Maamoun (2019) estimates that the Kyoto Protocol reduced GHG emissions of Annex B countries by 7% on average below a no-Kyoto scenario over 2005 - 2012. Aichele and Felbermayr (2013) conclude that Kyoto reduced CO_2 and GHG emissions by 10% compared to the counterfactual. By contrast, Almer and Winkler (2017) find no evidence for binding emission targets under Kyoto inducing significant and lasting emission reductions for any of the Annex B or non-Annex B countries. The authors identify both negative and positive associations between Kyoto and emissions for several countries in several years, but no coherent picture emerges. Hartl (2019) calculates a Kyoto leakage share in global carbon dioxide trade of 4.3% for 2002-2009.

In terms of transformative potential, the Kyoto Protocol has been found to increase international patent applications for renewable energy technologies, especially in the case of solar energy technologies and especially in countries with more stringent emission reduction targets, and has even led to an increase in patent applications in developing countries not obliged to reduce emissions under Kyoto (Miyamoto and Takeuchi 2019). Kyoto also had a positive and statistically significant impact on the cost-effectiveness of renewable energy projects, as well as renewable energy capacity development as it stimulated the introduction of domestic renewable energy policies (Liu et al. 2019).

The issue of institutional strength of Kyoto has been analysed by many authors, and much of this has been assessed in previous assessment reports. Since AR5, several papers question the environmental efficacy of the Kyoto Protocol based on its institutional design (Rosen 2015; Kuriyama and Abe 2018). Particular attention has focused on Kyoto's market mechanisms (Erickson et al. 2014; Kollmuss et al. 2015).

As described in previous IPCC reports and above, the 1997 Kyoto Protocol included three international market-based mechanisms. These operated among Annex I Parties (i.e. International Emissions Trading and Joint Implementation) and between Annex I Parties and non-Annex I countries (i.e. the CDM) (Grubb et al. 2014; World Bank 2018). Joint Implementation led to limited volumes of emissions credit transactions, mostly from economies in transition but also some Western European countries; International Emissions Trading also led only to limited transaction volumes (Shishlov et al. 2016).

Of the Kyoto Protocol's mechanisms, the CDM market has led to a greater amount of activity, with a 'gold rush' period between 2005 and 2012. The main buyer of CDM credits were private companies surrendering them within the European Union (EU) Emissions Trading System (ETS). Once the EU tightened its rules and restricted the use of CDM credits in 2011, there was a sharp drop in the price of CDM credits in 2012. This price never recovered, as the demand for CDM was very weak after 2012, in part because of the difficulties encountered in securing the entry into force of the Doha Amendment (Michaelowa et al. 2019b).

Assessing the effectiveness of Kyoto's market mechanisms is challenging, and the results have been mixed. (Aichele and Felbermayr 2013; Iwata and Okada 2014; Kuriyama and Abe 2018). Kuriyama and Abe (2018) assessed emission reduction quantities taking into account heightened criteria for additionality. They identified annual energy-related emissions reductions of 49 $MtCO_2e\ y^{-1}$ flowing from the CDM, and non-energy related emissions reductions of 177 $MtCO_2e\ y^{-1}$. Others have pointed to issues associated with non-energy related emission reductions that suggest the latter estimate may be of questionable reliability, while also noting that regulatory tightening led later CDM projects to perform better with respect to the additionality criterion (Michaelowa et al. 2019b). The CDM's contribution to capacity building in some developing countries has been identified as possibly its most important achievement (Spalding-Fecher et al. 2012; Gandenberger et al. 2015; Murata et al. 2016; Dong and Holm Olsen 2017; Lindberg et al. 2018; Xu et al. 2016). There is evidence that the CDM lowered compliance costs for Annex 1 countries by at least USD3.6 billion (Spalding-Fecher et al. 2012). In host countries, the CDM led to the establishment of national approval bodies and the development of an ecosystem of consultants and auditors (Michaelowa et al. 2019b) .

On the negative side, there are numerous findings that the CDM, especially at first, failed to lead to additional emissions cuts in host countries, meaning that the overall effect of CDM projects was to raise global emissions. Cames et al. (2016) concluded that over 70% of CDM projects led to emissions reductions that were likely less than projected, including the absence of additional reductions, while only 7% of projects led to actual additional emissions reductions that had a high likelihood of meeting or exceeding the ex-ante estimates. The primary reason the authors gave was the associated with the low price for CDM credits; this meant that the contribution of the CDM to project finance was negligible, suggesting that most CDM projects would have been built anyway. A meta-analysis of ex-post studies of global carbon markets, which include the CDM, found net combined effects on emission to be negligible (Green 2021). Across, the board, CDM projects have been criticised for lack of 'additionality', problems of baseline determination, uneven geographic coverage (Michaelowa and Michaelowa 2011a; Cames et al. 2016; Michaelowa et al. 2019b), as well as failing to address human rights concerns (Schade and Obergassel 2014).

14.3.3.2 Effectiveness of the Paris Agreement

Given the comparatively recent conclusion of the Paris Agreement, evidence is still being gathered to assess the effectiveness of the Paris Agreement in practice, in particular, since its long-term effectiveness hinges on states communicating more ambitious nationally determined contributions in successive cycles over time. Assessments of the Paris Agreement on paper are necessarily speculative and limited by the lack of credible counterfactuals. Despite these limitations, numerous assessments exist of the potential for international cooperation under the Paris Agreement to advance climate change mitigation.

These assessments are mixed and reflect uncertainty over the outcomes the Paris Agreement will achieve (Christoff 2016; Clémençon 2016; Young 2016; Dimitrov et al. 2019; Raiser et al. 2020; Keohane and Oppenheimer 2016). There is a divide between studies that do not expect a positive outcome from the Paris Agreement and those that do. The former base this assessment on factors such as: a lack of clarity in the expression of obligations and objectives; a lack of concrete plans collectively to achieve the temperature goal; extensive use of soft law (i.e. non legally-binding) provisions; limited incentives to avoid free-riding; and the Agreement's weak enforcement provisions (Allan 2019), as well as US non-cooperation under the Trump administration and the resulting gap in mitigation, finance and governance (Bang et al. 2016; Spash 2016; Tulkens 2016; Chai et al. 2017; Lawrence and Wong 2017; Thompson 2017; Barrett 2018; Kemp 2018). Studies expecting a positive outcome emphasise factors such as: the breadth of participation enabled by self-differentiated NDCs; the 'logic' of domestic climate policies driving greater national ambition; the multiplicity of actors engaged by the Paris Agreement's facilitative architecture; the falling cost of low-carbon technologies; provision for financial, technology and capacity-building support to developing country parties; possibilities for voluntary cooperation on mitigation under Article 6; and the potential for progressive ratcheting up of parties' pledges over time fostered by transparency of reporting and international scrutiny of national justifications of the 'fairness' of contributions (Caparrós 2016; Morgan and Northrop 2017; Urpelainen and Van de Graaf 2018; Hale 2020; Tørstad 2020; Chan 2016a; Falkner 2016b; Victor 2016). Turning to the assessment criteria articulated in this chapter, the following preliminary assessments of the Paris Agreement can be made.

In relation to the criterion of *environmental effectiveness*, the Paris Agreement exceeds the Kyoto Protocol in terms of coverage of GHGs and participation of states in mitigation actions. In terms of coverage of GHGs, the Kyoto Protocol limits its coverage to a defined basket of gases identified in its Annex A (Carbon dioxide (CO_2), Methane (CH_4), Nitrous oxide (N_2O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), Sulphur hexafluoride (SF_6), as well as nitrogen trifluoride (NF_3)). The Paris Agreement does not specify the coverage of gases, thus parties may cover the full spectrum of GHGs in their NDCs as encouraged by the accounting provisions in Annex II to Decision 18/CMA.1 (or conversely choose to exclude important mitigation sectors) and there is also the possibility to include other pollutants such as short-lived climate forcers like black carbon. Article 4.4 calls on developed countries to undertake economy-wide emissions reduction targets with the expectation that developing country parties will also move to introduce these over time. Moreover, the Paris Agreement makes express reference to Parties taking action to conserve and enhance 'sinks and reservoirs of greenhouse gases' (Article 5). As under the UNFCCC and Kyoto Protocol, this allows for coverage of AFOLU emissions, both CO_2 and emissions of other Kyoto Annex A gases, as well as other forms of carbon dioxide removal, including methane (Pekkarinen 2020). A few countries, particularly LDCs, include quantified non-CO_2 emissions reductions from the agricultural sector in their NDCs, and many others include agriculture in their economy-wide targets (Richards et al. 2018). Some studies find that agricultural development pathways with mitigation co-benefits can deliver 21–40% of needed mitigation for the 'well below 2°C' limit, thus necessitating 'transformative technical and policy options' (Wollenberg et al. 2016). Other studies indicate that broader 'natural climate solutions, including forests, can provide 37% of the cost-effective CO_2 mitigation needed through 2030 for a more than 66% chance of holding warming to below 2°C' (Griscom et al. 2017).

As the estimates in Table 4.3 (Chapter 4) demonstrate, communicated unconditional NDCs, if achieved, lead to a reduction of about 7% of world emissions by 2030 in relation to the Kyoto GHGs, and NDCs with conditional elements increase this reduction to about 12% (den Elzen et al. 2016). Although there are uncertainties in the extent to which countries will meet the conditional elements of their NDCs, the experience with the Cancun pledges has been positive, as countries will collectively meet their pledges by 2020, and even individual pledges will be met in most cases, although arguably helped by the COVID-19 pandemic (UNEP 2020). In any case, the main challenge that remains is to close the emissions gap, the difference between what has been pledged and what is needed to achieve by 2030 to reach a 1.5º C compatible path (respectively 2º C) (Roelfsema et al. 2020; UNEP 2020, see also Cross-chapter Box 4 in Chapter 4). In terms of participation of states in mitigation actions, the Paris Agreement performs better than the Kyoto Protocol. The latter contains mitigation targets only for developed countries listed in its Annex B, while the Paris Agreement extends binding procedural obligations in relation to mitigation contributions to all states. It is noted, however, that the Paris Agreement represented a weakening of commitments for those industrialised countries that were parties to the Kyoto Protocol, although a strengthening for those that were not, and for developing countries (Oberthür and Groen 2020). Finally, some analysts have suggested that the recent proliferation of national mid-century net-zero targets – currently 127 countries have considered or adopted such targets – can be attributed, at least in part, to participation in the Paris Agreement and having agreed to its Article 4 (Climate Action Tracker 2020a; Day et al. 2020).

In relation to the criterion of *transformative potential*, there is, as yet, limited empirical data or theoretical analysis on which to assess the Paris Agreement's transformative potential. The IPCC's 1.5°C report concluded that pathways limiting global warming to 1.5°C would require systems transitions that are 'unprecedented in terms of scale' (IPCC 2018b). There is limited evidence to suggest that this is underway, although there are arguments made that Paris has the right structure to achieve this. The linking of the UNFCCC financial apparatus, including the GCF, to the Paris Agreement, and the provisions on technology support and capacity-building, provide potential avenues for promoting increased investment flows into low-carbon technologies and development pathways, as (Labordena et al. 2017) show in the case of solar energy development in Africa. Similarly, Kern and Rogge (2016) argue that the Paris Agreement's global commitment towards complete decarbonisation may play a critical role in accelerating underlying system transitions, by sending a strong signal as to the actions needed by national governments and other international support. Victor et al. (2019) argue that international cooperation that enhances transformative potential needs to operate at the sectoral level, as the barriers to transformation are highly specific to each sector; the Paris Agreement's broad consensus around a clear level of ambition sends a strong signal on what is needed in each sector, but on its own will do little unless bolstered with sectoral-specific action (Geels et al. 2019). On the less optimistic side, it is noted that the extent of the 'investment signal' sent by the Agreement to business is unclear (Kemp 2018), and it is also unclear to what extent the Paris Agreement is fostering investment in break-through technologies. United States non-cooperation from 2017 to 2020 posed a significant threat to adequate investment flows through the GCF (Chai et al. 2017; Urpelainen and Van de Graaf 2018).

In relation to the criterion of *distributive outcomes*, the Paris Agreement performs well in some respects but less well in others, and its performance relative to the Kyoto Protocol is arguably lower in respect of some indicators such as industrialised country leadership, and differentiation in favour of developing countries. While the Kyoto Protocol implemented a multilaterally agreed burden sharing arrangement set out in the UNFCCC and reflected in Annex-based differentiation in mitigation obligations, the Paris Agreement relies on NDCs, accompanied by self-assessments of the fairness of these contributions; some of these do not accord with equity principles of international environmental law, although it is worth noting that the Kyoto Protocol was also not fully consistent with such principles. At present, mechanisms in the Paris Agreement for promoting equitable burden-sharing and evaluating the fairness of parties' contributions are undefined, although numerous proposals have been developed in the literature (Ritchie and Reay 2017; Herrala and Goel 2016; Robiou du Pont et al. 2017; Alcaraz et al. 2019; Sheriff 2019) (discussed in Section 14.3.2.3, above). Zimm and Nakicenovic (2020) analysed the first set of NDCs, and concluded that they would result in a decrease in the inequality of per capita emissions across countries. In relation to other indicators such as the provision of support, the distributive outcomes of the Paris Agreement are dependent on the availability of support through mechanisms such as the GCF to meet the mitigation and adaptation financing needs of developing countries (Antimiani et al. 2017; Chan et al. 2018). One study suggests that the implementation of the emissions reduction objectives stated in the NDCs implies trade-offs with poverty reduction efforts needed to achieve SDGs (Campagnolo and Davide 2019), while other studies offer evidence that the immediate economic, environmental, and social benefits of mitigation in line with developing countries' NDCs exceed those NDCs' costs, and ultimately align the the SDGs (Antwi-Agyei et al. 2018; Vandyck et al. 2018; Caetano et al. 2020) (see Chapter 17). In relation to the promotion of co-benefits the Paris Agreement has enhanced mechanisms for promoting co-benefits (e.g. in some cases for biodiversity conservation through the endorsement of REDD+ initiatives and activities) and linkages to sustainable development (e.g. through the Article 6.4 mechanism). Finally, in its preambular text the Paris Agreement endorses both a human rights perspective and the concept of just transitions, creating potential hooks for further elaboration and expansion of these principles in mitigation actions.

On the criterion of *economic performance*, the Paris Agreement's performance is potentially enhanced by the capacity for parties to link mitigation policies, therefore improving aggregate cost-effectiveness. Voluntary cooperation under Article 6 of the Paris Agreement could facilitate such linkage of mitigation policies (Chan et al. 2018). A combination of common accounting rules and the absence of restrictive criteria and conditions on the use of ITMOs could accelerate linkage and increase the latitude of parties to scale up the ambition of their NDCs. However, significant question marks remain over how the environmental integrity of traded emissions reductions can be ensured (Mehling 2019). The ability of Article 6 to contribute to the goal of the Paris Agreement will depend on the extent to which the rules ensure environmental integrity and avoid double counting, while utilising the full potential of cooperative efforts (Schneider et al. 2019; Michaelowa et al. 2019a).

In relation to the criterion of *institutional strength*, the Paris Agreement's signalling and guidance function is, however, arguably high. The Paris Agreement has the potential to interact with complementary approaches to climate governance emerging beyond it (Held and Roger 2018). It may also be used by publics – organised and mobilised in many countries and transnationally – as a point of leverage in domestic politics to encourage countries to take costly mitigation actions (Keohane and Oppenheimer 2016). More broadly, the Paris Agreement's architecture provides flexibility for decentralised forms of governance (Jordan et al. 2015; Victor 2016) (see further Section 14.5 below). The Agreement has served a catalytic and facilitative role in enabling and facilitating climate action from non-state and sub-state actors (Chan et al. 2015; Hale 2016; Chan et al. 2016; Bäckstrand et al. 2017; Kuyper et al. 2018b). Such action could potentially 'bridge' the ambition gap created by insufficient NDCs from parties (Hsu et al. 2019b). The 2018 UNEP Emissions Gap Report estimates that if 'cooperative initiatives are scaled up to their fullest potential', the impact of non-state and sub-national actors could be up to 15-23 $GtCO_2eq\ yr^{-1}$ by 2030 compared to current policy, which could bridge the gap (Lui et al. 2021). However, at present such a contribution is limited (Michaelowa and Michaelowa 2017; UNEP 2018a). Non-state actors are also playing a role in enhancing the ambition of individual NDCs by challenging their adequacy in national courts (see Chapter 13 and Section 14.5.3 below).

The Paris Agreement's institutional strength in terms of 'rules and standards to facilitate collective action' is disputed given the current lack of comparable information in NDCs (Peters et al. 2017; Pauw et al. 2018; Mayer 2019; Zihua et al. 2019), and the extent to which its language, as well as that of the Rulebook, strikes a balance in favour of discretion over prescriptiveness (Rajamani and Bodansky 2019). Similarly, in terms of 'mechanisms to enhance transparency and accountability', although detailed rules relating to transparency have been developed under the Paris Rulebook, these rules permit parties considerable self-determination in the extent and manner of application (Rajamani and Bodansky 2019), and may not lead to further ambition (Weikmans et al. 2020). Further the Paris Agreement's compliance committee is facilitative and designed to ensure compliance with the procedural obligations in the Agreement, rather than with the NDCs themselves, which are not subject to obligations of result. The Paris Agreement does, however, seek to support the building of transparency-related capacity of developing countries, potentially triggering institutional capacity-building at the national, sub-national and sectoral level (see 14.3.2.7).

Ultimately, the overall effectiveness of the Paris Agreement depends on its ability to lead to ratcheting up of collective climate action to meet the long-term global temperature goal (Bang et al. 2016; Christoff 2016; Young 2016; Dimitrov et al. 2019; Gupta and van Asselt 2019). As noted above, there is some evidence that this is already occurring. The design of the Paris Agreement, with 'nationally determined' contributions at its centre, countenances an initial shortfall in collective ambition in relation to the long-term global temperature goal on the understanding and expectation that Parties will enhance the ambition of their NDCs over time (Article 4). This is essential given the current shortfall in ambition. The pathways reflecting current NDCs, according to various estimates, imply global warming in the range of 3°C by 2100 (UNFCCC 2016b; UNEP 2018a) (Chapter 4, Box 3). NDCs will need to be substantially scaled up if the temperature goal of the Paris Agreement is to be met (Rogelj et al. 2018, 2016; Höhne et al. 2017, 2018; UNEP 2020). The Paris Agreement's 'ambition cycle' is designed to trigger such enhanced ambition over time. Some studies find that like-minded climate mitigation clubs can deliver substantial emission reductions (Hovi et al. 2017) and are reasonably stable despite the departure of a major emitter such as the United States (Sprinz et al. 2018), other studies find that conditional commitments in the context of a pledge and review mechanism are unlikely to substantially increase countries' contributions to emissions reductions (Helland et al. 2017), and hence need to be complemented by the adoption of instruments designed differently from the Paris Agreement (Barrett and Dannenberg 2016). In any case, high (but not perfect) levels of mean compliance rates with the Paris Agreement have to be assumed for reaching the 'well below 2°C' temperature goal (Sælen 2020; Sælen et al. 2020). This is by no means assured.

In conclusion, it remains to be seen whether the Paris Agreement will deliver the collective ambition necessary to meet the temperature goal. While the Paris Agreement does not contain strong and stringent obligations of result for major emitters, backed by a demanding compliance system, it establishes binding procedural obligations, lays out a range of normative expectations, and creates mechanisms for regular review, stock taking, and revision of NDCs. In combination with complementary approaches to climate governance, engagement of a wide range of non-state and sub-national actors, and domestic enforcement mechanisms, these have the potential to deliver the necessary collective ambition and implementation. Whether it will do so, remains to be seen.

START CROSS-CHAPTER BOX 10 HERE

Cross-Chapter Box 10: Policy Attribution - Methodologies for estimating the macro-level impact of mitigation policies on indices of GHG mitigation

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This report notes both a growing prevalence of mitigation policies over the past quarter century (Chapter 13), and 'signs of progress' including various quantified indices of GHG mitigation (Chapter 2, Table 2.4). Even though policies implemented and planned to date are clearly insufficient for meeting the Paris long-term temperature goals, a natural question is to what extent the observed macro-level changes (global, national, sectoral, technological) can be attributed to policy developments. This Assessment Report is the first to address that question. This box describes the methods for conducting such 'attribution analysis' as well as its key results, focusing on the extent to which polices have affected three main types of 'outcome indices':

• **GHG emissions**: emissions volumes and trends at various levels of governance including sub- and supra-national levels, and within and across sectors.

• **Proximate emission drivers:** trends in the factors that drive emissions, distinguished through decomposition analyses, notably: energy/GDP intensity and carbon/energy intensity (for energy-related emissions); indices of land use such as deforestation rates (for LULUCF/AFOLU); and more sector-specific component drivers such as the floor area per capita, or passenger kilometres per capita.

• **Technologies:** developments in key low-carbon technologies that are likely to have a strong influence on future emissions trends, notably levels of new investment and capacity expansions, as well as technology costs, with a focus on those highlighted in Chapter 2 Figure 2.30.

Policy attribution examines the extent to which emission-relevant outcomes on these indices – charted for countries, sectors and technologies, particularly in Chapter 2 and the sectoral chapters – may be reasonably attributed to policies implemented prior to the observed changes. Such policies include regulatory instruments such as energy efficiency programmes or technical standards and codes, carbon pricing, financial support for low-carbon energy technologies and efficiency, voluntary agreements, and regulation of land use practices. The sectoral chapters give more detail along with some accounts of policy, whilst trends in mitigation policy adoption are summarised in Chapter 13.

In reviewing hundreds of scientific studies cited in this report, the impacts of adopted policies on observed outcomes were assessed. The vast majority of these studies examine particular instruments in particular contexts, as covered in the sectoral chapters and Chapter 13; only a few have appraised global impacts of policies, directly or plausibly inferred (the most significant are cited in the figure in this box). Typically, studies consider 'mitigation policies' to be those adopted with either a primary objective of reducing GHG emissions or emissions reductions as one among multiple objectives.

Policies differ in design, scope, and stringency, may change over time as they require amendments or new laws, and often partially overlap with other instruments. Overall, the literature indicates that policy mixes are, theoretically and empirically, more effective in reducing emissions, stimulating innovation, and inducing behavioural change than stand-alone policy instruments (Chapter 5 section 5.6; Chapter 13, section 13.7) (Rosenow et al. 2017; Sethi et al. 2020; Best and Burke 2018). Nevertheless, these factors complicate analysis, because they give rise to the potential for double counting emissions reductions that have been observed, and which separate studies can attribute to different policy instruments.

Efforts to attribute observed outcomes to a policy or policy mix is also greatly complicated by the influence of many exogenous factors, including fossil fuel prices and socio-economic conditions. Likewise, technological progress can result from both exogenous causes, such as 'spillover' from other sectors, and policy pressure. Further, other policies, such as fossil fuel subsidies as well as trade-related policies, can partially counteract the effect of mitigation policies by increasing the demand for energy or carbon-intensive goods and services. In some cases, policies aimed at development, energy security, or air quality have climate co-benefits, while others increase emissions.

Studies have applied a number of methods to identify the actual effects of mitigation policies in the presence of such confounding factors. These include statistical attribution methodologies, including experimental and quasi-experimental design, instrumental variable approaches, and simple correlational methods. Typically, the relevant mitigation metric is the outcome variable, while measures of policies and other factors act as explanatory variables. Other methodologies include aggregations and extrapolations from micro-level data evaluation, and inference from combining multiple lines of analysis, including expert opinion. Additionally, the literature contains reviews, many of them systematic in nature, that assess and aggregate multiple empirical studies.

With these considerations in mind, multiple lines of evidence, based upon the literature, support a set of high-level findings, as illustrated in the figure in this box, as follows.

1. **GHG Emissions.** There is robust evidence with a high level of agreement that mitigation policies have had a discernible impact on emissions. Several lines of evidence indicate that mitigation policies have led to avoided global emissions to date by several billion tonnes CO_2-eq annually. The figure in this box shows a selection of results giving rise to this estimate.

As a starting point, one methodologically sophisticated econometric study links global mitigation policies (defined as climate laws and executive orders) to emission outcomes; it estimates emission savings of 5.9 $GtCO_2$ yr^{-1} in 2016 compared to a no-policy world (Eskander and Fankhauser 2020, see Chapter 13.6.2).

A second line of evidence derives from analyses of the Kyoto Protocol. Countries which took on Kyoto Protocol targets accounted for about 24% of global emissions during the first commitment period (2008-12). The most recent robust econometric assessment (Maamoun 2019) estimates that these countries cut GHG emissions by about 7% on average over 2005-2012, rising over the period to around 12% (1.3 $GtCO_2e\ yr^{-1}$) *relative to a no-Kyoto scenario.* This is consistent with estimates of Grunewald and Martinez (2016) of about 800 $MtCO_2e\ yr^{-1}$ averaged to 2009. Developing countries emission reduction projects through the CDM (defined in article 12 of the Kyoto Protocol) were certified as growing to over 240 $MtCO_2e\ yr^{-1}$ by 2012 (UNFCC 2021c). With debates about the full extent of 'additionality', academic assessments of savings from the CDM have been slightly lower with particular concerns around some non-energy projects (see Chapter 14.3.3.1).

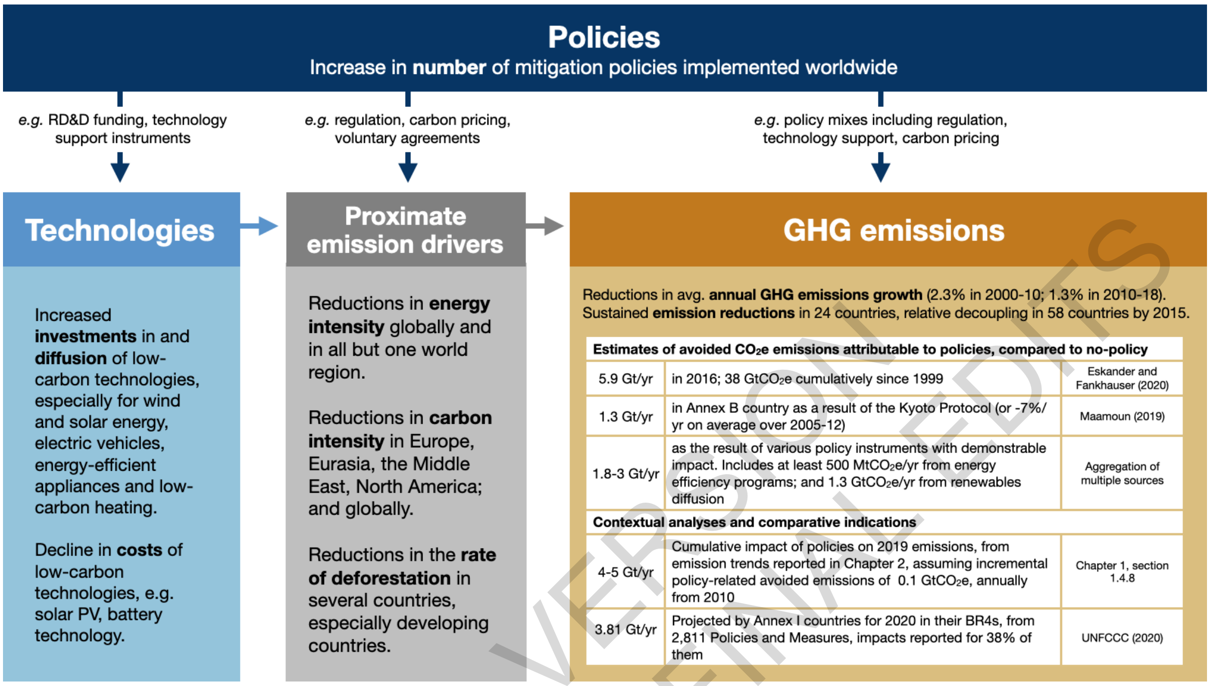
A third line of evidence derives from studies that identify policy-related, absolute reductions from historical levels in particular countries and sectors through decomposition analyses (e.g., Lamb et al. 2021; Le Quéré et al. 2019), or evaluate the impact of particular policies, such as carbon pricing systems. From a wide range of estimates in the literature (see Chapters 2.8.2.2 and 13.6), many evaluations of the EU ETS suggest that it has reduced emissions by around 3% to 9% relative to unregulated firms and/or sectors (Schäfer 2019; Colmer et al. 2020), whilst other factors, both policy (energy efficiency and renewable support) and exogenous trends, played a larger role in the overall reductions seen (Haites 2018).

These findings derived from the peer-reviewed literature are also consistent with two additional sets of analysis. The first set concerns trends in emissions, drawing directly from Chapters 6-11 and Chapter 2, showing that global annual emission growth has slowed as evidenced by annual emission increments of 0.55 $GtCO_2e\ yr^{-1}$ between 2011 and 2019 compared to 1.014 $GtCO_2e\ yr^{-1}$ in 2000-08. This suggests avoided emissions of 4-5 Gt yr^{-1} (see also Chapter 1, Figure 1.1d). The second set concerns emissions reductions projected by Annex I governments for 2020 in their fourth biennial reports to the UNFCCC. It is important to note that these are mostly projected annual savings from implemented policies (not *ex-post* evaluations), and there are considerable differences in countries' estimation methodologies. Nevertheless, combining estimates from 38% of the total of 2,811 reported policies and measures yields an overall estimate of 3.81$GtCO_2e\ yr^{-1}$ emission savings (UNFCCC 2020d).

2. **Proximate emission drivers.** With less overt focus on emissions, studies of trends in energy efficiency, carbon intensity, or deforestation often point to associated policies. The literature s includes an increasing number of studies on demonstrable progress in developing countries. For example, South and South-East Asia have seen energy intensity in buildings improving at ca. 5 – 6% yr^{-1} since 2010 (Chapter 2, Figure 2.22). In India alone, innovative programmes in efficient air conditioning, LED lighting, and industrial efficiency are reported as saving around 25 Mtoe in 2019-2020, thus leading to avoided emissions of over 150 $MtCO_2\ yr^{-1}$ (see Chapter 16, box 16.3; Malhotra et al. 2021). Likewise, reductions in deforestation rates in several South and Central American and Asian countries are at least partly attributable to ecosystem payments, land use regulation, and internal efforts (Chapter 7.6.2). Finally, the policy-driven displacement of fossil fuel combustion by renewables in energy has led to reductions in carbon intensity in several world regions (Chapters 2 and 6).

3. **Technologies.** The literature indicates unambiguously that the rapid expansion of low-carbon energy technologies is substantially attributable to policy (Chapter 6.7.5, Chapter 16.5). Technology-specific adoption incentives have led to a greater use of less carbon-intensive (e.g. renewable electricity) and less energy-intensive (especially in transport and buildings) technologies. As Chapters 2 and 6 of this report note, modern renewable energy sources currently satisfy over 9% of global electricity demand, and this is largely attributable to policy. There are no global-level studies estimating the avoided emissions due to renewable energy support policies, but there are methods that have been developed to link renewable energy penetration to avoided emissions, such as that of IRENA (2021). Using that method, and assuming that 70% of modern renewable energy expansion has been policy-induced, yields

an estimate of avoided emissions of 1.3 $GtCO_2e$ yr^{-1} in 2019. Furthermore, observed cost reductions are the result of policy-driven capacity expansion as well as publicly funded R&D, in individual countries and globally. These correspond with induced effects on number of patents, 'learning curve' correlations with deployed capacity, and cost component and related case study analyses (Kavlak et al. 2018; Nemet 2019; Popp 2019; Grubb et al. 2021).



Cross-Chapter Box 10, Figure 1: Policy impacts on key outcome indices: GHG emissions, proximate emission drivers, and technologies, including several lines of evidence on GHG abatement attributable to policies.

END CROSS-CHAPTER BOX 10 HERE

14.4 Supplementary means and mechanisms of implementation

As discussed above, the Paris Agreement sets in place a new framework for international climate policy albeit one that is embedded in the wider climate regime complex (Coen et al. 2020). Whereas international governance had earlier assumed centre stage, the Paris Agreement recognises the salience of domestic politics in the governance of climate change (Kinley et al. 2020). The new architecture also provides more flexibility for recognising the benefits of working in diverse forms and groups and allows for more decentralised "polycentric" forms of governance (Jordan et al. 2015; Victor 2016). The next two sections address this complementarity between the Paris Agreement and other agreements and institutions.

The Paris Agreement identifies a number of pathways, or means of implementation, towards accomplishing rapid mitigation and the achieving of its temperature goal: finance; capacity building; technology and innovation; and, cooperative approaches and markets (see sections 14.3.2.7-14.3.2.10 above). In this section, we examine each of these means and mechanisms of implementation, and the agreements and institutions lying outside of the Paris Agreement that contribute to each. In the following Section, 14.5, we examine the agreements and institutions playing other governance roles: regulating activities in particular sectors; linking climate mitigation with other activities such as adaptation; and, stimulating and coordinating the actions of non-state actors at a global scale.

Figure 14.3 maps out the interlinkages described in the text of the sections 14.4 and 14.5. It is an incomplete list, but illustrates clearly that across multiple types of governance, there are multiple instruments or organisations with activities connected to the different governance roles associated with the Paris Agreement and the UNFCCC more generally.

Type	Instrument / Organization	Mitigation	Transparency	Sinks	Markets	Finance	Technology	Capacity building
Global treaties	Montreal Protocol	14.5.1.1				14.5.1.1		
	CBD	14.5.1.1		14.5.2.1				
	UNCCD			14.5.2.1				14.5.2.1
	Minimata Mercury Convention	14.5.1.1						
United Nations Programmes and Specialised Agencies	UN REDD+ programme	14.5.1.1		14.5.2.1		14.5.2.1		14.4.3
	UNEP	14.5.1.1						14.4.3
	UNDP							14.4.3
	UNIDO							14.4.1.2
	UNOSSC							14.4.1.2
	FAO			14.5.2.1				14.4.1.2
	ICAO	14.5.2.3			14.5.2.3		14.5.2.3	
	IMO	14.5.2.3	14.5.2.3				14.5.2.3	
Other global organisations	IEA						14.5.2.2	
	IRENA					14.5.2.2	14.5.2.2	14.5.2.2
	MDBs	14.4.1.2	14.4.1.2	14.5.4	14.4.4	14.4.1.2		14.4.3
Regional, multi- and bilateral agreements	LRTAP	14.5.1.1						
	MIGA					14.5.2.2		
	PPCA	14.5.2.2						
	Regional trade agreements	14.5.1.3			14.5.1.3		14.5.1.3	
	Bilateral development programs				14.4.4	14.4.1.1	14.4.1.1	14.4.3
	International science programmes						14.4.2	
	South South Cooperation					14.5.1.4	14.5.1.4	14.4.3
Non-state transnational actors	Global city networks	14.5.5		14.5.5		14.5.5	14.5.5	14.5.5
	Environmental NGOs	14.5.2.2	14.5.4			14.5.3		
	Social movements	14.5.3		14.5.3				
	Business partnerships	14.5.4	14.5.4			14.5.4	14.5.4	14.5.4

Figure 14.3 Climate governance beyond the UNFCCC. The figure shows those relationships, marked in blue, between international governance activities, described in the text, that relate to activities of the UNFCCC and Paris Agreement.

14.4.1 Finance

International cooperation on climate finance is underpinned by various articles of the UNFCCC including Articles 4.3, 4.4, 4.5, 4.7 and 11.5 (UNFCCC 1992). This was further amplified through the commitment by developed countries in the Copenhagen Accord and the Cancun Agreements to mobilise jointly through various sources USD100 billion yr^{-1} by 2020 to meet the needs of the developing countries (UNFCCC 2010b). This commitment was made in the context of meaningful mitigation action and transparency of implementation. As mentioned earlier in Section 14.3.2.8, in the Paris Agreement the binding obligation on developed country parties to provide financial resources to assist developing country parties applies to both mitigation and adaptation (UNFCCC 2015a, Art. 9.1). In 2019, climate finance provided and mobilised by developed countries was in the order of USD79.6 billion, coming from different channels including bilateral and multilateral channels, and also through mobilisation of the private sector attributable to these channels (OECD 2021). A majority (two-thirds) of these flows targeted mitigation action exclusively (see also Chapter 15). These estimates, however, have been criticised on various grounds, including that they are an overestimate and do not represent climate specific net assistance only; that in grant equivalence terms the order of magnitude is lower; and the questionable extent of transparency of information on mobilised private finance, as well as the direction of these flows (Carty et al. 2020). On balance, such assessments need to be viewed in the context of the original commitment, the source of the data and the evolving guidance, and modalities and procedures from the UNFCCC processes. As mentioned in Chapter 15, the measurement of climate finance flows continues to face definitional, coverage and reliability issues despite progress made by various data providers and collators (see section 15.3.2 in Chapter 15).

The multiplicity of actors providing financial support has resulted in a fragmented international climate finance architecture as indicated in Section 14.3.2.8. It is also seen as a system which allows for speed, flexibility and innovation (Pickering et al. 2017). However, the system is not yet delivering adequate flows given the needs of developing countries (see Section 14.3.2.8). An early indication of these self-assessed needs is provided in the conditional NDCs. Of the 136 conditional NDCs submitted by June 2019, 110 have components or additional actions conditioned on financing support for mitigation and 79 have components or additional actions for support for adaptation (Pauw et al. 2020). While the Paris Agreement did not explicitly countenance conditionality for actions in developing countries, it is generally understood that the ambition and effectiveness of climate ambition in these countries is dependent on financial support (Voigt and Ferreira 2016b).

14.4.1.1 Bilateral finance

The Paris Agreement and the imperative for sustainable development reinforce the need to forge strong linkages between climate and development (Fay et al. 2015). This in turn has highlighted the urgent need for greater attention to the relationship between development assistance and finance, and climate change (Steele 2015).

The UNFCCC website cites some 20 bilateral development agencies providing support to climate change programs in developing countries (UNFCCC 2020a). These agencies provide a mix of development cooperation, policy advice and support and financing for climate change projects. Since the year 2000, the OECD Development Assistance Committee has been tracking trends in climate-related development finance and assistance. The amount of bilateral development finance with climate relevance has increased substantially since 2000 (OECD 2019a). For 2019, it was reported to be USD28.8 billion in direct finance and USD2.6 billion through export credit agencies. Further, another USD34.1 billion of the climate finance provided through multilateral channels is attributable to the developed countries (OECD 2021). The OECD methodology has been critiqued as it uses Rio markers the limitations of which could lead to erroneous reporting and assessment of finance provided as well as the mitigation outcome (Michaelowa and Michaelowa 2011b; Weikmans and Roberts 2019). This issue is to be addressed through the modalities, procedures and guidance under the Enhanced Transparency Framework of the Paris Agreement (see Section 14.3.2.4), through the mandate to Subsidiary Body for Scientific and Technological Advice (SBSTA) to develop Common Tabular Formats (CTFs) for the reporting of information on, *inter alia*, financial support provided, mobilised and received (UNFCCC 2019k). Until then, the Biennial Assessment Report prepared by the Standing Committee on Finance provides the best available information on financial support.

14.4.1.2 Multilateral finance

Multilateral Development Banks (MDBs) comprise six global development banks that include the European Investment Bank (EIB), International Fund for Agricultural Development (IFAD), International Investment Bank (IIB), New Development Bank (NDB), OPEC Fund for International Development (OFID), and the World Bank Group, six regional development banks that include the African Development Bank (AfDB), Asian Development Bank (AsDB), Asian Infrastructure Investment Bank (AIIB), European Bank for Reconstruction and Development (EBRD), Inter-American Development Bank (IADB), and the Islamic Development Bank (IsDB), and thirteen sub-regional development banks that include the Arab Bank for Economic Development in Africa (BADEA), Arab Fund for Economic and Social Development (AFESD), Black Sea Trade and Development Bank (BSTDB), Caribbean Development Bank (CDB), Central American Bank for Economic Integration (CABEI), Development Bank of the Central African States (BDEAC), Development Bank of Latin America (CAF), East African Development Bank (EADB), Eastern and Southern African Trade and Development Bank (TDB), Economic Cooperation Organization Trade and Development Bank (ETDB), ECOWAS Bank for Investment and Development (EBID), Eurasian Development Bank EDB), and the West African Development Bank (BOAD). Together they play a key role in international cooperation at the global, regional and sub-regional level because of their growing mandates and proximity to policymakers (Engen and Prizzon 2018). For many, climate change is a growing priority and for some, because of the needs of the regions, or sub-regions in which they operate, climate change is embedded in many of their operations.

In 2015, twenty representative MDBs and members of the International Development Finance Club unveiled five voluntary principles to mainstream climate action in their investments, including commitment to climate strategies, managing climate risks, promoting climate smart objectives, improving climate performance and accounting for their own actions (World Bank 2015a; Institute for Climate Economics 2017). The members subscribing to these principles have since grown to 44 in January 2020. Arguably, it is only through closer linkages between climate and development that significant inroads can be made in addressing climate change. MDBs can play a major role through the totality of their portfolios (Larsen et al. 2018).

The MDBs as a cohort have been collaborating and coordinating in reporting on climate financing since 2012 following a commitment made in 2012 at the Rio +20 summit (MDB 2012). This has engendered other forms of collaboration among the MDBs, including: commitments to collectively total at least USD65 billion annually by 2025 in climate finance, with USD50 billion for low and middle income economies; to mobilise a further USD40 billion annually by 2025 from private sector investors, including through the increased provision of technical assistance, use of guarantees, and other de-risking instruments; and to commit to helping clients deliver on the goals of the Paris Agreement; building a transparency framework on impact of MDBs' activities and enabling clients to move away from fossil fuels (Asian Development Bank 2019). While the share of MDBs in direct climate financing is small, their role in influencing national development banks and local financial institutions, and leveraging and crowding in private investments in financing sustainable infrastructure, is widely recognised (NCE 2016). However, with this recognition there is also an exhortation to do more to align with the goals of the Paris Agreement, including a comprehensive examination of their portfolios beyond investments that directly support climate action to also enabling the long-term net zero GHG emissions trajectory (Cochran and Pauthier 2019; Larsen et al. 2018). Further, a recent assessment has shown that MDBs perform relatively better in mobilising other public finance than private co- financing (Thwaites 2020). In addition, the banks have launched or are members of significant initiatives such as the Climate and Clean Air Coalition (CCAC) to reduce short lived climate pollutants, the Carbon Pricing Leadership Coalition (CPLC), the Coalition for Climate Resilient Investment (CCRI) and the Coalition of Finance Ministers for climate action. These help to spur action at different levels, from economic analysis, to carbon financing and convenors of finance and development ministers for climate action, with leadership of many of these initiatives led by the World Bank.

The multilateral climate funds also have a role in the international climate finance architecture. This includes, as mentioned in Section 14.3.2.8, those established under the UNFCCC's financial mechanism, its operating entities, the Global Environment Facility (GEF), which also manages two special funds, the Special Climate Change Fund (SCCF) and the Least Developed Countries Fund (LDCF); the Green Climate Fund (GCF), also an operating entity of the financial mechanism which in 2015, was given a special role in supporting the Paris Agreement. The GCF aims to provide funding at scale, balanced between mitigation and adaptation, using various financial instruments including grants, loans, equity, guarantees or others to activities that are aligned with the priorities of the countries compatible with the principle of country ownership (GCF 2011). The GCF faces many challenges. While some see the GCF as an opportunity to transform and rationalise what is now a complex and fragmented climate finance architecture with insufficient resources and overlapping remits (Nakhooda et al. 2014), others see it as an opportunity to address the frequent tensions which arise between mitigation-focused transformation and national priorities of countries. This tension is at the heart of the principle of country ownership and the need for transformational change (Winkler and Dubash 2016).

Leveraging private funds and investments by the public sector, taking risks to unlock climate action are also expressed strategic aims of the GCF.

The UN system is also supporting climate action through much needed technical assistance and capacity building, which is complementary to the financial flows insofar as it enables countries with relevant tools and methodologies to assess their needs, develop national climate finance roadmaps, establish relevant institutional mechanisms to receive support and track it, enhance readiness to access financing, and include climate action across relevant national financial planning and budgeting processes (UN 2017a). The United Nations Development Programme (UNDP) is the largest implementer of climate action among the UN Agencies, with others, such as the Food and Agriculture Organisation (FAO), United Nations Environment Programme (UNEP), United Nations Industrial Development Organisation (UNIDO), and United Nations Office for South-South Cooperation (UNOSSC), providing relevant support.

The current architecture of climate finance is one that is primarily based on north-south, developed-developing country dichotomies. The Paris Agreement, however, has clearly recognised the role of climate finance flows across developing countries, thereby enhancing the scope of international cooperation (Voigt and Ferreira 2016b). Estimates of such flows, though, are not readily available. According to one estimate in 2020 the flows among non-OECD countries were of the order of USD29 billion (CPI 2021).

14.4.1.3 Private sector financing

There is a growing recognition of the importance of mobilising private sector financing including for climate action (World Bank 2015b; Michaelowa et al. 2020b). An early example of the mobilisation of the private sector in a cooperative mode for mitigation outcomes is evidenced from the Clean Development Mechanism of the Kyoto Protocol and the linking with the European Union's Emissions Trading Scheme, both triggered by relevant provisions in the Kyoto Protocol (see Section 14.4.4) and lessons learnt from this are relevant for development of market mechanisms in the post Paris Agreement period (Michaelowa et al. 2019b). In 2019/2020, on an average for the two years, public and private climate financing was on the order of USD632 billion, of which USD310 billion originated from the private sector. However, as much as 76% of the (overall) finance stayed in the country of origin. This trends holds true also for private finance (CPI 2021). Figure 14.4 depicts the international climate finance flows totalling USD161 billion reported in 2020, about 19% were private flows. For (international) mitigation financing flows of USD116 billion, the share provided by private sources was 24%.

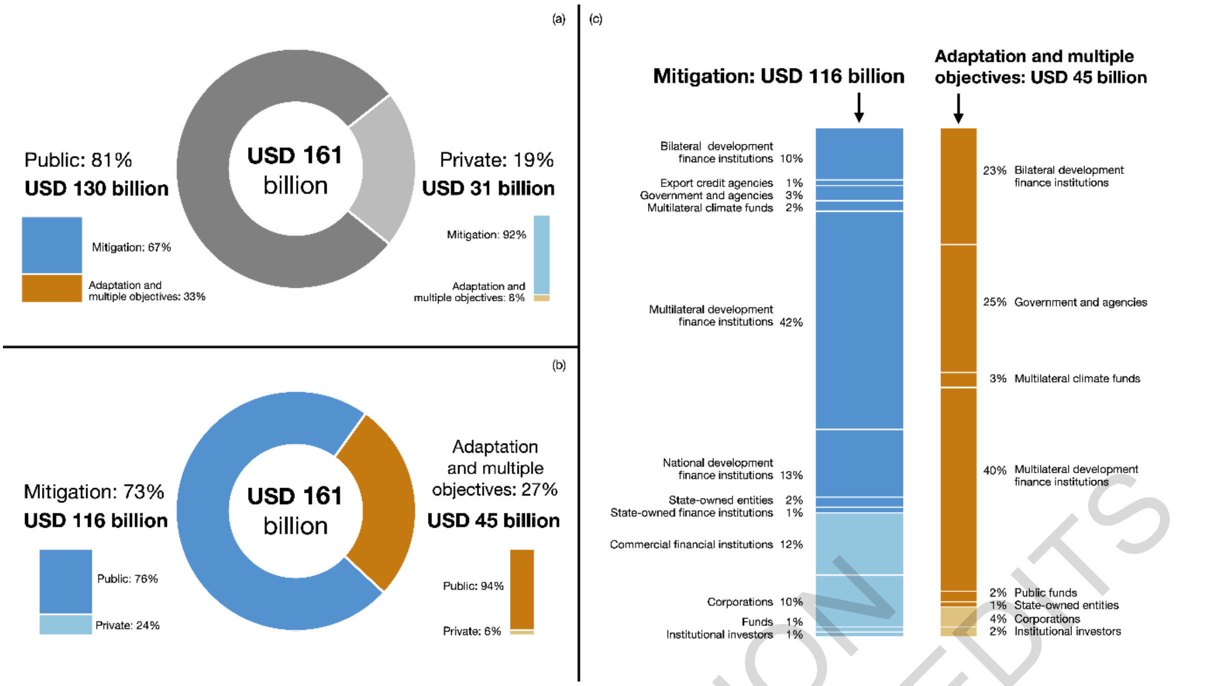


Figure 14.4 International Finance Flows. Total international climate financial flows for 2020 were USD161 billion. By comparison, public sector bilateral and multilateral finance in 2017 for fossil fuel development, including gas pipelines, was roughly USD4 billion. Part (a) disaggregates total financial flows according to public and private sources, and indicates the breakdown between mitigation on the one hand, and adaptation and multiple objectives on the other, within each source. Part (b) disaggregates total financial flows according to intended purpose, namely mitigation or adaptation and multiple objectives, and disaggregates each type according to source. Part (c) provides additional detail on the relative contributions of different public and private sources. Sources: (CPI 2021; OECD 2021).

Foreign direct investments and its greening is seen as a channel for increasing cooperation. An assessment of the greenfield foreign direct investment in different sectors shows the growing share of renewable energy at USD92.2 billion (12% of the volume and 38% of the number of projects) (FDI Intelligence 2020). Coal, oil and gas sectors maintain the top spot for capital investments globally. Over the last decade there is growing issuance of green bonds with non-financial private sector issuance gaining ground (Almeida 2020). While it is questionable if green bonds have a significant impact on shifting capital from non-sustainable to sustainable investments, they do incentivise the issuing organisations to enhance their green ambition and have led to an appreciation within capital markets of green frameworks and guidelines and signalling new expectations (Maltais and Nykvist 2020). In parallel, institutional investors including pension funds are seeking investments that align with the Paris Agreement (IIGCC 2020). However, the readiness of institutional investors to make this transition is arguable (OECD 2019b; Ameli et al. 2020). This evidence suggests that international private financing could play an important role but this potential is yet to be realised (see Chapter 15).

14.4.2 Science, technology and innovation

Science, technology and innovation are essential for the design of effective measures to address climate change and, more generally, for economic and social development (de Coninck and Sagar 2015a). The OECD finds that single countries alone often cannot provide effective solutions to today's global challenges, as these cross national borders and affect different actors (OECD 2012). Madani (2020) shows how conflict, including international sanctions, can reduce science and innovation capacity, which is not evenly distributed, particularly across the developed and the developing world. For this reason, many countries have introduced strategies and policies to enhance international cooperation in science and technology (Chen et al. 2019). Partnerships and international cooperation can play a role in establishing domestic innovation systems, which enable more effective science and technology innovation (de Coninck and Sagar 2015b,a).

International cooperation in science and technology occurs across different levels, with a growing number of international cooperation initiatives aimed at research and collaborative action in technology development. (Weart 2012) finds that such global efforts are effective in advancing climate change science due to the international nature of the challenge. Global research programmes and institutions have also provided the scientific basis for major international environmental treaties. For example, the Long-Range Transboundary Air Pollution Convention and the Montreal Protocol were both informed by scientific assessments based on collaboration and cooperation of scientists across several geographies (Andresen et al. 2000). Furthermore, the Global Energy Assessment (GEA 2012) provided the scientific basis and evidence for the 2030 Agenda for Sustainable Development, in particular SDG7 to ensure access to affordable, reliable and sustainable modern energy for all. The GEA drew on the expertise of scientists from over 60 countries and institutions. Several other platforms exist to provide scientists and policymakers an opportunity for joint research and knowledge sharing, such as The World in 2050, an initiative that brings together scientists from some 40 institutions from around the world to provide the science for SDG and Paris Agreement implementation (TWI2050 2018).

Non-state actors are also increasingly collaborating internationally. Such collaborations, referred to as international cooperative initiatives (ICIs), bring together multi-stakeholder groups across industry, communities, and regions, and operate both within and outside the UNFCCC process. Lui et al. (2021) find that such initiatives could make a major contribution to global emissions reduction, Bakhtiari (2018) finds that the impact on greenhouse gas reduction of these initiatives is hindered due to a lack of coordination between ICIs, overlap with other activities conducted by the UNFCCC and governments, and a lack of monitoring system to measure impact. Increasing the exchange of information between ICIs, enhancing monitoring systems, and increasing collaborative research in science and technology would help address these issues (Boekholt et al. 2009; Bakhtiari 2018).

At the level of research institutes, there has been a major shift to a more structured and global type of cooperation in research; Wagner et al. (2017) found significant increases in both the proportion of papers written by author teams from multiple countries, and in the number of countries participating in such collaboration, over the time period 1990 - 2013. Although only a portion of these scientific papers address the issue of climate change specifically, this growth of scientific collaboration across borders provides a comprehensive view of the conducive environment in which climate science collaboration has grown.

However, there are areas in which international cooperation can be strengthened. Both the Paris Agreement and the 2030 Agenda for Sustainable Development call for more creative forms of international cooperation in science that help bridge the science and policy interface, and provide learning processes and places to deliberate on possible policy pathways across disciplines on a more sustainable and long-lasting basis. Scientific assessments, such as the IPCC and IPBES offer this possibility, but processes need to be enriched for this to happen more effectively (Kowarsch et al. 2016)

A particular locus for international cooperation on technology development and innovation is found within institutions and mechanisms of the UN climate regime. The UNFCCC, in Article 4.1(c), calls on 'all parties' to 'promote and cooperate in the development, application and diffusion, including transfer, of technologies, practices and processes that control, reduce or prevent anthropogenic emissions of greenhouse gases' and places responsibility on developed country parties to 'take all practicable steps to promote, facilitate and finance, as appropriate, the transfer of, or access to environmentally sound technologies and know-how to other parties, particularly developing country parties, to enable them to implement the provisions of the Convention' (UNFCCC 1992, Art. 4.5). The issue of technology development and transfer has continued to receive much attention in the international climate policy domain since its initial inclusion in the UNFCCC in 1992 – albeit often overshadowed by dominant discourses around market-based mechanisms – and its role in reducing GHG emissions and adapting to the consequences of climate change 'is seen as becoming ever more critical' (de Coninck and Sagar 2015a). Milestones in the development of international cooperation on climate technologies under the UNFCCC have included: (1) the development of a technology transfer framework and establishment of the Expert Group on Technology Transfer (EGTT) under the Subsidiary Body for Scientific and Technological Advice (SBSTA) in 2001; (2) recommendations for enhancing the technology transfer framework put forward at the Bali Conference of the Parties in 2007 and creation of the Poznan strategic program on technology transfer under the Global Environmental Facility (GEF); and (3) the establishment of the Technology Mechanism by the Conference of the Parties in 2010 as part of the Cancun Agreements (UNFCCC 2010b). The Technology Mechanism is presently the principal avenue within the UNFCCC for facilitating cooperation on the development and transfer of climate technologies to developing countries (UNFCCC 2015b). As discussed in Section 14.3.2.9 above, the Paris Agreement tasks the Technology Mechanism also to serve the Paris Agreement (UNFCCC 2015b, Art. 10.3).

The Technology Mechanism consists of the Technology Executive Committee (TEC) (replacing the EGTT), as its policy arm, and the Climate Technology Centre and Network (CTCN), as its implementation arm (UNFCCC 2015b). The TEC focuses on identifying and recommending policies that can support countries in enhancing and accelerating the development and transfer of climate technologies (UNFCCC 2020b). The CTCN facilitates the transfer of technologies through three core services: (1) providing technical assistance at the request of developing countries; (2) creating access to information and knowledge on climate technologies; and (3) fostering collaboration and capacity-building (CTCN 2020a). The CTCN 'network' consists of a diverse set of climate technology stakeholders from academic, finance, non-government, private sector, public sector, and research entities, together with more than 150 National Designated Entities, which serve as CTCN national focal points. Through its network, the CTCN seeks to mobilise policy and technical expertise to deliver technology solutions, capacity-building and implementation advice to developing countries (CTCN 2020b). At the Katowice UNFCCC Conference of the Parties in 2018, the TEC and CTCN were requested to incorporate the technology framework developed pursuant to Article 10 of the Paris Agreement into their respective workplans and programmes of work (UNFCCC 2019f).

The Joint Annual Report of the TEC and CTCN for 2019 indicated that, as of July 2019, the CTCN had engaged with 93 developing country parties regarding a total of 273 requests for technical assistance, including 11 multi-country requests. Nearly three-quarters (72.9%) of requests received by the CTCN had a mitigation component, with two-thirds of those mitigation requests related to either renewable energy or energy efficiency. Requests for decision-making or information tools are received most frequently (28% of requests), followed by requests for technology feasibility studies (20%) and technology identification and prioritisation (18%) (TEC and CTCN 2019).

The CTCN is presently funded from 'various sources, ranging from the [UNFCCC] Financial Mechanism to philanthropic and private sector sources, as well as by financial and in-kind contributions from the co-hosts of the CTCN and from participants in the Network' (TEC and CTCN 2019, para. 97). Oh (2020b) describes the institution as 'mainly financially dependent on bilateral donations from developed countries and multilateral support'. Nevertheless, inadequate funding of the CTCN poses a problem for its effectiveness and capacity to contribute to implementation of the Paris Agreement. A 2017 independent review of the CTCN identified 'limited availability of funding' as a key constraint on its ability to deliver services at the expected level and recommended that '[b]etter predictability and security over financial resources will ensure that the CTCN can continue to successfully respond to its

COP mandate and the needs and expectations of developing countries' (Ernst & Young 2017, para. 84). The 2019 Joint Report of the TEC and CTCN indicates that resource mobilisation for the Network remains a challenge (TEC and CTCN 2019, pp. 23-24).

The importance of 'financial support' for strengthening cooperative action on technology development and transfer was recognised in Article 10.6 of the Paris Agreement. The technology framework established by the Paris Rulebook specifies actions and activities relating to the thematic area of 'support' as including: (a) enhancing the collaboration of the Technology Mechanism with the Financial Mechanism; (b) identifying and promoting innovative finance and investment at different stages of the technology cycle; (c) providing enhanced technical support to developing country parties, in a country-driven manner, and facilitating their access to financing for innovation, enabling environments and capacity-building, developing and implementing the results of TNAs, and engagement and collaboration with stakeholders, including organisational and institutional support; and (d) enhancing the mobilisation of various types of support, including pro bono and in-kind support, from various sources for the implementation of actions and activities under each key theme of the technology framework.

Notwithstanding the technology framework's directive for enhanced collaboration of the Technology and Financial Mechanisms of the UNFCCC, linkages between them, and particularly to the GCF, continue to engender political contestation between developing and developed countries (Oh 2020b). Developing countries sought to address concerns over the unsustainable funding status of the CTCN by advocating linkage through a funding arrangement or financial linkage, whereas developed countries favour the design of an institutional linkage maintaining the different and separate mandates of the CTCN and the GCF (Oh 2020a,b). With no resolution reached, the UNFCCC COP requested the Subsidiary Body for Implementation, at its fifty-third session, to take stock of progress in strengthening the linkages between the Technology Mechanism and the Financial Mechanism with a view to recommending a draft decision for consideration and adoption by the Glasgow COP, scheduled for 2021 (UNFCCC 2019l).

14.4.3 Capacity Building

International climate cooperation has long focused on supporting developing countries in building capacity to implement climate mitigation actions. While there is no universally agreed definition of capacity-building and the UNFCCC does not define the term (Khan et al. 2020), elements of capacity-building can be discerned from the Convention's provisions on education and training programmes (UNFCCC 1992, Art. 6), as well as the reference in Article 9(2)(d) of the UNFCCC to the Subsidiary Body for Scientific and Technological Advice (SBSTA) providing support for 'endogenous capacity-building in developing countries.'

Capacity-building is generally conceived as taking place at three levels: individual (focused on knowledge, skills and training), organisational/institutional (focusing on organisational performance and institutional cooperation) and systemic (creating enabling environments through regulatory and economic policies (Khan et al. 2020; UNFCCC 2021b). In its annual synthesis report for 2018, the UNFCCC secretariat compiled information submitted by parties on the implementation of capacity-building in developing countries, highlighting cooperative and regional activities on NDCs, including projects to build capacity for implementation, workshops related to transparency under the Paris Agreement and collaboration to provide coaching and training (UNFCCC 2019h). A number of developing country Parties also highlighted their contributions to South–South cooperation (discussed further in Section 14.5.1.4 below), and identified capacity-building projects undertaken with others (e.g. capacity-building for risk management in Latin America and the Caribbean, improving capacity for measurement, reporting and verification (MRV) through the Alliance of the Pacific and a climate action package launched by Singapore).

Beyond the UNFCCC, other climate cooperation and partnership activities on capacity building include climate-related bilateral cooperation and those organised by the OECD, IFDD (Francophonie Institute for Sustainable Development), UNDP-NCSP programme, UNEP and the World Bank.

Climate-related bilateral cooperation provides important human and institutional capacity building supports for climate change actions and activities in developing countries, particularly through developed countries' bilateral cooperation structures, such as the French Development Agency (AFD), the German Development Agency (The Deutsche Gesellschaft für Internationale Zusammenarbeit – GIZ), the Japanese International Cooperation Agency (JICA) and others.

There are also a number of regional cooperative structures with capacity-building components, including ClimaSouth, Euroclima+, the UN-REDD Programme, the Caribbean Regional Strategic Programme for Resilience, the Caribbean Climate Online Risk and Adaptation Tool, a project on accelerating low carbon and resilient society realisation in the Southeast Asian region, the World Health Organisation's Global Salm-Surv network, the Red Iberoamericana de Oficinas de Cambio Climático network and the Africa Adaptation Initiative. Many climate-related capacity-building initiatives, including those coordinated or funded by international or regional institutions, are implemented at the national and sub-national level, often with the involvement of universities, consultancy groups and civil society actors.

It is also noted that comprehensive support is provided by the GCF to developing countries (GCF, 2020). This support is made available and accessible for all developing countries through three different GCF tools: the Readiness Programme, the Project Preparation Facility, and the funding of transformative projects and programmes. The goal of the Readiness Programme is to strengthen institutional capacities, governance mechanisms, and planning and programming competencies in support of developing countries' transformational long-term climate policies (GCF, 2020). Despite a decades-long process of capacity-building efforts under many development and environmental regimes, including the UNFCCC, progress has been uneven and largely unsuccessful in establishing institution-based capacity in developing countries (Robinson 2018). In an effort to improve capacity-building efforts within the UNFCCC, in 2015, the Paris Committee on Capacity-building (PCCB) was established by the COP decision accompanying the Paris Agreement as the primary body for enhancing capacity-building efforts, including by improving coherence and coordination in capacity-building activities (UNFCCC 2016a, para. 71). The activities of the Committee include the provision of guidance and technical support on climate change training and capacity building, raising awareness and sharing climate information and knowledge. During 2020, the PCCB was able, despite the Covid-19 situation, to hold its 4th meeting, implement and assess its 2017-2020 work plan, and develop and agree on its future roadmap (2021-2024) (UNFCCC Subsidiary Body for Implementation 2020). Non-governmental organisations such as the Coalition on Paris Agreement Capacity-building provide expert input to the PCCB.

Quantifying the contribution of capacity-building efforts to climate mitigation is acknowledged to be 'difficult, if not impossible' (Hsu et al. 2019a). Nonetheless, such activities 'may play a valuable role in building a foundation for future reductions' by providing 'necessary catalytic linkages between actors' (Hsu et al. 2019a).

14.4.4 Cooperative mechanisms and markets

In theory, trading carbon assets can reduce the costs of global climate mitigation, by helping facilitate abatement of greenhouse gases at least-cost locations. This could help countries ratchet up their ambitions more than in a situation without such mechanisms (Mehling et al. 2018), particularly if mechanisms are scaled up from projects and programmes (Michaelowa et al. 2019b). Progress as to developing such mechanisms has however so far been moderate and uneven.

Of the three international market-based mechanisms under the 1997 Kyoto Protocol discussed in Section 14.3.2.7, and in previous IPCC reports, only the CDM or a similar mechanism may have a role to play under the Paris Agreement, although the precise terms are yet to be decided.

Article 6, also discussed in Section 14.3.2.7, is the main framework to foster enhanced cooperation within the Paris Agreement. Although there is an emerging global landscape of activities based on Article 6 (Greiner et al. 2020), such as the bilateral treaty signed under the framework of Article 6 in October 2020 by Switzerland and Peru, the possibilities of bilateral cooperation are yet to be fully exploited. As discussed above, adequate accounting rules are key to the success of Article 6. Sectoral agreements are also a promising cooperative mechanism, as discussed in Section 14.5.2. In fact, both bilateral and sectoral agreements have the potential to enhance the ambition of the parties involved and can eventually serve as building blocks towards more comprehensive agreements (see the discussion in Section 14.2.2).

A relevant and promising new development is the international linkage of existing regional or national emission trading systems. Several emission trading systems are now operational in different jurisdictions, including the EU, Switzerland, China, South Korea, New Zealand, Kazakhstan and several US states and Canadian provinces (Wettestad and Gulbrandsen 2018). More systems are in the pipeline, including Mexico and Thailand (ICAP 2019). The link between the EU and Switzerland entered into force in January 2020 and other linkages are being negotiated. Scholars analyse the potential benefits of these multilateral linkages and demonstrate that these can be significant (Doda et al. 2019; Doda and Taschini 2017). Over time, the linkages of national emission trading systems can be seen as building blocks to a strategic enlargement of international cooperation (Caparrós and Péreau 2017; Mehling 2019). The World Bank has emerged as an important lynchpin and facilitator of knowledge-building and sharing of lessons about the design and linking of carbon markets, through initiatives such as the Partnership for Market Readiness, Networked Carbon Markets and the Carbon Pricing Leadership Coalition (Wettestad et al. 2021).

However, it is important to distinguish between theory and practice. The practice of ETS linking so far demonstrates a few attempts that did not result in linkages due to shifts of governments and political preferences (for instance the process between the EU and Australia, and Ontario withdrawing from the WCI) (Bailey and Inderberg 2018). It is worth noting that the linking of carbon markets raises problems of distribution of costs and loss of political control and hence does not offer a politically easy alternative route to a truly international carbon market. Careful, piece-meal and incremental linking may be the most feasible approach forward (Green et al. 2014; Gulbrandsen et al. 2019). It is premature for any serious assessment of the practice of ETS linking to be conducted. Environmental effectiveness, transformative potential, economic performance, institutional strength and even distributional outcomes can potentially be significant and positive if linking is done carefully (Doda and Taschini 2017; Mehling et al. 2018; Doda et al. 2019), but are all marginal if one focuses on existing experiences (Haites 2016; Schneider et al. 2017; Spalding-Fecher et al. 2012; La Hoz Theuer et al. 2019; Schneider et al. 2019).

14.4.5 International Governance of SRM and CDR

While Solar Radiation Modification (SRM) and Carbon Dioxide Removal (CDR) were often referred to as 'geoengineering' in earlier IPCC reports and in the literature, IPCC SR1.5 started to explore SRM and CDR more thoroughly and to highlight the differences between – but also within – both approaches more clearly. This section assesses international governance of both SRM and CDR, recognizing that CDR, as a mitigation option, is covered elsewhere in this report, whereas SRM is not. Chapter 12 of this report covers the emerging national, sub-national and non-state governance of CDR, while chapters 6, 7 and 12 also assess the mitigation potential, risks and co-benefits of some CDR options. Chapters 4 and 5 of the WGI Report assess the physical climate system and biogeochemical responses to different SRM and CDR methods. The Cross Working Group Box 5 on SRM (WGII, Chapter 16 and Cross-Working Group Box 4 in WGIII below) gives a brief overview of solar radiation modification methods, risks, benefits, ethics and governance.

START CROSS-WORKING GROUP BOX 4 HERE

Cross-Working Group Box in WGII and Cross-Working Group Box 4 in WGIII

Cross-Working Group Box 4: Solar Radiation Modification (SRM)

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Proposed Solar Radiation Modification Schemes

This cross-working group box assesses Solar Radiation Modification (SRM) proposals, their potential contribution to reducing or increasing climate risk, as well as other risks they may pose (categorised as risks from responses to climate change in the IPCC AR6 risk definition in 1.2.1.1), and related perception, ethics and governance questions.

SRM refers to proposals to increase the reflection of shortwave radiation (sunlight) back to space to counteract anthropogenic warming and some of its harmful impacts (de Coninck et al. 2018) (Cross-Working Group Box 4; WGI Chapter 4 and Chapter 5). A number of SRM options have been proposed, including: Stratospheric Aerosol Interventions (SAI), Marine Cloud Brightening (MCB), Ground-Based Albedo Modifications (GBAM), and Ocean Albedo Change (OAC). Although not strictly a form of SRM, Cirrus Cloud Thinning (CCT) has been proposed to cool the planet by increasing the escape of longwave thermal radiation to space and is included here for consistency with previous assessments (de Coninck et al. 2018). SAI is the most-researched proposal. Modeling studies show SRM could reduce surface temperatures and potentially ameliorate some climate change risks (with more confidence for SAI than other options), but SRM could also introduce a range of new risks.

There is high agreement in the literature that for addressing climate change risks SRM cannot be the main policy response to climate change and is, at best, a supplement to achieving sustained net zero or net negative CO_2 emission levels globally (de Coninck et al. 2018; MacMartin et al. 2018; Buck et al. 2020; National Academies of Sciences Engineering and Medecine 2021). SRM contrasts with climate change mitigation activities, such as emission reductions and CDR, as it introduces a ‘mask’ to the climate change problem by altering the Earth’s radiation budget, rather than attempting to address the root cause of the problem, which is the increase in GHGs in the atmosphere. In addition, the effects of proposed SRM options would only last as long as a deployment is maintained— e.g. requiring ca. yearly injection of aerosols in the case of SAI as the lifetime of aerosols in the stratosphere is 1-3 years (Niemeier et al. 2011) or continuous spraying of sea salt in the case of MCB as the lifetime of sea salt aerosols in the atmosphere is only about 10 days—which contrasts with the long lifetime of CO_2 and its climate effects, with global warming resulting from CO_2 emissions likely remaining at a similar level for a hundred years or more (MacDougall et al. 2020) and long-term climate effects of emitted CO_2 remaining for several hundreds to thousands of years (Solomon et al. 2009).

Which scenarios?

The choice of SRM deployment scenarios and reference scenarios is crucial in assessment of SRM risks and its effectiveness in attenuating climate change risks (Keith and MacMartin 2015; Honegger et al. 2021a). Most climate model simulations have used scenarios with highly stylized large SRM forcing to fully counteract large amounts of warming in order to enhance the signal-to-noise ratio of climate responses to SRM (Kravitz et al. 2015; Sugiyama et al. 2018a; Krishnamohan et al. 2019).

The effects of SRM fundamentally depend on a variety of choices about deployment (Sugiyama et al. 2018b), including: its position in the portfolio of human responses to climate change (e.g., the magnitude of SRM used against the background radiative forcing), governance of research and potential deployment strategies, and technical details (latitude, materials, and season, among others, see WGI Chapter 4.6.3.3). The plausibility of many SRM scenarios is highly contested and not all scenarios are equally plausible because of socio-political considerations (Talberg et al. 2018), as with, for example, CDR (Fuss et al. 2014, 2018). Development of scenarios and their selection in assessments should reflect a diverse set of societal values with public and stakeholder inputs (Sugiyama et al. 2018a; Low and Honegger 2020), as depending on the focus of a limited climate model simulation, SRM could look grossly risky or highly beneficial (Pereira et al. 2021).

In the context of reaching the long-term global temperature goal of the Paris Agreement, there are different hypothetical scenarios of SRM deployment: early, substantial mitigation with no SRM, more limited or delayed mitigation with moderate SRM, unchecked emissions with total reliance on SRM, and regionally heterogeneous SRM. Each scenario presents different levels and distributions of SRM benefits, side effects, and risks. The more intense the SRM deployment, the larger is the likelihood for the risks of side effects and environmental risks (e.g., Heutel et al., 2018). Regional disparities in climate hazards may result from both regionally-deployed SRM options such as GBAM, and more globally uniform SRM such as SAI (Jones et al. 2018; Seneviratne et al. 2018). There is an emerging literature on smaller forcings of SAI to reduce global average warming, for instance, to hold global warming to 1.5°C or 2°C alongside ambitious conventional mitigation (Jones et al. 2018; MacMartin et al. 2018), or bring down temperature after an overshoot (Tilmes et al. 2020). If emissions reductions and CDR are deemed insufficient, SRM may be seen by some as the only option left to ensure the achievement of the Paris Agreement's temperature goal by 2100.

Cross-Working Group Box 4, Table 1: SRM options and their potential climate and non-climate impacts. Description, potential climate impacts, potential impacts on human and natural systems, and termination effects of a number of SRM options: Stratospheric Aerosol Interventions (SAI), Marine Cloud Brightening (MCB), Ocean Albedo Change (OAC), Ground-Based Albedo Modifications (GBAM), and Cirrus Cloud Thinning (CCT).

SRM option	SAI	MCB	OAC	GBAM	CCT
Description	Injection of reflective aerosol particles directly into the stratosphere or a gas which then converts to aerosols that reflect sunlight	Spraying sea salt or other particles in marine clouds, making them more reflective	Increase surface albedo of the ocean (e.g., by creating microbubbles or placing reflective foam on the surface)	Whitening roofs, changes in land use management (e.g., no-till farming, bioengineering to make crop leaves more reflective), desert albedo enhancement, covering glaciers with reflective sheeting	Seeding to promote nucleation of cirrus clouds, reducing optical thickness and cloud lifetime to allow more outgoing longwave radiation to escape to space
Potential climate impacts *other*	Change precipitation and runoff	Change in land-sea contrast in	Change in land-sea contrast in	Changes in regional precipitation	Changes in temperature and

than reduced warming	pattern; reduced temperature and precipitation extremes; precipitation reduction in some monsoon regions; decrease in direct and increase in diffuse sunlight at surface; changes to stratospheric dynamics and chemistry; potential delay in ozone hole recovery; changes in surface ozone and UV radiation	temperature and precipitation, regional precipitation and runoff changes	temperature and precipitation, regional , precipitation and runoff changes.	pattern, regional extremes and regional circulation	precipitation pattern, altered regional water cycle, increase in sunlight reaching the surface
Potential impacts on human and natural systems	Changes in crop yields, changes in land and ocean ecosystem productivity, acid rain (if using sulphate), reduced risk of heat stress to corals	Changes in regional ocean productivity, changes in crop yields, reduced heat stress for corals, changes in ecosystem productivity on land, sea salt deposition over land	Unresearched	Altered photosynthesis, carbon uptake and side effects on biodiversity	Altered photosynthesis and carbon uptake
Termination effects	Sudden and sustained termination would result in rapid warming, and abrupt changes to water cycle. Magnitude of termination depends on the degree of warming offset.	Sudden and sustained termination would result in rapid warming, and abrupt changes to water cycle. Magnitude of termination depends on the degree of warming offset.	Sudden and sustained termination would result in rapid warming. Magnitude of termination depends on the degree of warming offset.	GBAM can be maintained over several years without major termination effects because of its regional scale of application. Magnitude of termination depends on the degree of warming offset.	Sudden and sustained termination would result in rapid warming. Magnitude of termination depends on the degree of warming offset.
References (also see main text of this box)	(Visioni et al. 2017) Tilmes et al. (2018) Simpson et al. (2019)	Latham et al. (2012) Ahlm et al. (2017) Stjern et al. (2018)	Evans et al. (2010) Crook et al. (2015)	Davin et al. (2014) Crook et al. (2015) Zhang et al. (2016)	Storelvmo and Herger (2014) Crook et al. (2015)

				Field et al. (2018) Seneviratne et al. (2018)	Jackson et al. (2016) Duan et al. (2020) Gasparini et al. (2020)

SRM risks to human and natural systems and potential for risk reduction

Since AR5, hundreds of climate modelling studies have simulated effects of SRM on climate hazards (Kravitz et al. 2015; Tilmes et al. 2018). Modelling studies have shown SRM has the potential to offset some effects of increasing GHGs on global and regional climate, including the increase in frequency and intensity of extremes of temperature and precipitation, melting of Arctic sea ice and mountain glaciers, weakening of Atlantic meridional overturning circulation, changes in frequency and intensity of tropical cyclones, and decrease in soil moisture (WGI, Chapter 4). However, while SRM may be effective in alleviating anthropogenic climate warming either locally or globally, it would not maintain the climate in a present-day state nor return the climate to a pre-industrial state (climate averaged over 1850-1900, See WGI Chapter 1, Box 1.2) in all regions and in all seasons even when used to fully offset the global mean warming (*high confidence*); WGI Chapter 4}. This is because the climate forcing and response to SRM options are different from the forcing and response to GHG increase. Because of these differences in climate forcing and response patterns, the regional and seasonal climates of a world with a global mean warming of 1.5 or 2°C achieved via SRM would be different from a world with similar global mean warming but achieved through mitigation (MacMartin et al. 2018). At the regional scale and seasonal timescale there could be considerable residual climate change and/or overcompensating change (e.g., more cooling, wetting or drying than just what's needed to offset warming, drying or wetting due to anthropogenic greenhouse gas emissions), and there is low confidence in understanding of the climate response to SRM at the regional scale (WGI, Chapter 4).

SAI implemented to partially offset warming (e.g., offsetting half of global warming) may have potential to ameliorate hazards in multiple regions and reduce negative residual change, such as drying compared to present-day climate, that are associated with fully offsetting global mean warming (Irvine and Keith 2020), but may also increase flood and drought risk in Europe compared to unmitigated warming (Jones et al. 2021). Recent modelling studies suggest it is conceptually possible to meet multiple climate objectives through optimally designed SRM strategies (WGI, Chapter 4). Nevertheless, large uncertainties still exist for climate processes associated with SRM options (e.g. aerosol-cloud-radiation interaction) (WGI, Chapter 4) (Kravitz and MacMartin 2020).

Compared with climate hazards, many fewer studies have examined SRM risks—the potential adverse consequences to people and ecosystems from the combination of climate hazards, exposure and vulnerability—or the potential for SRM to reduce risk (Curry et al. 2014; Irvine et al. 2017). Risk analyses have often used inputs from climate models forced with stylized representations of SRM, such as dimming the sun. Fewer have used inputs from climate models that explicitly simulated injection of gases or aerosols into the atmosphere, which include more complex cloud-radiative feedbacks. Most studies have used scenarios where SAI is deployed to hold average global temperature constant despite high emissions.

There is *low confidence* and large uncertainty in projected impacts of SRM on crop yields due in part to a limited number of studies. Because SRM would result in only a slight reduction in CO_2 concentrations relative to the emission scenario without SRM (Chapter 5, WGI), the CO_2 fertilization effect on plant productivity is nearly the same in emissions scenarios with and without SRM. Nevertheless, changes in climate due to SRM are likely to have some impacts on crop yields. A single study indicates MCB may reduce crop failure rates compared to climate change from a doubling of CO_2 pre-industrial concentrations (Parkes et al. 2015). Models suggest SAI cooling would reduce crop productivity at higher latitudes compared to a scenario without SRM by reducing the growing season length, but benefit crop productivity in lower latitudes by reducing heat stress (Pongratz et al. 2012; Xia et al. 2014; Zhan et al. 2019). Crop productivity is also projected to be reduced where SAI reduces rainfall relative to the scenario without SRM, including a case where reduced Asian summer monsoon rainfall causes a reduction in groundnut yields (Xia et al. 2014; Yang et al. 2016). SAI will increase the fraction of diffuse sunlight, which is projected to increase photosynthesis in forested canopy, but will reduce the direct and total available sunlight, which tends to reduce photosynthesis. As total sunlight is reduced, there is a net reduction in crop photosynthesis with the result that any benefits to crops from avoided heat stress may be offset by reduced photosynthesis, as indicated by a single statistical modeling study (Proctor et al. 2018). SAI would reduce average surface ozone concentration (Xia et al. 2017) mainly as a result of aerosol-induced reduction in stratospheric ozone in polar regions, resulting in reduced downward transport of ozone to the troposphere (Pitari et al. 2014; Tilmes et al. 2018). The reduction in stratospheric ozone also allows more UV radiation to reach the surface. The reduction in surface ozone, together with an increase in surface UV radiation, would have important implications for crop yields but there is *low confidence* in our understanding of the net impact.

Few studies have assessed potential SRM impacts on human health and wellbeing. SAI using sulfate aerosols is projected to deplete the ozone layer, increasing mortality from skin cancer, and SAI could increase particulate matter due to offsetting warming, reduced precipitation and deposition of SAI aerosols, which would increase mortality, but SAI also reduces surface-level ozone exposure, which would reduce mortality from air pollution, with net changes in mortality uncertain and depending on aerosol type and deployment scenario (Effiong and Neitzel 2016; Eastham et al. 2018; Dai et al. 2020). However, these effects may be small compared to changes in risk from infectious disease (e.g., mosquito-borne illnesses) or food security due to SRM influences on climate (Carlson et al. 2020). Using volcanic eruptions as a natural analog, a sudden implementation of SAI that forced the ENSO system may increase risk of severe cholera outbreaks in Bengal (Trisos et al. 2018; Pinke et al. 2019). Considering only mean annual temperature and precipitation, SAI that stabilizes global temperature at its present-day level is projected to reduce income inequality between countries compared to the highest warming pathway (RCP8.5) (Harding et al. 2020). Some integrated assessment model scenarios have included SAI (Arino et al. 2016; Emmerling and Tavoni 2018; Heutel et al. 2018; Helwegen et al. 2019; Rickels et al. 2020) showing the indirect costs and benefits to welfare dominate, since the direct economic cost of SAI itself is expected to be relatively low (Moriyama et al. 2017; Smith and Wagner 2018). There is a general lack of research on the wide scope of potential risk or risk reduction to human health, wellbeing and sustainable development from SRM and on their distribution across countries and vulnerable groups (Carlson et al. 2020; Honegger et al. 2021a).

SRM may also introduce novel risks for international collaboration and peace. Conflicting temperature preferences between countries may lead to counter-geoengineering measures such as deliberate release of warming agents or destruction of deployment equipment (Parker et al. 2018). Game-theoretic models and laboratory experiments indicate a powerful actor or group with a higher preference for SRM may use SAI to cool the planet beyond what is socially optimal, imposing welfare losses on others although this cooling does not necessarily imply excluded countries would be worse off relative to a world of unmitigated warming (Ricke et al. 2013; Weitzman 2015; Abatayo et al. 2020). In this context counter-geoengineering may promote international cooperation or lead to large welfare losses (Helwegen et al. 2019; Abatayo et al. 2020).

Cooling caused by SRM would increase the global land and ocean CO_2 sinks (*medium confidence*), but this would not stop CO_2 from increasing in the atmosphere or affect the resulting ocean acidification under continued anthropogenic emissions (*high confidence*) (WGI Chapter 5).

Few studies have assessed potential SRM impacts on ecosystems. SAI and MCB may reduce risk of coral reef bleaching compared to global warming with no SAI (Latham et al. 2013; Kwiatkowski et al. 2015), but risks to marine life from ocean acidification would remain, because SRM proposals do not reduce elevated levels of anthropogenic atmospheric CO_2 concentrations. MCB could cause changes in marine net primary productivity by reducing light availability in deployment regions, with important fishing regions off the west coast of South America showing both large increases and decreases in productivity (Partanen et al. 2016; Keller 2018).

There is large uncertainty in terrestrial ecosystem responses to SRM. By decoupling increases in atmospheric greenhouse gas concentrations and temperature, SAI could generate substantial impacts on large-scale biogeochemical cycles, with feedbacks to regional and global climate variability and change (Zarnetske et al. 2021). Compared to a high CO_2 world without SRM, global-scale SRM simulations indicate reducing heat stress in low latitudes would increase plant productivity, but cooling would also slow down the process of nitrogen mineralization which could decrease plant productivity (Glienke et al. 2015; Duan et al. 2020). In high latitude and polar regions SRM may limit vegetation growth compared to a high CO_2 world without SRM, but net primary productivity may still be higher than pre-industrial climate (Glienke et al. 2015). Tropical forests cycle more carbon and water than other terrestrial biomes but large areas of the tropics may tip between savanna and tropical forest depending on rainfall and fire (Beer et al. 2010; Staver et al. 2011). Thus, SAI-induced reductions in precipitation in Amazonia and central Africa are expected to change the biogeography of tropical ecosystems in ways different both from present-day climate and global warming without SAI (Simpson et al. 2019; Zarnetske et al. 2021). This would have potentially large consequences for ecosystem services (Chapter 2 and Chapter 9). When designing and evaluating SAI scenarios, biome-specific responses need to be considered if SAI approaches are to benefit rather than harm ecosystems. Regional precipitation change and sea salt deposition over land from MCB may increase or decrease primary productivity in tropical rainforests (Muri et al. 2015). SRM that fully offsets warming could reduce the dispersal velocity required for species to track shifting temperature niches whereas partially offsetting warming with SAI would not reduce this risk unless rates of warming were also reduced (Trisos et al. 2018; Dagon and Schrag 2019). SAI may reduce high fire risk weather in Australia, Europe and parts of the Americas, compared to global warming without SAI (Burton et al. 2018). Yet SAI using sulfur injection could shift the spatial distribution of acid-induced aluminum soil toxicity into relatively undisturbed ecosystems in Europe and North America (Visioni et al. 2020). For the same amount of global mean cooling, SAI, MCB, and CCT would have different effects on gross and net primary productivity because of different spatial patterns of temperature, available sunlight, and hydrological cycle changes (Duan et al. 2020). Large-scale modification of land surfaces for GBAM may have strong trade-offs with biodiversity and other ecosystem services, including food security (Seneviratne et al. 2018). Although existing studies indicate SRM will have widespread impacts on ecosystems, risks and potential for risk reduction for marine and terrestrial ecosystems and biodiversity remain largely unknown.

A sudden and sustained termination of SRM in a high CO_2 emissions scenario would cause rapid climate change (*high confidence*; WGI Chapter 4). More scenario analysis is needed on the potential likelihood of sudden termination (Kosugi 2013; Irvine and Keith 2020). A gradual phase-out of SRM combined with emission reduction and CDR could avoid these termination effects (*medium confidence*) (MacMartin et al. 2014; Keith and MacMartin 2015; Tilmes et al. 2016). Several studies find that large and extremely rapid warming and abrupt changes to the water cycle would occur within a decade if a sudden termination of SAI occurred (McCusker et al. 2014; Crook et al. 2015). The size of this 'termination shock' is proportional to the amount of radiative forcing being masked by SAI. A sudden termination of SAI could place many thousands of species at risk of extinction, because the resulting rapid warming would be too fast for species to track the changing climate (Trisos et al. 2018).

Public perceptions of SRM

Studies on the public perception of SRM have used multiple methods: questionnaire surveys, workshops, and focus group interviews (Burns et al. 2016; Cummings et al. 2017). Most studies have been limited to Western societies with some exceptions. Studies have repeatedly found that respondents are largely unaware of SRM (Merk et al. 2015). In the context of this general lack of familiarity, the publics prefer carbon dioxide removal (CDR) to SRM (Pidgeon et al. 2012), are very cautious about SRM deployment because of potential environmental side effects and governance concerns, and mostly reject deployment for the foreseeable future. Studies also suggest conditional and reluctant support for research, including proposed field experiments, with conditions of proper governance (Sugiyama et al. 2020). Recent studies show that the perception varies with the intensity of deliberation (Merk et al. 2019), and that the public distinguishes different funding sources (Nelson et al. 2021). Limited studies for developing countries show a tendency for respondents to be more open to SRM (Visschers et al. 2017; Sugiyama et al. 2020), perhaps because they experience climate change more directly (Carr and Yung 2018). In some Anglophone countries, a small portion of the public believes in chemtrail conspiracy theories, which are easily found in social media (Tingley and Wagner 2017; Allgaier 2019). Since researchers rarely distinguish different SRM options in engagement studies, there remains uncertainty in public perception.

Ethics

There is broad literature on ethical considerations around SRM, mainly stemming from philosophy or political theory, and mainly focused on SAI (Flegal et al. 2019). There is concern that publicly debating, researching and potentially deploying SAI could involve a 'moral hazard', with potential to obstruct ongoing and future mitigation efforts (Morrow 2014; Baatz 2016; McLaren 2016), while empirical evidence is limited and mostly at the individual, not societal, level (Burns et al. 2016; Merk et al. 2016, 2019). There is low agreement whether research and outdoors experimentation will create a 'slippery slope' toward eventual deployment, leading to a lock-in to long-term SRM, or can be effectively regulated at a later stage to avoid undesirable outcomes (Hulme 2014; Parker 2014; Callies 2019; McKinnon 2019). Regarding potential deployment of SRM, procedural, distributive and recognitional conceptions of justice are being explored, (Svoboda and Irvine 2014; Svoboda 2017; Preston and Carr 2018; Hourdequin 2019). With the SRM research community's increasing focus on distributional impacts of SAI, researchers have started more explicitly considering inequality in participation and inclusion of vulnerable countries and marginalized social groups (Flegal and Gupta 2018; Whyte 2018; Táíwò and Talati 2021), including considering stopping research (Stephens and Surprise 2020; National Academies of Sciences Engineering and Medecine 2021). There is recognition that SRM research has been conducted predominantly by a relatively small number of experts in the Global North, and that more can be done to enable participation from diverse peoples and geographies in setting research agendas and research governance priorities, and undertaking research, with initial efforts to this effect (e.g., Rahman et al. 2018), noting unequal power relations in participation could influence SRM research governance and potential implications for policy (Winickoff et al. 2015; Frumhoff and Stephens 2018; Whyte 2018; Biermann and Möller 2019; McLaren and Corry 2021; National Academies of Sciences Engineering and Medecine 2021; Táíwò and Talati 2021).

Governance of research and of deployment

Currently, there is no dedicated, formal international SRM governance for research, development, demonstration, or deployment (see WGIII Chapter 14). Some multilateral agreements—such as the UN Convention on Biological Diversity or the Vienna Convention on the Protection of the Ozone Layer—indirectly and partially cover SRM, but none is comprehensive and the lack of robust and formal SRM governance poses risks (Ricke et al. 2013; Talberg et al. 2018; Reynolds 2019a). While governance objectives range broadly, from prohibition to enabling research and potentially deployment (Sugiyama et al. 2018b; Gupta et al. 2020), there is agreement that SRM governance should cover all interacting stages of research through to any potential, eventual deployment with rules, institutions, and norms (Reynolds 2019b). Accordingly, governance arrangements are co-evolving with respective SRM technologies across the interacting stages of research, development, demonstration, and—potentially—deployment (Rayner et al. 2013; Parker 2014; Parson 2014). Stakeholders are developing governance already in outdoors research; for example, for MCB and OAC experiments on the Great Barrier Reef (McDonald et al. 2019). Co-evolution of governance and SRM research provides a chance for responsibly developing SRM technologies with broader public participation and political legitimacy, guarding against potential risks and harms relevant across a full range of scenarios, and ensuring that SRM is considered only as a part of a broader portfolio of responses to climate change (Stilgoe 2015; Nicholson et al. 2018). For SAI, large-scale outdoor experiments even with low radiative forcing could be transboundary and those with deployment-scale radiative forcing may not be distinguished from deployment, such that (MacMartin and Kravitz 2019) argue for continued reliance on modeling until a decision on whether and how to deploy is made, with modeling helping governance development. For further discussion of SRM governance see Chapter 14, WGIII.

END CROSS-WORKING GROUP BOX 4 HERE

14.4.5.1 Global governance of solar radiation modification and associated risks

Solar Radiation Modification, in the literature also referred to as 'solar geoengineering', refers to the intentional modification of the Earth's shortwave radiative budget, such as by increasing the reflection of sunlight back to space, with the aim of reducing warming. Several SRM options have been proposed, including Stratospheric Aerosol Injection (SAI), Marine Cloud Brightening (MCB), Ground-Based Albedo Modifications, and Ocean Albedo Change (OAC). SRM has been discussed as a potential response option within a broader climate risk management strategy, as a supplement to emissions reduction, carbon dioxide removal and adaptation (Crutzen 2006; Shepherd 2009; Caldeira and Bala 2017; Buck et al. 2020), for example as a temporary measure to slow the rate of warming (Keith and MacMartin 2015) or address temperature overshoot (MacMartin et al. 2018; Tilmes et al. 2020). SRM assessments of potential benefits and risks still primarily rely on modelling efforts and their underlying scenario assumptions (Sugiyama et al. 2018a), for example in the context of the Geoengineering Model Intercomparison Project GeoMIP6 (Kravitz et al. 2015). Recently, small-scale MCB and OAC experiments started to take place on the Great Barrier Reef (McDonald et al. 2019).

Stratospheric aerosol intervention (SAI) – the most researched SRM method – poses significant international governance challenges since it could potentially be deployed uni- or minilaterally and alter the global mean temperature much faster than any other climate policy measure, at comparatively low direct costs (Parson 2014; Nicholson et al. 2018; Smith and Wagner 2018; Sugiyama et al. 2018b; Reynolds 2019a). While being dependent on the design of deployment systems, both geophysical benefits and adverse effects would potentially be unevenly distributed (WGI Chapter 4). Perceived local harm could exacerbate geopolitical conflicts, not the least depending on which countries are part of a deployment coalition (Maas and Scheffran 2012; Zürn and Schäfer 2013), but also because immediate attribution of climatic impacts to detected SAI deployment would not be possible. Uncoordinated or poorly researched deployment by a limited number of states, triggered by perceived climate emergencies, could create international tensions (Corry 2017; Lederer and Kreuter 2018). An additional risk is that of rapid temperature rise following an abrupt end of SAI activities (Parker and Irvine 2018; Rabitz 2019).

While there is room for national and even sub-national governance of SAI – for example on research (differentiating indoor from open-air) (Jinnah et al. 2018; Hubert 2020) and public engagement (Bellamy and Lezaun 2017; Flegal et al. 2019) – international governance of SAI faces the challenge that comprehensive institutional architectures designed too far in advance could prove either too restrictive or too permissive in light of subsequent political, institutional, geophysical and technological developments (Sugiyama et al. 2018a; Reynolds 2019a). Views on governance encompass a broad range, from aiming to restrict to wanting to enable research and potentially deployment; in between these poles, other suggest authors stress the operationalization of the precautionary approach: preventing deployment until specific criteria regarding scientific consensus, impact assessments and governance issues are met (Tedsen and Homann 2013; Wieding et al. 2020). Many scholars suggest that governance arrangements ought to co-evolve with respective SRM technologies (Parker 2014), including that it stay at least one step ahead of research, development, demonstration, and—potentially—deployment (Rayner et al. 2013; Parson 2014). With the modelling community's increasing focus on showing that, and in what ways, SAI could help to minimise climate change impacts in the Global South, the SRM governance literature has come to include considerations of how SAI could contribute to global equity (Horton and Keith 2016; Flegal and Gupta 2018; Hourdequin 2018).

Given that risks and potential benefits of SRM proposals differ substantially and their large-scale deployment is highly speculative, there is a wide array of concrete proposals for near-term anticipatory or adaptive governance. Numerous authors suggest a wide range of governance principles; (Nicholson et al. 2018) encapsulate most of these in suggesting a list of four: (1) Guard against potential risks and harm; (2) Enable appropriate research and development of scientific knowledge; (3) Legitimise any future research or policymaking through active and informed public and expert community engagement; (4) Ensure that SRM is considered only as a part of a broader, mitigation-centred portfolio of responses to climate change. Regarding international institutionalisation, options range from formal integration into existing UN bodies like the UNFCCC (Nicholson et al. 2018) or the Convention on Biological Diversity (CBD) (Bodle et al. 2014) to the creation of specific, but less formalised global fora (Parson and Ernst 2013) to forms of club governance (Lloyd and Oppenheimer 2014; Bodansky 2013). Recent years have also seen the emergence of transnational non-state actors focusing on SRM governance, primarily expert networks and NGOs (Horton and Koremenos 2020).

Currently, there is no targeted international law relating to SRM, although some multilateral agreements—such as the Convention on Biological Diversity, the UN Convention on the Law of the Sea, the Environmental Modification Convention, or the Vienna Convention on the Protection of the Ozone Layer and its Montreal Protocol—contain provisions applicable to SRM (Jinnah and Nicholson 2019; Bodansky 2013; Reynolds 2019a).

14.4.5.2 Carbon Dioxide removal

Carbon dioxide removal refers to a cluster of technologies, practices, and approaches that remove and sequester carbon dioxide from the ocean and atmosphere and durably store it in geological, terrestrial, or ocean reservoirs, or in products (see Table 12.6). In contrast to SRM, CDR does not necessarily impose transboundary risks, except insofar as misleading accounting of its use and deployment could give a false picture of countries' overall mitigation efforts. CDR is clearly a form of climate change mitigation, and as described in chapter 12 is needed to counterbalance residual GHG emissions that may prove hard to abate (e.g., from industry, aviation or agriculture) in the context of reaching net zero emissions both globally – in the context of Article 4 of the Paris Agreement – and nationally. CDR could also later be used for reducing atmospheric CO_2 concentrations by providing net negative emissions on the global level (Fuglestvedt et al. 2018; Bellamy and Geden 2019). Despite the common feature of removing carbon dioxide, technologies like afforestation/reforestation, soil carbon sequestration, bioenergy with carbon capture and storage (BECCS), direct air capture with carbon storage, enhanced weathering, ocean alkalinity enhancement or ocean fertilisation are very different, as are the governance challenges. Chapter 12 highlights the sustainable development risks associated with land and water use that are connected to the biological approaches to CDR. As a public good which largely lacks incentives to be pursued as a business case, most types of CDR require a suite of dedicated policy instruments that address both near-term needs as well as long-term continuity at scale (Honegger et al. 2021b).

CDR methods other than afforestation/reforestation and soil carbon sequestration have only played a minor role in UNFCCC negotiations so far (Fridahl 2017; Rumpel et al. 2020). To accelerate, and indeed better manage CDR globally, stringent rules and practices regarding emissions accounting, MRV and project-based market mechanisms have been proposed (Honegger and Reiner 2018; Mace et al. 2018). Given their historic responsibility, it can be expected that developed countries would carry the main burden of researching, developing, demonstrating and deploying CDR, or finance such projects in other countries (Pozo et al. 2020; Fyson et al. 2020). McLaren et al. (2019) suggest that there is a rationale for separating the international commitments for net negative emissions from those for emission reductions.

Specific regulations CDR options have been limited to those posing transboundary risks, namely the use of ocean fertilization. In a series of separate decisions from 2008 - 13, the London Convention / Protocol parties limited ocean fertilization activities to only those of a research character, and in 2012 the CBD made a non-legally binding decision to do the same, further requiring such research activities to be limited scale, and carried out under controlled conditions, until more knowledge is gained to be able to assess the risks (GESAMP 2019; Burns and Corbett 2020). In doing so they have taken a precautionary approach (Sands & Peel, 2018). The London Convention/Protocol has also developed an Assessment Framework for Scientific Research Involving Ocean Fertilisation (London Convention/Protocol 2010) and in 2013 adopted amendments (which are not yet in force) to regulate marine carbon dioxide removal activities, including ocean fertilisation.

14.5 Multi-level, multi-actor governance

The Paris Agreement sets in place a new framework for international climate policy (Paroussos et al. 2019), which some cite as evidence of 'hybrid multilateralism' (Savaresi 2016; Christoff 2016; Bäckstrand et al. 2017). While a trend of widening involvement of non-state actors was evident prior to conclusion of the Paris Agreement, particularly at UNFCCC COPs, the 'new landscape of international climate cooperation' features an 'intensified interplay between state and non-state actors,' including civil society and social movements, business actors, and subnational or substate actors, such as local governments and cities (Bäckstrand et al. 2017, p. 562). This involvement of other actors beyond states in international climate cooperation is facilitated by the Paris Agreement's 'hybrid climate policy architecture' (Bodansky et al. 2016) (Section 14.3.1.1 above), which acknowledges the primacy of domestic politics in climate change and invites the mobilisation of international and domestic pressure to make the Agreement effective (Falkner 2016b). In this landscape, there is greater flexibility for more decentralised 'polycentric' forms of climate governance and recognition of the benefits of working in diverse forms and groups to realise global climate mitigation goals (Oberthür 2016; Jordan et al. 2015) (see also Chapter 1, 1.9) .

Increasing attention has focused on the role of multi-level, multi-actor cooperation among actors, groupings and agreements beyond the UNFCCC climate regime as potential 'building blocks' towards enhanced international action on climate mitigation (Falkner 2016a; Caparrós and Péreau 2017; Potoski 2017; Stewart et al. 2017). This can include agreements on emissions and technologies at the regional or sub-global level; what scholars often refer to as climate club' (Nordhaus 2015; Hovi et al. 2016; Green 2017; Sprinz et al. 2018). One forum through which such agreements are often discussed, in support of UNFCCC objectives, are high-level meetings of political leaders, such of the G7 and G20 states (Livingston 2016). It also includes cooperation on narrower sets of issues than are found within the Paris Agreement; for instance, other international environmental agreements dealing with a particular subset of GHGs; linkages with, or leveraging of, efforts or agreements in other spheres such as adaptation, human rights or trade; agreements within particular economic sectors; or transnational initiatives involving global cooperative efforts by different types of non-state actors. Cooperative efforts in each of these forums are reviewed in the following sections of the chapter. Section 14.5.1 discusses international cooperation at multiple governance levels (global, sub-global and regional); Section 14.5.2 discusses cooperation with international sectoral agreements and institutions such as in the forestry, energy and transportation sectors; and Sections 14.5.3-14.5.5 discuss transnational cooperation across civil society and social movements, business partnerships and investor coalitions, and between sub-national entities and cities, respectively.

A key idea underpinning this analysis is that decomposition of the larger challenge of climate mitigation into 'smaller units' may facilitate more effective cooperation (Sabel and Victor 2017) and complement cooperation in the UN climate regime (Stewart et al. 2017). However, it is recognised that significant uncertainty remains over the feasibility and costs of these efforts (Sabel and Victor 2017), as well as whether they ultimately strengthen progress on climate mitigation in the multilateral climate arena (Falkner 2016a).

14.5.1 International cooperation at multiple governance levels

14.5.1.1 Role of other environmental agreements

International cooperation on climate change mitigation takes place at multiple governance levels, including under a range of multilateral environmental agreements (MEAs) beyond those of the international climate regime.

The 1987 Montreal Ozone Protocol is the leading example of a non-climate MEA with significant implications for mitigating climate change (Barrett 2008). The Montreal Protocol regulates a number of substances that are both ozone depleting substances (ODS) and GHGs with a significant global warming potential (GWP), including chlorofluorocarbons, halons and hydrochlorofluorocarbons (HCFCs). As a result, implementation of phase-out requirements for these substances under the Montreal Protocol has made a significant contribution to mitigating climate change (Molina et al. 2009) (See also Section 9.9.7.1). Velders et al. (2007) found that over the period from 1990 to 2010, the reduction in GWP100-weighted ODS emissions expected with compliance to the provisions of the Montreal Protocol was 8 $GtCO_2eq\ yr^{-1}$, an amount substantially greater than the first commitment period Kyoto reduction target. Young et al. (2021) suggest that the Montreal Protocol may also be helping to mitigate climate change through avoided decreases in the land carbon sink.

The 2016 Kigali Amendment to the Montreal Protocol applies to the production and consumption of hydrofluorocarbons (HFCs). HFCs, which are widely used as refrigerants (Abas et al. 2018), have a high GWP100 of 14600 for HFC-23, and are not ODS (See also Section 9.9.7.1). The Kigali Amendment addresses the risk that the phase-out of HCFCs under the Montreal Protocol and their replacement with HFCs could exacerbate global warming (Akanle 2010; Hurwitz et al. 2016), especially with the predicted growth in HFC usage for applications like air conditioners (Velders et al. 2015). In this way it creates a cooperative rather than a conflictual relationship between addressing ozone depletion and the climate protection goals of the UNFCCC regime (Hoch et al. 2019). The Kigali Amendment requires developed country parties to phase down HFCs by 85% from 2011-2013 levels by 2036. Developing country parties are permitted longer phase-down periods (out to 2045 and 2047), but must freeze production and consumption between 2024 and 2028 (Ripley and Verkuijl 2016; UN 2016). A ban on trade in HFCs with non-parties will come into effect from 1 January 2033. For HFC-23, which is a by-product of HCFC production rather than an ODS, parties are required to report production and consumption data, and to destroy all emissions of HFC-23 occurring as part of HCFCs or HFCs to the extent practicable from 2020 onwards using approved technologies (Ripley and Verkuijl 2016).

Full compliance with the Kigali Amendment is predicted to reduce HFC emissions by 61% of the global baseline by 2050 (Höglund-Isaksson et al. 2017), with avoided global warming in 2100 due to HFCs from a baseline of 0.3-0.5°C to less than 0.1°C (WMO 2018). Examining the interplay of the Kigali Amendment with the Paris Agreement, Hoch et al. (2019) show how the Article 6 mechanisms under the Paris Agreement could generate financial incentives for HFC mitigation and related energy efficiency improvements. Early action under Article 6 of the Paris Agreement could drive down baseline levels of HFCs for developing countries (calculated in light of future production and consumption in the early and mid-2020s) thus generating long-term mitigation benefits under the Kigali Amendment (Hoch et al. 2019). However, achievement of the objectives of the Kigali Amendment is dependent on its ratification by key developed countries, such as the United States, and the provision of funds by developed countries through the Protocol's Multilateral Fund to meet developing countries agreed incremental costs of implementation (Roberts 2017). The Kigali Amendment came into force on 1 January 2019 and has been ratified by 118 of the 198 parties to the Montreal Protocol.

MEAs dealing with transboundary air pollution, such as the Convention on Long-Range Transboundary Air Pollution (CLRTAP) and its implementing protocols, which regulate non-GHGs like particulates, nitrogen oxides and ground-level ozone, can also have potential benefits for climate change mitigation (Erickson 2017). Studies have indicated that rigorous air quality controls targeting short-lived climate forcers, like methane, ozone and black carbon, could slow global mean temperature rise by about 0.5°C by mid-century (Schmale et al. 2014). Steps in this direction were taken with 2012 amendments to the CLRTAP Gothenburg Protocol (initially adopted in 1999) to include black carbon, which is an important driver of climate change in the Arctic region (Yamineva and Kulovesi 2018). The amended Protocol, which has 28 parties including the US and EU, entered into force in October 2019. However, its limits on black carbon have been criticised as insufficiently ambitious in light of scientific assessments (Khan and Kulovesi 2018). There is still a non-negligible uncertainty in the assessment of radiative forcing of each Short-Lived Climate Forcers (SLCFs), and the results of AR6-WGI have been updated since AR5. For example, the assessment of Emission-based Radiative Forcing from Black Carbon emissions was revised downward in AR6 (AR6-WGI-6.4.2). When discussing co-benefits with MEAs related to transboundary air pollution, attention should be paid to the uncertainty in radiative forcing of SLCFs and the update of relevant scientific knowledge.

Another MEA that may play a role in aiding climate change mitigation is the 2013 Minamata Mercury Convention, which came into force on 16 August 2017. Coal burning for electricity generation represents the second largest source (behind artisanal and small-scale gold mining) of anthropogenic mercury emissions to air (UNEP 2013). Efforts to control and reduce atmospheric emissions of mercury from coal-fired power generation under the Minamata Convention may reduce GHG emissions from this source (Eriksen and Perrez 2014; Selin 2014). For instance, Giang et al. (2015) have modelled the implications of the Minamata Convention for mercury emissions from coal-fired power generation in India and China, concluding that reducing mercury emissions from present-day levels in these countries is likely to require 'avoiding coal consumption and transitioning toward less carbon-intensive energy sources' (Giang et al. 2015). Parties to the Minamata Convention include five of the six top global CO_2 emitters – China, the United States, the EU, India and Japan (Russia has not ratified the Convention). The Minamata Convention also establishes an Implementation and Compliance Committee to review compliance with its provisions on a 'facilitative' basis (Eriksen and Perrez 2014).

MEAs that require state parties to conserve habitat (such as the Convention on Biological Diversity) or to protect certain ecosystems like wetlands (such as the Ramsar Wetlands Convention) may also have co-benefits for climate change mitigation through the adoption of well-planned conservation policies (Phelps et al. 2012; Gilroy et al. 2014). At a theoretical level, REDD+ activities have been identified as a particular opportunity for achieving climate mitigation objectives while also conserving tropical forest biodiversity and ecosystem services. Elements of REDD+ that promise greatest effectiveness for climate change mitigation (*e.g.* greater finance combined with reference levels which reduce leakage by promoting broad participation across countries with both high and low historical deforestation rates) also offer the greatest benefits for biodiversity conservation (Busch et al. 2011). However, actual biodiversity and ecosystem service co-benefits are dependent on the design and implementation of REDD+ programmes (Ehara et al. 2014; Panfil and Harvey 2016), with limited empirical evidence to date of emissions reductions from these programmes (Newton et al. 2016; Johnson et al. 2019), and concerns about whether they meet equity and justice considerations (Schroeder and McDermott 2014) (See also Chapter 7, section 7.6.1).

14.5.1.2 Linkages with sustainable development, adaptation, loss and damage, and human rights

As discussed in Chapter 1, the emerging framing for the issue of climate mitigation is that it is no longer to be considered in isolation but rather in the context of its linkages with other areas. Adaptation, loss and damage, human rights and sustainable development are all areas where there are clear or potential overlaps, synergies, and conflicts with the cooperation underway in relation to mitigation.

The IPCC defines adaptation as: 'in human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effect; human intervention may facilitate adjustment to expected climate and its effects' (See Annex I: Glossary).

Adaptation involves actions to lessen the harm associated with climate change, or take advantage of potential gains (Smit and Wandel 2006). It can seek to reduce present and future exposure to specific climate risks (Adger et al. 2003), mainstream climate information into existing planning efforts (Gupta et al. 2010; van der Voorn et al. 2012, 2017), and reduce vulnerability (or increase resilience) of people or communities to the effects of climate change (Kasperson and Kasperson 2001). There is a body of literature highlighting potential synergies and conflicts between adaptation actions – in any of the three areas above – and mitigation actions - and potential strategies for resolving them (Locatelli et al. 2011; Casado-Asensio and Steurer 2014; Duguma et al. 2014; Suckall et al. 2015; Watkiss et al. 2015; van der Voorn et al. 2020). In a strategic context, this issue has been analyzed in Bayramoglu et al. (2018), Eisenack and Kähler (2016) and Ingham et al. (2013), among others. Bayramoglu et al. (2018) analyze the strategic interaction between mitigation, as a public good, and adaptation, essentially a private good, showing that the fear that adaptation will reduce the incentives to mitigate carbon emissions may not be justified. On the contrary, adaptation can reduce free-rider incentives (lead to larger self-enforcing agreements), yielding higher global mitigation levels and welfare, if adaptation efforts cause mitigation levels between different countries to be complements instead of strategic substitutes (on the conditions for adaptation and mitigation to be substitutes or complements, see (Ingham et al. 2013).

Distinct from project or programmatic level activities, however, international cooperation for adaptation operates to provide finance and technical assistance (Bouwer and Aerts 2006). In most cases it involves transboundary actions, such as in the case of transboundary watershed management (Wilder et al. 2010; Milman et al. 2013; van der Voorn et al. 2017). In others it involves the mainstreaming of climate change projections into existing treaties, such as for the protection of migratory species (Trouwborst et al. 2012).

International cooperation in mitigation and adaptation share many of the same challenges, including the need for effective institutions. The UNFCCC, for example, addresses international financial support for adaptation and for mitigation in the same general category, and subjects them to the same sets of institutional constraints (Peterson and Skovgaard 2019). Sovacool and Linnér (2016) argue that the history of the UNFCCC and its sub-agreements has been shaped by an implicit bargain that developing countries participate in global mitigation policy in return for receiving financial and technical assistance for adaptation and development from industrialised countries and international green funds. Khan and Roberts (2013) contend that this played out poorly under the Kyoto framework: the Protocol's basic architecture, oriented around legally binding commitments, was not amenable to merging the issues of adaptation and mitigation. Kuyper et al. Kuyper et al. (2018a) argue that the movement from Kyoto to Paris represents a shift in this regard; Paris was designed not primarily as a mitigation policy instrument, but rather one encompassing mitigation, adaptation, and development concerns. While this argument suggests that the Paris architecture, involving voluntary mitigation actions and a greater attention to issues of financial support and transparency, functions better to leverage adaptation support into meaningful mitigation actions, there are only few papers that examine this issue. Stua (2017a,b) explores the relevance of the so-called 'share of proceeds' included in Article 6 of the Paris Agreement as a key tool for leveraging adaptation though mitigation actions.

There are recognised limits to adaptation (Dow et al. 2013), and exceeding these limits results in loss and damage, a topic that is gathering salience in the policy discourse. Roberts et al. (2014) focused on 'loss and damage', essentially those climate change impacts which cannot be avoided through adaptation. The Paris Agreement contains a free-standing article on loss and damage (UNFCCC 2015a), focused on cooperation and facilitation, under which parties have established a clearing house on risk transfer, and a task force on displacement (UNFCCC 2016a). The COP decision accompanying the Paris Agreement specifies that 'Article 8 does not involve or provide a basis for any liability or compensation' (UNFCCC 2016a). There is range of views on the treatment of loss and damage in the Paris Agreement, how responsibility for loss and damage should be allocated (Lees 2017; McNamara and Jackson 2019), and how it could be financed (Gewirtzman et al. 2018; Roberts et al. 2017). Some scholars argue that there are continuing options to pursue compensation and liability in the climate change regime (Mace and Verheyen 2016; Gsottbauer et al. 2018). There have also been efforts to establish accountability of companies—particularly 'carbon majors' —for climate damage in domestic courts (Ganguly et al. 2018; Benjamin 2021). For states that have suffered loss and damage there is also the option to pursue 'state responsibility' claims under customary international law and international human rights law (Wewerinke-Singh 2018; Wewerinke-Singh and Salili 2020).

One scholar argues that climate impacts are 'incremental violence structurally over-determined by international relations of power and control' that affect most those who have contributed the least to GHG emissions (Dehm 2020). Calls for compensation or reparation for loss and damage are therefore a demand for climate justice (Dehm 2020). Many small island states entered declarations on acceptance of the UNFCCC and Paris Agreement that they continue to have rights under international law regarding state responsibility for the adverse effects of climate change, and that no provision in these treaties can be interpreted as derogating from any claims or rights concerning compensation and liability due to the adverse effects of climate change.

The adoption in 2013 of the Warsaw International Mechanism on Loss and Damage as part of the United Nations Framework Convention on Climate Change (UNFCCC) occurred despite the historic opposition of the United States to this policy. Vanhala and Hestbaek (2016) examine the roles of 'frame contestation' (contestations over different framings of loss and damage, whether as 'liability and compensation' or 'risk management and insurance' or other) and ambiguity in accounting for the evolution and institutionalisation of the loss and damage norm within the UNFCCC. However, there is little international agreement on the scope of loss and damage programmes, and especially how they would be funded and by whom (Gewirtzman et al. 2018). Moreover, non-economic loss and damage (NELD) forms a distinct theme that refers to the climate-related losses of items both material and non-material that are not commonly traded in the market, but whose loss is still experienced as such by those affected. Examples of NELD include loss of cultural identity, sacred places, human health and lives (Serdeczny 2019). The Santiago Network is part of the Warsaw International Mechanism, to catalyse the technical assistance of relevant organisations, bodies, networks and experts, for the implementation of relevant approaches to avert, minimise and address loss and damage at the local, national and regional level, in developing countries that are particularly vulnerable to the adverse effects of climate change (UNFCCC 2020c).

There are direct links between climate mitigation efforts, adaptation and loss and damage - the higher the collective mitigation ambition and the likelihood of achieving it, the lower the scale of adaptation ultimately needed and the lower the scale of loss and damage anticipated. The liability of states, either individually or collectively, for loss and damage is contested, and no litigation has yet been successfully launched to pursue such claims. The science of attribution, however, is developing (Otto et al. 2017; Skeie et al. 2017; Marjanac and Patton 2018; Patton 2021) and while it has the potential to address the thorny issue of causation, and thus compensation (Stuart-Smith et al. 2021), it could also be used to develop strategies for climate resilience (James et al. 2014).

There are also direct links between mitigation and sustainable development. The international agendas for mitigation and sustainable development have shaped each other, around concepts such as common but differentiated responsibilities and respective capabilities, as well as the distinction – in the UNFCCC and later the Kyoto Protocol – between Annex I and non-Annex I countries (Victor 2011; Patt 2015). The same implicit bargain that developing countries would support mitigation efforts in return for assistance with respect to adaptation also applies to support for development (Sovacool and Linnér 2016). That linkage between mitigation and sustainable development has become even more specific with the Paris Agreement and the 2030 Agenda for Sustainable Development, each of which explicitly pursues a set of goals that encompass both mitigation and development (Schmieg et al. 2017), reflecting the recognition that achieving sustainable development and climate mitigation goals are mutually dependent (Gomez-Echeverri 2018). It is well-accepted that the long-term effects of climate mitigation will benefit sustainable development. A more contested finding is whether the mitigation actions themselves promote or hinder short-term poverty alleviation. One study, analysing the economic effects of developing countries' NDCs, finds that mitigation actions slow down poverty reduction efforts (Campagnolo and Davide 2019). Other studies suggest possible synergies between low-carbon development and economic development (Hanger et al. 2016; Labordena et al. 2017; Dzebo et al. 2019). These studies typically converge on the fact that financial assistance flowing from developed to developing countries enhances any possible synergies or lessens the conflicts. However, mitigation measures can also have negative impacts on gender equality, and peace and justice (Dzebo et al. 2019). The IMF has also taken on board the climate challenge and is examining the role of fiscal and macroeconomic policies to address the climate challenge for supporting its members with appropriate policy responses.

The literature also identifies institutional synergies at the international level, related to the importance of addressing climate change and development in an integrated, coordinated and comprehensive manner across constituencies, sectors and administrative and geographical boundaries (Le Blanc 2015). The literature also stresses the important role that robust institutions have in making this happen, including in international cooperation in key sectors for climate action as well for development (Waage et al. 2015). Since the publication of AR5, which emphasised the need for a type of development that combines both mitigation and adaptation as a way to strengthen resilience, much of the literature has focused on ways to address these linkages and the role institutions play in key sectors that are often the subject of international cooperation – for example, environmental and soil degradation, climate, energy, water resources, forestry (Hogl et al. 2016). An assessment of thematic policy coherence between the voluntary domestic contributions regarding the Paris Agreement and the 2030 Agenda should be integrated in national policy cycles for sustainable and climate policy-making to identify overlaps, gaps, mutual benefits and trade-offs in national policies (Janetschek et al. 2020).

It is only since 2008 that the relationship between climate change and human rights has become a focus of international law and policy making. It is not just climate impacts that threaten the enjoyment of human rights but also the mitigation responses to climate change that affect human rights (Shi et al. 2017). The issue of human rights–climate change linkages was first taken up by the UN Human Rights Council (HRC) in 2008, but has since rapidly gained ground with UN human rights treaty bodies issuing comments (e.g. (Human Rights Committee 2018)), recommendations (e.g. (Committee on the Elimination of Discrimination against Women 2018)) and even a joint statement (e.g. (Office of the High Commissioner for Human Rights 2019)) on the impacts of climate change on the enjoyment of human rights. Climate change effects and related disasters have the potential to affect human rights broadly, for instance, by giving rise to deaths, disease or malnutrition (right to life, right to health), threatening food security or livelihoods (right to food), impacting upon water supplies and compromising access to safe drinking water (right to water), destroying coastal settlements through storm surge (right to adequate housing), and in some cases forcing relocation as traditional territories become uninhabitable (UNGA 2019). In addition, the right to a healthy environment, recognized in 2021 as an autonomous right at the international level by the Human Rights Council (UN Human Rights Council 2021), arguably extends to a right to a 'safe climate' shaped in part by the Paris Agreement (UNGA 2019).

As the intersections between climate impacts and human rights have become increasingly clear, litigants have begun to use human rights arguments, with a growing receptivity among courts towards such arguments in climate change cases (Peel and Osofsky 2018; Savaresi and Auz 2019; Macchi and van Zeben 2021). In the landmark Urgenda climate case in 2019, the Dutch Supreme Court interpreted the European Convention on Human Rights in light of customary international law and the UN climate change regime and ordered the state to reduce greenhouse gas emissions by 25% by 2020 compared to 1990 (The Supreme Court of the Netherlands 2019). In the Neubauer case in 2021, the German Federal Constitutional Court ordered the German legislature, in light of its obligations, including on rights protections, to set clear provisions for reduction targets from 2031 onward by the end of 2022 (German Constitutional Court 2021). There are cases in the Global South as well (Peel and Lin 2019; Setzer and Benjamin 2020), with the Supreme Court in Nepal in its 2018 decision in Shrestha, ordering the government to amend its existing laws and introduce a new consolidated law to address climate mitigation and adaptation as this would protect the rights to life, food, and a clean environment, and give effect to the 2015 Paris Agreement (The Supreme Court of Nepal 2018). There are dozens of further cases in national and regional courts, increasingly based on human rights claims. and this trend is only likely to grow (Beauregard et al. 2021; Shi et al. 2017; Peel and Osofsky 2018). These cases face procedural hurdles, such as standing, as well as substantive difficulties, for instance, with regard to the primarily territorial scope of state obligations to protect human rights (Mayer 2021; Boyle 2018), however, there are increasing instances of successful outcomes across the world.

14.5.1.3 Trade agreements

As discussed in AR5, policies to open up trade can have a range of effects on GHG emissions, just as mitigation policies can influence trade flows among countries. Trade rules may impede mitigation action by limiting countries' discretion in adopting trade-related climate policies, but they also have the potential to stimulate the international adoption and diffusion of mitigation technologies and policies (Droege et al. 2017).

The mitigation impacts of trade agreements are difficult to ascertain, and the limited evidence is mixed. Examining the effects of three free trade agreements (FTAs) – Mercosur, the North American Free Trade Agreement (NAFTA) and the Australia-United States Free Trade Agreement – on GHG emissions, (Nemati et al. 2019) find that these effects depend on the relative income levels of the countries involved, and that FTAs between developed and developing countries may increase emissions in the long run. However, studies also suggest that FTAs incorporating specific environmental or climate-related provisions can help reduce GHG emissions (Baghdadi et al. 2013; Sorgho and Tharakan 2020).

Investment agreements, which are often integrated in FTAs, seek to encourage the flow of foreign investment through investment protection. While international investment agreements hold potential to increase low-carbon investment in host countries (PAGE 2018), these agreements have tended to protect investor rights, constraining the latitude of host countries in adopting environmental policies (Miles 2019). Moreover, international investment agreements may lead to 'regulatory chill', which may lead to countries refraining from or delaying the adoption of mitigation policies, such as phasing out fossil fuels (Tienhaara 2018). More contemporary investment agreements seek to better balance the rights and obligations of investors and host countries, and in theory offer greater regulatory space to host countries (UNCTAD 2019), although it is unclear to what extent this will hold true in practice.

In their NDCs, parties mention various trade-related mitigation measures, including import bans, standards and labelling schemes, border carbon adjustments (BCAs; see also Chapter 13), renewable energy support measures, fossil fuel subsidy reform, and the use of international market mechanisms (Brandi 2017). Some of these 'response measures' (Chan 2016b) may raise questions concerning their consistency with trade agreements of the World Trade Organisation (WTO). Non-discrimination is one of the foundational rules of the WTO. This means, among others, that 'like' imported and domestic products are not treated differently ('national treatment') and that a WTO member should not discriminate between other members ('most-favoured-nation treatment'). These principles are elaborated in a set of agreements on the trade in goods and services, including the General Agreement on Tariffs and Trade (GATT), the General Agreement on Trade in Services (GATS), the Agreement on Technical Barriers to Trade (TBT), and the Agreement on Subsidies and Countervailing Measures (ASCM).

Several measures that can be adopted as part of carbon pricing instruments to address carbon leakage concerns have been examined in the light of WTO rules. For instance, depending on the specific design, the free allocation of emissions allowances under an ETS could be considered a subsidy inconsistent with the ASCM (Rubini and Jegou 2012; Ismer et al. 2021). The WTO compatibility of another measure to counter carbon leakage, BCAs, has also been widely discussed (Box 14.2). Alternatives to BCAs, such as consumption charges on carbon-intensive materials (Pollitt et al. 2020), can be consistent with WTO law, as they do not involve discrimination between domestic and foreign products based on their carbon intensity (Ismer and Neuhoff 2007; Tamiotti 2011; Pauwelyn 2013; Holzer 2014; Ismer and Haussner 2016; Cosbey et al. 2019; European Commission 2019; Mehling et al. 2019; Porterfield 2019; Ismer et al. 2020).

START BOX 14.2 HERE

Box 14.2 Border carbon adjustments and international climate and trade cooperation

Analyses of the WTO compatibility of BCAs (Hillman 2013; Trachtman 2017; Ismer and Neuhoff 2007; Tamiotti 2011; Pauwelyn 2013; Holzer 2014; Cosbey et al. 2019; Mehling et al. 2019; Porterfield 2019) gained new currency following the legislative proposal to introduce a 'carbon border adjustment mechanism' in the EU (European Commission 2021). BCAs can in principle be designed and implemented in accordance with international trade law, but the details matter (Tamiotti et al. 2009). To increase the likelihood that a BCA will be compatible with international trade law, studies suggest that it would need to: have a clear environmental rationale (i.e. reduce carbon leakage); apply to imports and exclude exports; consider the actual carbon intensity of foreign producers; account for the mitigation efforts by other countries; and provide for fairness and due process in the design and implementation (Trachtman 2017; Pauwelyn 2013; Cosbey et al. 2019; Mehling et al. 2019).

BCAs may also raise concerns regarding their consistency with international climate change agreements (Hertel 2011; Davidson Ladly 2012; Ravikumar 2020). To mitigate these concerns, BCAs could include special provisions (e.g. exemptions) for LDCs, or channel revenues from the BCA to developing countries to support low-carbon and climate-resilient development (Grubb 2011; Springmann 2013; Mehling et al. 2019). Moreover, international dialogue on principles and best practices guiding BCAs could help to ensure that such measures do not hinder international cooperation on climate change and trade (Bernasconi-Osterwalder and Cosbey 2021).

END BOX 14.2 HERE

Other regulatory measures may also target the GHG emissions associated with the production of goods (Dobson 2018). These measures include bans on carbon-intensive materials, emissions standards for the production process of imported goods, and carbon footprint labels (Kloeckner 2012; Holzer and Lim 2020; Gerres et al. 2021). The compatibility of such measures with trade agreements remains subject to debate. While non-discriminatory measures targeting the emissions from a product itself (e.g. fuel efficiency standards for cars) are more likely to be allowed than measures targeting the production process of a good (Green 2005), some studies suggest that differentiation between products based on their production process may be compatible with WTO rules (Benoit 2011; McAusland and Najjar 2015). (Mayr et al. 2020) find that sustainability standards targeting the emissions from indirect land-use change associated with the production of biofuels may be inconsistent with the TBT Agreement. Importantly, trade rules express a strong preference for the international harmonisation of standards over unilateral measures (Delimatsis 2016).

Renewable energy support measures may be at odds with the ASCM, the GATT, and the WTO Agreement on Trade-Related Investment Measures. In WTO disputes, measures adopted in Canada, India, and the United States to support clean energy generation were found to be inconsistent with WTO law due to the use of discriminatory local content requirements, such as the requirement to use domestically produced goods in the production of renewable energy (Cosbey and Mavroidis 2014; Kulovesi 2014; Lewis 2014; Wu and Salzman 2014; Charnovitz and Fischer 2015; Shadikhodjaev 2015; Espa and Marín Durán 2018).

Some measures may both lower trade barriers and potentially bring about GHG emission reductions. An example is the liberalisation of trade in environmental goods (Hu et al. 2020). In 2012, the APEC economies agreed to reduce tariffs for a list of 54 environmental goods (including e.g. solar cells; but excluding e.g. biofuels or batteries for electric vehicles). However, negotiations on an Environmental Goods Agreement under the WTO stalled in 2016 due in part to disagreement over which goods to include (de Melo and Solleder 2020). Another example is fossil fuel subsidy reform, which may reduce GHG emissions (Jewell et al. 2018; Chepeliev and van der Mensbrugghe 2020; Erickson et al. 2020) and lower trade distortions (Burniaux et al. 2011; Moerenhout and Irschlinger 2020). However, fossil fuel subsidies have largely remained unchallenged before the WTO due to legal and political hurdles (Asmelash 2015; De Bièvre et al. 2017; Meyer 2017; Steenblik et al. 2018; Verkuijl et al. 2019).

With limited progress in the multilateral trading system, some studies suggest that regional FTAs hold potential for strengthening climate governance. In some cases, climate-related provisions in such FTAs can go beyond provisions in the Kyoto Protocol and Paris Agreement, addressing for instance cooperation on carbon markets or electric vehicles (Gehring et al. 2013; van Asselt 2017; Morin and Jinnah 2018; Gehring and Morison 2020). However, Morin and Jinnah (2018) find that these provisions are at times vaguely formulated, not subject to third-party dispute settlement, and without sanctions or remedy in case of violations. Moreover, such provisions are not widely used in FTAs, and they are not adopted by the largest GHG emitters. For instance, the 2019 United States-Mexico-Canada Agreement, NAFTA's successor, does not include any specific provisions on climate change, although it could implement cooperative mitigation actions through its Commission for Environmental Cooperation (Laurens et al. 2019).

A trend in international economic governance has been the adoption of 'mega-regional' trade agreements involving nations responsible for a substantial share of world trade, such as the Comprehensive and Progressive Agreement for Trans-Pacific Partnership (CPTPP), the EU-Canada

Comprehensive Economic and Trade Agreement (CETA), and the Regional Comprehensive Economic Partnership (RCEP) in East Asia. Given the size of the markets covered by these agreements, they hold potential to diffuse climate mitigation standards (Meltzer 2013; Holzer and Cottier 2015). While CETA includes climate-related provisions and parties have made a broad commitment to implement the Paris Agreement (Laurens et al. 2019), and the CPTPP includes provisions promoting cooperation on clean energy and low-emissions technologies, the RCEP does not include specific provisions ont climate change.

Studies have discussed various options to minimise conflicts, and strengthen the role of trade agreements in climate action, although the mitigation benefits and distributional effects of these options have yet to be assessed. Some options require multilateral action, including: (1) the amendment of WTO agreements to accommodate climate action; (2) the adoption of a 'climate waiver' that temporarily relieves WTO members from their obligations; (3) a 'peace clause' through which members commit to refraining from challenging each other's measures; (4) an 'authoritative interpretation' by WTO members of ambiguous WTO provisions; (5) improved transparency of the climate impacts of trade measures; (6) the inclusion of climate expertise in WTO disputes; and (7) intensified institutional coordination between the WTO and UNFCCC (Hufbauer et al. 2009; Epps and Green 2010; Bacchus 2016; Droege et al. 2017; Das et al. 2019). In addition, issue-specific suggestions have been put forward, such as reinstating an exception for environmentally motivated subsidies under the ASCM (Horlick and Clarke 2017).

Options can also be pursued at the plurilateral and regional level. Several studies suggest that climate clubs (see Section 14.2.2) could employ trade measures, such as lower tariffs for climate-related goods and services, or BCAs, to attract club members (Nordhaus 2015; Brewer et al. 2016; Keohane et al. 2017; Stua 2017a; Banks and Fitzgerald 2020). Another option is to negotiate a new agreement addressing both climate change and trade. Negotiations between six countries (Costa Rica, Fiji, Iceland, New Zealand, Norway, Switzerland) were launched in 2019 on a new Agreement on Climate Change, Trade and Sustainability (ACCTS), which, if successfully concluded, would liberalise trade in environmental goods and services, create new rules to remove fossil fuel subsidies, and develop guidelines for voluntary eco-labels (Steenblik and Droege 2019). At the regional level, countries could further opt for the inclusion of climate provisions in the (re)negotiation of FTAs (Yamaguchi 2020; Morin and Jinnah 2018). Moreover, the conduct of climate impact assessments of FTAs could help identify options to achieve both climate and trade objectives (Porterfield et al. 2017). In their assessment of the feasibility of various options for reform, Das et al. (2019) find that the near-term feasibility of options that require consensus at the multilateral level (notably amendments of WTO agreements) is low. By contrast, options involving a smaller number of parties, as well as options that can be implemented by WTO members on a voluntary basis, face fewer constraints.

For international investment agreements, various other suggestions have been put forward to accommodate climate change concerns. These include incorporating climate change through ongoing reform processes, such as reform of investor-state dispute settlement under the UN Commission on International Trade Law (UNCITRAL); modernisation of the Energy Charter Treaty; the (re)negotiation of international investment agreements; and the adoption of a specific treaty to promote investment in climate action (Brauch et al. 2019; Tienhaara and Cotula 2020; Yamaguchi 2020; Cima 2021).

14.5.1.4 South-South cooperation

South-South (SSC) and triangular (TrC) cooperation are bold, innovative, and rapidly developing means of strengthening cooperation for the achievement of the SDGs (FAO 2018). SSC is gaining momentum in achieving sustainable development and climate actions in developing countries (UN 2017b). Through SSC, countries are able to map their capacity needs and knowledge gaps and find sustainable, cost-effective, long-lasting and economically viable solutions (FAO 2019). In the UN Climate Change

Engagement Strategy 2017 (UNOSC 2017), South-South Cooperation Action Plan is identified as a substantive pillar to support.

In 2019, the role of South-South and triangular cooperation was further highlighted with the BAPA+40 Outcome document (UN 2019), noting outstanding contributions to alleviating global inequality, promoting sustainable development and climate actions, promoting gender equality and enriching multilateral mechanisms. Furthermore, the role of triangular cooperation was explicitly recognized in the document reflecting its increasingly relevant role in the implementation of the SDGs (UN 2019).

There has been a recent resurgence of South-South cooperation. Gray and Gills (Gray and Gills 2016), signalled inter alia by the South-South Cooperation Action Plan adopted by the UN as a substantive pillar to support the implementation of the UN Climate Change Engagement Strategy 2017 (UNOSC 2017). (Liu et al. 2017a) explored prospects for South–South cooperation for large-scale ecological restoration, which is an important solution to mitigate climate change. Emphasis is given to experience and expertise sharing, co-financing, and co-development of new knowledge and know-how for more effective policy and practice worldwide, especially in developing and newly industrialised countries.

Janus et al. (2014) explore evolving development cooperation and its future governance architecture based on The Global Partnership for Effective Development Cooperation (GPEDC) and The United Nations (UN) Development Cooperation Forum (DCF). Drawing on evidence from the hydropower, solar and wind energy industry in China, Urban (2018) introduces the concept of 'geographies of technology transfer and cooperation' and challenges the North-South technology transfer and cooperation paradigm for low carbon innovation and climate change mitigation. While North-South technology transfer and cooperation (NSTT) for low carbon energy technology has been implemented for decades, South-South technology transfer and cooperation (SSTT) and South-North technology transfer and cooperation (SNTT) have only recently emerged. Kirchherr and Urban (2018) provide a meta-synthesis of the scholarly writings on NSTT, SSTT and SNTT from the past 30 years. The discussion focuses on core drivers and inhibitors of technology transfer and cooperation, outcomes as well as outcome determinants. A case study of transfer of low-carbon energy innovation and its opportunities and barriers, based on first large Chinese-funded and Chinese-built dam in Cambodia is presented by Hensengerth (2017).

Hensengerth (2017) explore the role that technology transfer/cooperation from Europe played in shaping firm level wind energy technologies in China and India and discuss the recent technology cooperation between the Chinese, Indian, and European wind firms. The research finds that firm-level technology transfer/cooperation shaped the leading wind energy technologies in China and to a lesser extent in India. Thus, the technology cooperation between China, India, and Europe has become multi-faceted and increasingly Southern-led.

Rampa et al. (2012) focus on the manner in which African states understand and approach new opportunities for cooperation with emerging powers, especially China, India and Brazil, including the crucial issue of whether they seek joint development initiatives with both traditional partners and emerging powers. UN (2018) presents and analyses case studies of SSTT in Asia-Pacific and Latin America and Caribbean regions. Illustrative case studies on TrC can be consulted in Shimoda and Nakazawa (2012), and specific cases on biofuel SSC and TrC in UNCTAD (2012).

The central argument in the majority of these case studies is that South–South cooperation, which is value-neutral, is contributing to sustainable development and capacity building (Rampa et al. 2012; Shimoda and Nakazawa 2012; UN 2018). An important new development in SSC is that in relation to some technologies the cooperation is increasingly led by Southern countries (for instance, wind energy between Europe, India and China), challenging the classical North–South technology cooperation paradigm. More broadly, parties should ensure the sustainability of cooperation, rather than focusing on short-term goals (Eyben 2013). The Belt and Road Initiative (BRI) is a classic example of a recent

SSC Initiative led by China. According to a joint study by Tsinghua University and Vivid Economics the 126 countries in the BRI region, excluding China, currently account for about 28% of global GHG emissions, but this proportion may increase to around 66% by 2050 if the carbon intensity of these economies only decreases slowly (according to historical patterns shown by developing countries). In this context it is important to highlight that China has already outlined a vision for a green BRI, and recently increased its commitment through the Green Investment Principles (GIP) initiative, announcing a new international coalition to improve sustainability and promote green infrastructure (Jun and Zadek 2019).

Information on triangular cooperation is more readily available than on South-South cooperation though some UN organisations such as UNDP and FAO have established platforms for the latter which also includes climate projects. Further, although there are many South-South cooperation initiatives involving the development and transfer of climate technologies the understanding of the motivations, approaches and designs is limited and not easily accessible. There is no dedicated platform for South-South and triangular cooperation on climate technologies. Hence, it is still too early to fully assess the achievements in the field of climate action (UNFCCC and UNOSSC 2018). In order to maximise its unique contribution to Agenda 2030, southern providers recognise the benefits of measuring and monitoring South–South cooperation, and there is a clear demand for better information from partner countries. Di Ciommo (2017) argues that ´better data could support monitoring and evaluation, improve effectiveness, explore synergies with other resources, and ensure accountability´ to a diverse set of stakeholders. Besharati et al. (2017) present a framework of 20 indicators, organised in five dimensions that researchers and policy makers can use to access the quality and effectiveness of SSC and its contribution to sustainable development.

The global landscape of development cooperation has changed dramatically in recent years, with countries of the South engaging in collaborative learning models to share innovative, adaptable and cost-efficient solutions to their development and socio-economic-environmental challenges, ranging from poverty and education to climate change. The proliferation of new actors and cross-regional modalities had enriched the understanding and practice of development cooperation and generated important changes in the global development architecture towards a more inclusive, effective, and horizontal development agenda. South-South cooperation will grow in the future, while it is complimentary to North-South cooperation. However, there are knowledge gaps in relation to the precise volume, impact, effectiveness and quality of development cooperation from emerging development partners. This gap needs to be plugged, and evidence on such cooperation strengthened.

14.5.2 International sectoral agreements and institutions

Sectors refer to distinct areas of economic activity, often subject to their own governance regimes; examples include energy production, mobility, and manufacturing. A sectoral agreement could include virtually any type of commitment with implications for mitigation. It could establish sectoral emission targets, on either an absolute or an indexed basis. It could also require states (or particular groups of states, if commitments are differentiated) to adopt uniform or harmonised policies and measures for a sector, such as technology-based standards, taxes, or best-practice standards, as well as providing for cooperation on technology research or deployment.

14.5.2.1 Forestry, land-use and REDD+

Since 2008, several, often overlapping, voluntary and non-binding international efforts and agreements have been adopted to reduce net emissions from the forestry sector. These initiatives have varying levels of private sector involvement and different objectives, targets, and timelines. Some efforts focus on reducing emissions from deforestation and degradation, while other focus on the enhancement of sinks through restoration of cleared or degraded landscapes. These initiatives do not elaborate specific policies, procedures, or implementation mechanisms. They set targets, frameworks, and milestones, aiming to catalyse further action, investment, and transparency in conservation and consolidate individual country efforts.

After the UN-sponsored Tropical Forestry Action Plan (Winterbottom 1990; Seymour and Busch 2016), among the longest standing programs in the forestry sector are the World Bank-sponsored F Forest Carbon Partnership Facility in 2007, which helps facilitate funding for REDD+ readiness and specific projects, in addition to preparing countries for results-based payments and future carbon markets while securing local communities' benefits managed sub-nationally, and the UN REDD+ Programme initiated in 2008, which aims to reduce forest emissions and enhance carbon stocks in forests while contributing to national sustainable development in developing countries, after the 2007 COP13 in Bali formally adopted REDD+ in the UNFCCC decisions and incorporated it in the Bali Plan of Action. As discussed above, Article 5 of the Paris Agreement encourages parties to take action to implement and support REDD+. These efforts tend to focus on reducing emissions through the creation of protected areas, payments for ecosystem services, and/or land tenure reform (Pirard et al. 2019). The UNREDD+ programme supports national REDD+ efforts, inclusion of stakeholders in relevant dialogues, and capacity building toward REDD+ readiness in partner countries. To date the conservation and emissions impacts of REDD+ remain misunderstood (Pirard et al. 2019), but while existing evidence suggests that reductions in deforestation from subnational REDD+ initiatives have been limited (Bos et al. 2017) it shows an increasing prominence (Maguire et al. 2021). Additionally, the Green Climate Fund has carried out results-based payments within REDD+. Eight countries have so far received significant funding (GCF 2021). The shift in the REDD+ focus from ecosystem service payment to domestic policy realignments and incentive structure has changed the way REDD+ was developed and implemented (Brockhaus et al. 2017). Large-scale market resources have not fully materialised as a global carbon market system that explicitly integrates REDD+ remains under development (Angelsen 2017). Public funding for REDD+ is also limited (Climate Focus 2017). Leading up to the adoption of the Paris Agreement, the governments of Germany, Norway, and the United Kingdom formed a partnership in 2014 called 'GNU' to support results-based financing for REDD+, with Norway emerging as one of, if not the single largest major donor for REDD+ through its pledge in 2007 of approximately USD3 billion annually. Norway pledged USD1 billion for Brazil in 2008 and the same for Indonesia in 2010 (Schroeder et al. 2020). Meanwhile, REDD+ Early Movers was established with support from Germany, and the Central African Forest Initiative (CAFI), a collaborative partnership between the European Union, Germany, Norway, France, and the United Kingdom. It supports six central African countries in fighting deforestation.

More recently, the Lowering Emissions by Accelerating Forest Finance (LEAF) Coalition was established, consisting of the governments of Norway, the UK, and the US and initially nine companies in accelerating REDD+ with a jurisdictional approach. LEAF uses the Architecture for REDD+ Transaction, The REDD+ Environmental Excellence Standard (ART-TREES), is coordinated by Emergent, a non-profit intermediary between tropical countries and the private sector. Three jurisdictions in Brazil and two countries have already submitted concept notes to ART to receive results-based payments. REDD+ initiatives with a jurisdictional approach have also been adopted in various markets, such as the CORSIA (Maguire 2021). In addition to Brazil, Indonesia has attracted significant interest as a host country for REDD+. Indonesia ranks second, after Brazil, as the largest producer of deforestation-related GHG emissions (Zarin et al. 2016), but it has committed to a large reduction of deforestation in its NDC (Government of Indonesia 2016). Australia has collaborated on scientific research and emission reduction monitoring (Tacconi 2017). It took a while, however, before emission reductions were witnessed (Meehan et al. 2019). The expansion of commodity plantations, however, conflict with reduction ambitions (Anderson et al. 2016; Irawan et al. 2019) In addition to implementation at the site and jurisdictional levels, legal enforcement (Tacconi et al. 2019) as well as policy and regulatory reforms (Ekawati et al. 2019) appears to be needed.

Another relevant initiative is one under the 2015 United Nations Convention to Combat Desertification (UNCCD), which targets land degradation neutrality i.e., 'a state whereby the amount and quality of land resources, necessary to support ecosystem functions and services and enhance food security, remains stable or increases within specified temporal and spatial scales and ecosystems' (Orr et al. 2017). This overarching goal was recognised as also being critical to reaching the more specific avoided deforestation and degradation and restoration goals of the UNFCCC and UNCBD. The Land Degradation Neutrality (LDN) initiative from UNCCD includes target setting programmes (TSP) that assist countries by providing practical tools and guidance for the establishment of the voluntary targets and formulate associated measures to achieve LDN and accelerate implementation of projects (Chasek et al. 2019). Today, 124 countries have committed to their LDN national targets (UNCCD 2015). The LDN Fund is an investment vehicle launched in UNCCD COP 13 in 2017, which exists to provide long-term financing for private projects and programmes for countries to achieve their LDN targets. According to the UNCCD, most of the funds will be invested in developing countries.

Recent efforts towards the enhancement of sinks from the forestry sector have the overarching goal of reaching zero *gross* deforestation globally, i.e., eliminating the clearing of all natural forests. The New York Declaration on Forests (NYDF) was the first international pledge to call for a halving of natural forest loss by 2020 and the complete elimination of natural forest loss by 2030 (Climate Focus 2016). It was endorsed at the United Nations Climate Summit in September 2014. By September 2019 the list of NYDF supporters included over 200 actors: national governments, sub-national governments, multi-national companies, groups representing indigenous communities, and non-government organisations. These endorsers have committed to doing their part to achieve the NYDF's ten goals, which include ending deforestation for agricultural expansion by 2020, reducing deforestation from other sectors, restoring forests, and providing financing for forest action (Forest Declaration 2019). These goals are assessed and tracked through the NYDF Progress Assessment, which includes NYDF Assessment Partners that collect data, generate analysis, and release the finding based on the NYDF framework and goals.

The effectiveness of these agreements, which lack binding rules, can only be judged by the supplementary actions they have catalysed. The NYDF contributed to the development of several other zero-deforestation pledges, including the Amsterdam Declarations by seven European nations to achieve fully sustainable and deforestation-free agro-commodity supply chains in Europe by 2020 and over 150 individual company commitments to not source products associated with deforestation (Donofrio et al. 2017; Lambin et al. 2018). Recent studies indicate that these efforts currently lack the potential to achieve wide-scale reductions in clearing and associated emissions due to weak implementation (Garrett et al. 2019), although in some cases in Indonesia and elsewhere the commodity supply chain sustainability drive appears to contribute to lowering deforestation (Wijaya et al. 2019; Chain Reaction Research 2020; Schulte et al. 2020). The NYDF may have triggered small additional reductions in deforestation in some areas, particularly for soy, and to a lesser extent cattle, in the Brazilian Amazon (Lambin et al. 2018), but these effects were temporary, as efforts are being actively reversed and deforestation has increased again significantly. Deforestation rates have escalated in Brazil, with the rate in June 2019 (the first dry-season month in the new administration) up 88% over the 2018 rate in the same month (INPE 2019). Curtis et al. (2018) find global targets are clearly not being met. More recent increase in deforestation rate remains to be assessed. NYDF confirms that the initiative did not reach its zero-deforestation goal (NYDF Assessment Partners 2020).

In 2010, the parties to the CBD adopted the Strategic Plan for Biodiversity 2011–2020 which included 20 targets known as the Aichi Biodiversity targets (Marques et al. 2014). Of relevance to the forestry sector, Aichi Target 15 sets the goal of enhancing ecosystem resilience and the contribution of biodiversity to carbon stocks though conservation and restoration, including 'restoration of at least 15% of degraded ecosystems' (UNCBD 2010). The plan elaborates milestones, including the development of national plans for potential restoration levels and contributions to biodiversity protection, carbon sequestration, and climate adaptation to be integrated into other national strategies, including REDD+. In 2020, however, the CBD found that while progress was evident for the majority of the Aichi Biodiversity Targets, it was not sufficient for the achievement of the targets by 2020 (CBD 2020).

Recent efforts toward negative emissions through restoration include the Bonn Challenge, the African Forest Landscape Restoration Initiative (AFR 100) and Initiative 20X20. The Bonn Challenge, initiated in 2011 by the Government of Germany and the IUCN, is intended to catalyse the existing international AFOLU commitments. It aims to bring 150 million hectares (Mha) of the world's deforested and degraded land into restoration by 2020, and 350 Mha by 2030. AFR has the goal of restoring 100 Mha specifically in Africa (AUDA-NEPAD 2019), while 20X20 aims to restore 20 Mha in Latin America and the Caribbean (Anderson and Peimbert 2019). Increasing commitments for restoration have created momentum for restoration interventions (Chazdon et al. 2017; Mansourian et al. 2017; Djenontin et al. 2018). To date 97 Mha has been pledged in NDCs. Yet only a small part of this goal has been achieved. The Bonn Challenge Barometer – a progress-tracking framework and tool to support pledgers - indicates that 27 Mha (InfoFLR 2018) are currently being restored, equivalent to 1.379 $GtCO_2eq$ sequestered (Dave et al. 2019). A key challenge in scaling up restoration has been to mobilise sufficient financing (Liagre et al. 2015; Djenontin et al. 2018). This underscores the importance of building international financing for restoration (equivalent to the Forest Carbon Partnership Facility focused on avoided deforestation and degradation).

In sum, existing international agreements have had a small impact on reducing emissions from the AFOLU sector and some success in achieving the enhancement of sinks through restoration. However, these outcomes are nowhere near levels required to meet the Paris Agreement temperature goal –which would require turning land use and forests globally from a net anthropogenic source during 1990-2010 to a net sink of carbon by 2030, and providing a quarter of emission reductions planned by countries (Grassi et al. 2017). The AFOLU sector has so far contributed only modestly to net mitigation (see Chapter 7).

14.5.2.2 Energy sector

International cooperation on issues of energy supply and security has a long and complicated history. There exists a plethora of institutions, organisations, and agreements concerned with managing the sector. There have been efforts to map the relevant actors, with authors in one case identifying six primary organisations (Kérébel and Keppler 2009), in another sixteen (Lesage et al. 2010), and in a third fifty (Sovacool and Florini 2012). At the same time, very little of that history has had climate mitigation as its core focus. Global energy governance has encompassed five broad goals – security of energy supply and demand, economic development, international security, environmental sustainability, and domestic good governance – and as only one of these provides an entry point for climate mitigation, effort in this direction has often been lost (van de Graaf and Colgan 2016). To take one example, during the 1980s and 1990s a combination of bilateral development support and lending practices from multilateral development banks pushed developing countries to adopt power market reforms consistent with the Washington Consensus: towards liberalised power markets and away from state-owned monopolies. The goals of these reforms did not include an environmental component, and among the results was new investment in fossil-fired thermal power generation (Foster and Rana 2020).

As Goldthau and Witte (2010) document, the majority of governance efforts, outside of oil and gas producing states, was oriented towards ensuring reliable and affordable access for oil and gas imports. For example, the original rationale for the creation of the International Energy Agency (IEA), during the oil crisis of 1973-74, was to manage a mechanism to ensure importing countries' access to oil (van de Graaf and Lesage 2009). On the other side of the aisle, oil exporting countries created the international institution of OPEC to enable them to influence oil output, thereby stabilising prices and revenues for exporting countries (Fattouh and Mahadeva 2013). For years, energy governance was seen as a zero-sum game between these poles (Goldthau and Witte 2010). The only international governance agency focusing on low carbon energy sources was the International Atomic Energy Agency, with a dual mission of promoting nuclear energy and nuclear weapons non-proliferation (Scheinman 1987).

More recently, however, new institutions have emerged, and existing institutions have realigned their missions, in order to promote capacity building and global investment in low carbon energy technologies. Collectively, these developments may support the emergence of a nascent field of global sustainable energy governance, in which a broad range of global, regional, national, sub-national and non-state actors, in aggregate, shape, direct and implement the low carbon transition through climate change mitigation activities, which produce concomitant societal benefits (Bruce 2018). Beginning in the 1990s, for example, the IEA began to broaden its mission from one concerned primarily with security of oil supplies, which encompassed conservation of energy resources, to one also concerned with the sustainability of energy use, including work programs on energy efficiency and clean energy technologies and scenarios (van de Graaf and Lesage 2009). Scholars have suggested that it was the widespread perception that the IEA was primarily interested in promoting the continued use of fossil fuels, and underplaying the potential role of renewable technologies, that led a number of IEA member states to successfully push for the creation of a parallel organisation, the International Renewable Energy Agency (IRENA), which was then established in 2009 (van de Graaf 2013). An assessment of IRENA's activities in 2015 suggested that the agency has a positive effect related to three core activities: offering advisory services to member states regarding renewable energy technologies and systems; serving as a focal point for data and analysis for renewable energy; and, mobilising other international institutions, such as multilateral development banks, promoting renewable energy (Urpelainen and Van de Graaf 2015). The United Nations, including its various agencies such as the Committee on Sustainable Energy within the United Nations Economic Commission for Europe, has also played a role in the realignment of global energy governance towards mitigation efforts. As a precursor to SDG 7, the United Nations initiated in 2011 the *Sustainable Energy for All* initiative, which in addition to aiming for universal access to modern energy services, included the goals of doubling the rate of improvement in energy efficiency, and doubling by 2030 the share of renewable energy in the global energy mix (Bruce 2018).

Sub-global agreements have also started to emerge, examples of issue-specific climate clubs. In 2015, seventy solar-rich countries signed a framework agreement dedicated towards promoting solar energy development (ISA 2015). In 2017 the Powering Past Coal Alliance was formed, uniting a set of states, businesses, and non-governmental organisations around the goal of eliminating coal-fired power generation by 2050 (Jewell et al. 2019; Blondeel et al. 2020). Scholars have argued that greater attention to supply-side agreements such as this – focusing on reducing and ultimately eliminating the supply of carbon-intensive energy sources – would strengthen the UNFCCC and Paris Agreement (Collier and Venables 2014; Piggot et al. 2018; Asheim et al. 2019; Newell and Simms 2020). Chapter 6 of this report, on energy systems, notes the importance of regional cooperation on electric grid development, seen as necessary to enable higher shares of solar and wind power penetration (RGI 2011). Finally, a number of transnational organisations and activities have emerged, such as *REN21*, a global community of renewable energy experts (REN21 2019), and *RE100*, an NGO led initiative to enlist multilateral companies to shift towards 100% renewable energy in their value chains (RE100 2019).

Whether a result of the above activities or not, multilateral development banks' lending practices have shifted in the direction of renewable energy (Delina 2017), a point also raised in Chapter 15 of this Assessment Report. Activities include new sources of project finance, concessional loans, as well as loan guarantees, the latter through the Multilateral Investment Guarantee Agency (Multilateral Investment Guarantee Agency 2019). This appears to matter. For example, Frisari and Stadelmann (2015) find concessional lending by multilateral development banks to solar energy projects in Morocco and India to have reduced overall project costs, due to more attractive financing conditions from additional lenders, as well as reducing the costs to local governments. Labordena et al. (2017) projected these results into the future, and found that with the drop in financing costs, renewable energy projects serving all major demand centres in sub-Saharan Africa could reach cost parity with fossil fuels by 2025, whereas without the drop in financing costs associated with concessional lending, this would not be the case. Similarly, Creutzig et al. (2017) suggest that greater international attention to finance could be instrumental in the full development of solar energy.

Despite improvements in the international governance of energy, it still appears that a great deal of this is still concerned with promoting further development of fossil fuels. One aspect of this is the development of international legal norms. A large number of bilateral and multilateral agreements, including the 1994 Energy Charter Treaty, include provisions for using a system of investor-state dispute settlement (ISDS) designed to protect the interests of investors in energy projects from national policies that could lead their assets to be stranded. Numerous scholars have pointed to ISDS being able to be used by fossil-fuel companies to block national legislation aimed at phasing out the use of their assets (Bos and Gupta 2019; Tienhaara 2018). Another aspect is finance; Gallagher et al. (2018) examine the role of national development finance systems, focusing in particular on China. While there has been a great deal of finance devoted to renewable energy, they find the majority of finance devoted to projects associated either with fossil fuel extraction or with fossil fuel-fired power generation. Ascensão et al. (2018) similarly suggest that activities associated with the Belt and Road Initiative could play a role in slowing down mitigation efforts in developing countries.

Given the complexity of global energy governance, it is impossible to make a definitive statement about its overall contribution to mitigation efforts. Three statements, do however, appear to be robust. First, prior to the emergence of climate change on the global political agenda, international cooperation in the area of energy was primarily aimed at expanding and protecting the use of fossil energy, and these goals were entrenched in a number of multilateral organisations. Second, since the 1990s, international cooperation has gradually taken climate mitigation on board as one of its goals, seeing a realignment of many pre-existing organisations priorities, and the formation of a number of new international arrangements oriented towards the development renewable energy resources. Third, the realignment is far from complete, and there are still examples of international cooperation having a chilling effect on climate mitigation, particularly through financing and investment practices, including legal norms designed to protect the interests of owners of fossil assets.

14.5.2.3 Transportation

The transportation sector has been a particular focus of cooperative efforts on climate mitigation that extend beyond the sphere of the UNFCCC climate regime. A number of these cooperative efforts involve transnational public-private partnerships, such as the European-based Transport Decarbonisation Alliance, which brings together countries, regions, cities and companies working towards the goal of a 'net-zero emission mobility system before 2050' (TDA 2019). Other efforts are centred in specialised UN agencies, such as the International Civil Aviation Organisation (ICAO) and the International Maritime Organisation (IMO).

Measures introduced by the ICAO and IMO have addressed CO_2 emissions from international shipping and aviation. Emissions from these parts of the transportation sector are generally excluded from national emissions reduction policies and NDCs because the 'international' location of emissions release makes allocation to individual nations difficult (Bows-Larkin 2015; Lyle 2018; Hoch et al. 2019). The measures adopted by ICAO take the form of standards and recommended practices that are adopted in national legislation. IMO publishes 'regulations' but does not have a power of enforcement, with non-compliance a responsibility of flag states that issue a ship's 'MARPOL' certificate.

As discussed in Chapter 2 and Figure SPM.4, international aviation currently accounts for approximately 1% of global GHG emissions, with international shipping contributing 1.2% of global GHG emissions. These international transport emissions are projected to be between approximately 60-

220% of global emissions of CO_2 in 2050, as represented by the four main illustrative model pathways in SR1.5 (Rogelj et al. 2018; UNEP 2020) Notably, however, the climate impact of aviation emissions is estimated to be 2-4 times higher due to non-CO_2 effects (Terrenoire et al. 2019; Lee et al. 2021a). Increases in trans-Arctic shipping and tourism activities with sea ice loss are also forecast to have strong regional effects due to ships' gas and particulate emissions (Stephenson et al. 2018).

The Kyoto Protocol required Annex I parties to pursue emissions reductions from aviation and marine bunker fuels by working through IMO and ICAO (UNFCCC 1997, Art. 2.2). Limited progress was made by these organisations on emissions controls in the ensuing decades (Liu 2011b), but greater action was prompted by conclusion of the SDGs and Paris Agreement (Martinez Romera 2016), together with unilateral action, such as the EU's inclusion of aviation emissions in its Emissions Trading Scheme (ETS) (Dobson 2020).

The Paris Agreement neither explicitly addresses emissions from international aviation and shipping, nor repeats the Kyoto Protocol's provision requiring parties to work through ICAO/IMO to address these emissions (Hoch et al. 2019). This leaves unclear the status of the Kyoto Protocol's article 2.2 directive after 2020 (Martinez Romera 2016; Dobson 2020), potentially opening up scope for more attention to aviation and shipping emissions under the Paris Agreement (Doelle and Chircop 2019). Some commentators have suggested that emissions from international aviation and shipping should be part of the Paris Agreement (Gençsü and Hino 2015; Traut et al. 2018), and shipping and aviation industries themselves may prefer emissions to be treated under an international regime rather than a nationally-oriented one (Gilbert and Bows 2012). In the case of shipping emissions, there is nothing in the Paris Agreement to prevent a party from including international shipping in some form in its NDC (Doelle and Chircop 2019) Under the Paris Rulebook, parties "should report international aviation and marine bunker fuel emissions as two separate entries and should not include such emissions in national totals but report them distinctly, if disaggregated data are available" (UNFCCC 2019d).

ICAO has an overarching climate goal to "limit or reduce the impact of aviation greenhouse gas emissions on the global climate" with respect to international aviation. In order to achieve this, ICAO has two global aspirational goals for the international aviation sector, of 2% annual fuel efficiency improvement through 2050 and carbon neutral growth from 2020 onwards (ICAO 2016). In order to achieve these global aspirational goals, ICAO is pursuing a 'basket' of mitigation measures for the aviation sector consisting of technical and operational measures, such as a CO_2 emissions standard for new aircraft adopted in 2016, measures on sustainable alternative fuels and a market-based measure, known as the Carbon Offset and Reduction Scheme for International Aviation (CORSIA), which the triennial ICAO Assembly of 193 Member States resolved to establish in 2016 (ICAO 2016). In line with the 2016 ICAO Assembly Resolution that established CORSIA, in mid-2018, the ICAO's 36-member state governing Council adopted a series of Standards and Recommended Practices (SARPs), now contained in Annex 16, Volume IV of the Chicago Convention (1944), as a common basis for CORSIA's implementation and enforcement by each state and its aeroplane operators. From 1 January 2019, the CORSIA SARPs require states and their operators to undertake an annual process of monitoring, verification, and reporting of emissions from all international flights, including to establish CORSIA's emissions baseline (ICAO 2019).

Based on this emissions data, CORSIA's carbon offsetting obligations commence in 2021, with 3-year compliance cycles, including a pilot phase in 2021-2023. States have the option to participate in the pilot phase and the subsequent voluntary 3-year cycle in 2024-2026. CORSIA becomes mandatory from 2027 onwards for states whose share in the total international revenue tonnes per kilometre (RTK) is above a certain threshold (Hoch et al. 2019). Under CORSIA, aviation CO_2 emissions are not capped, but rather emissions that exceed the CORSIA baseline are compensated through use of 'offset units' from emissions reduction projects in other industries (Erling 2018). However, it is unclear whether the goal of carbon neutral growth and further CO_2 emissions reduction in the sector will be sufficiently incentivised solely through the use of such offsets in combination with ICAO's manufacturing standards, programs, and state action plans, without additional measures being taken, for example, constraints on demand (Lyle 2018). If countries such as China, Brazil, India and Russia do not participate in CORSIA's voluntary offsetting requirements this could significantly undermine its capacity to deliver fully on the sectoral goal by limiting coverage of the scheme to less than 50% of international aviation CO_2 emissions in the period 2021-2026 (Climate Action Tracker 2020b; Hoch et al. 2019). In addition, a wide range of offsets are approved as 'eligible emissions units' in CORSIA, including several certified under voluntary carbon offset schemes, which may go beyond those eventually agreed under the Paris Agreement Article 6 mechanism (Hoch et al. 2019). It is noted, however, that ICAO applies a set of 'Emissions Unit Eligibility Criteria' agreed in March 2019, which specify required design elements for eligible programs. In June 2020, the ICAO Council decided to define 2019 emissions levels, rather than an average of 2019 and 2020 emissions, as the baseline year for at least the first three years of CORSIA, although there were significant reductions (45-60%) in aviation CO_2 emissions in 2020 compared with 2019 as a result of reductions in air travel associated with the COVID-19 pandemic (Climate Action Tracker 2020b).

Other measures adopted by ICAO include an aircraft CO_2 emissions standard that applies to new aircraft type designs from 2020, and to aircraft type designs already in production as of 2023 (Smith and Ahmad 2018). Overall, CORSIA and regional measures, such as the EU ETS, are estimated to reduce aviation carbon emissions by only 0.8% per year from 2017-2030 (noting, however, that 'if non-CO_2 emissions are included in the analysis, then emissions will increase') (Larsson et al. 2019). Accordingly, pathways consistent with the temperature goal of the Paris Agreement are likely to require more stringent international measures for the aviation sector (Larsson et al. 2019).

Similar to ICAO, the IMO has a stated vision of remaining committed to reducing greenhouse gas emissions from international shipping and, as a matter of urgency, aims to phase them out as soon as possible in this century. IMO has considered a range of measures to monitor and reduce shipping emissions. In 2016, the IMO's Marine Environment Protection Committee (MEPC) approved an amendment to the MARPOL Convention Annex VI for the introduction of a Mandatory Global Data Collection scheme for fuel oil consumption of ships (Dobson 2020). Other IMO measures have focused on energy efficiency (Martinez Romera 2016). The IMO's Energy Efficiency Design Index (EEDI), which is mandatory for new ships, is intended, over a ten-year period, to improve energy efficiency by up to 30% in several categories of ships propelled by diesel engines (Smith and Ahmad 2018). In May 2019, the MEPC approved draft amendments to the MARPOL Convention Annex VI, which if adopted, will bring forward the entry into force of the third phase of the EEDI requirements to 2022 instead of 2025 (IMO 2019; Joung et al. 2020).

However, it is unlikely that the EEDI and other IMO technical and operational measures will be sufficient to produce 'the necessary emissions reduction because of the future growth in international seaborne trade and world population' (Shi and Gullett 2018). Consequently, in 2018, the IMO adopted an initial strategy on reduction of GHG emissions from ships (IMO 2018). This includes a goal for declining carbon intensity of the sector by reducing CO_2 emissions per transport work, as an average across international shipping, by at least 40% by 2030, and pursuing efforts towards 70% by 2050, compared to 2008 levels (IMO 2018, para. 3.1). The strategy also aims for peaking of total annual GHG emissions from international shipping as soon as possible and a reduction by at least 50% by 2050 compared to 2008 levels, whilst pursuing efforts towards phasing them out 'as soon as possible in this century' as a point 'on a pathway of CO_2 emissions reduction consistent with the Paris Agreement temperature goals' (IMO 2018, para. 2, 3.1). The shipping industry is on track to overachieve the 2030 carbon intensity target but not its 2050 target (Climate Action Tracker 2020c). The initial IMO strategy is to be kept under review by the MEPC with a view to adoption of a revised strategy in 2023.

The IMO's initial strategy identifies a series of candidate short-term (2018-2023), medium-term (2023-2030) and long-term (beyond 2030) measures for achieving its emissions reduction goals, including possible market-based measures in the medium-to-long term (IMO 2018, paras. 4.7-4.9). Further progress on market-based measures faces difficulty in light of conflicts between the CBDRRC principle of the climate regime and the traditional non-discrimination approach and principle of no more favourable treatment enshrined in MARPOL and other IMO conventions (Zhang 2016). Both the CBDRRC and non-discrimination principles are designated as 'principles guiding the initial strategy' (IMO 2018, para. 3.2). The challenges encountered in introducing global market-based measures for shipping emissions under the IMO have prompted regional initiatives such as the proposed extension of the EU ETS to emissions from maritime activities (Christodoulou et al. 2021), which was announced on 14 July 2021 by the EU Commission as part of its 'Fit for 55' legislative package (European Commission 2021).

While the IMO strategy is viewed as a reasonable first step that is ambitious for the shipping industry, achieving the 'vision' of alignment with the temperature goals of the Paris Agreement requires concrete implementation measures and strengthened targets in the next iteration in 2023 (Doelle and Chircop 2019; Climate Action Tracker 2020c). As a step towards this, in 2020, the IMO's MEPC put forward draft amendments to the MARPOL convention that would require ships to combine a technical and an operational approach to reduce their carbon intensity. These amendments were formally adopted by the Committee at its session in June 2021.

14.5.3 Civil society and social movements

Transnationally organised civil society actors have had long-standing involvement in international climate policy, with a particular focus on consulting or knowledge-sharing where they are present in transnational climate governance initiatives (Michaelowa and Michaelowa 2017). The term 'civil society' generally denotes 'the voluntary association of individuals in the public sphere beyond the realms of the state, the market and the family' (de Bakker et al. 2013, p. 575). Whereas civil society organisations are usually involved in lobbying or advocacy activities in a public arena, social movements focus on mobilisation and action for social change (Daniel and Neubert 2019). Examples of civil society groups involved in international climate policy include non-governmental organisations (NGOs) such as Greenpeace International, the World Wide Fund for Nature, the Environmental Defence Fund, the World Resources Institute, Friends of the Earth and Earthjustice among many others, as well as NGO networks such as the Climate Action Network (CAN), which has over 1300 NGO members in more than 130 countries, working to promote government and individual action to limit human-induced climate change to ecologically sustainable levels (Climate Action Network International 2020). The influence of civil society engagement in global climate governance is well-acknowledged, with these organisations' globally dispersed constituencies and non-state status offering perspectives that differ in significant ways from those of many negotiating states (Derman 2014).

Historically, the issue of climate change did not give rise to intense, organised transnational protest characteristic of social movements (McAdam 2017). During the 1990s and early 2000s, the activities of the global climate movement were concentrated in developed countries and largely sought to exercise influence through participation in UNFCCC COPs and side events (Almeida 2019). The mid-2000s onwards, however, saw the beginnings of use of more non-institutionalised tactics, such as simultaneous demonstrations across several countries, focusing on a grassroots call for climate justice that grew out of previous environmental justice movements (Almeida 2019). Groups representing Indigenous, youth, women, and labour rights brought to the fore new tools of contention and new issues in the UNFCCC, such as questions of a just transition and gender equity (Allan 2020).

Climate justice has been variously defined, but centres on addressing the disproportionate impacts of climate change on the most vulnerable populations and calls for community sovereignty and functioning (Schlosberg and Collins 2014; Tramel 2016). Contemporary climate justice groups mobilise multiple strands of environmental justice movements from the Global North and South, as well as from distinct indigenous rights and peasant rights movements, and are organised as a decentralised network of semiautonomous, coordinated units (Claeys and Delgado Pugley 2017; Tormos-Aponte and García-López 2018). The climate justice movement held global days of protest in most of the world's countries in 2014 and 2015, and mobilised another large campaign in 2018 (Almeida 2019). The polycentric arrangement of the global climate movement allows simultaneous influence on multiple sites of climate governance, from the local to the global levels (Tormos-Aponte and García-López 2018).

Prominent examples of new climate social movements that operate transnationally are Extinction Rebellion and Fridays for Future, which collectively held hundreds of coordinated protests across the globe in 2019-2021, marking out 'the transnational climate justice movement as one of the most extensive social movements on the planet' (Almeida 2019). Fridays for Future is a children's and youth movement that began in August 2018, inspired by the actions of then 15-year old Greta Thunberg who pledged to strike in front of the Swedish parliament every Friday to protest against a lack of action on climate change in line with the Paris Agreement targets (Fridays for Future 2019). Fridays for Future events worldwide encompass more than 200 countries and millions of strikers. The movement is unusual for its focus on children and the rights of future generations, with children's resistance having received little previous attention in the literature. Fridays for the Future is regarded as a progressive resistance movement that has quickly achieved global prominence (for example, Thunberg was invited to address governments at the UN Climate Summit in New York in September 2019) and is credited with helping to support the discourse about the responsibility of humanity as a whole for climate change (Holmberg and Alvinius 2019). Whereas Fridays for Future has focused on periodic protest action, Extinction Rebellion has pursued a campaign based on sustained non-violent direct citizen action that is focused on three key demands: declaration of a 'climate emergency', acting now to halt biodiversity loss and reduce greenhouse gas emissions to net zero by 2025, and creation of a citizen's assembly on climate and ecological justice (Booth 2019; Extinction Rebellion 2019). The movement first arose in the United Kingdom (UK) – where it claimed credit for adoption of a climate emergency declaration by the UK government – but now has a presence in 45 countries with some 650 groups having formed globally (Gunningham 2019).

The Paris Agreement's preamble explicitly recognises the importance of engaging "various actors" in addressing climate change, and the decision adopting the Agreement created the Non-State Actor Zone for Climate Action platform to aid in scaling up these efforts. Specific initiatives have also been taken to facilitate participation of particular groups, such as the UNFCCC's Local Communities and Indigenous Peoples Platform, which commenced work in Katowice in 2019. Climate movements based in the Global South, as well as in Indigenous territories, are playing an increasingly important role in transnational negotiations through networks such as the Indigenous Peoples Platform. These groups highlight the voices and perspectives of communities and peoples particularly affected by climate change. For instance, the Pacific Climate Warriors is a grassroots network of young people from various countries in the Pacific Islands region whose activities focus on resisting narratives of future inevitability of their Pacific homelands disappearing, and re-envisioning islanders as warriors defending rights to homeland and culture (McNamara and Farbotko 2017). Youth global climate activism, particularly involving young Indigenous climate activists, is another notable recent development. Although there remains little published literature on Indigenous youth climate activism (MacKay et al. 2020), analysis of online sources indicates the emergence of several such groups, including the Pacific Climate Warriors and Te Ara Whatu from Aotearoa New Zealand (Ritchie 2021), as well as Seed Mob in Australia.

Transnational civil society organisations advocating for climate justice in global governance have articulated policy positions around rights protections, responsibility-based approaches to climate finance, and the need for transparency and accountability (Derman 2014). Another recent area of activity, which overlaps with that of emerging investor alliances (discussed further in Section 14.5.4), is the sustainability of capital investment in fossil fuel assets. Efforts to shift away from fossil fuels led by civil society include the Beyond Coal Campaign (in the US and Europe) and the organisation for a Fossil Fuel Non-proliferation Treaty. 350.org has supported mobilisation of youth and university students around a campaign of divestment that has grown into a global movement (Gunningham 2019). As Mormann (2020) notes, as of November 2020 'more than 1,200 institutional investors managing over USD14 trillion of assets around the world have committed to divest some or all of their fossil fuel holdings' (Mormann 2020). Studies suggest that the direct impacts of the divestment movement have so far been small, given a failure to differentiate between different types of fossil fuel companies, a lack of engagement with retail investors, and a lack of guidance for investors on clean energy re-investment (Osofsky et al. 2019; Mormann 2020). The movement has had a more significant impact on public discourse by raising the profile of climate change as a financial risk for investors (Bergman 2018). Blondeel et al. (2019) also find that broader appeal of the divestment norm was achieved when moral arguments were linked to financial ones, through the advocacy of economic actors, such as Bank of England's governor.

Climate justice campaigns by transnational civil society organisations increasingly embrace action through the courts. Chapter 13 discusses the growth and policy impact of such 'climate litigation' brought by civil society actors in domestic courts, which is attracting increasing attention in the literature (Setzer and Vanhala 2019; Peel and Osofsky 2020). Transnational and international court actions focused on climate change, by contrast, have been relatively few in number (Peel and Lin 2019). This reflects—at least in part—the procedural hurdles to bringing such claims, as in many international courts and tribunals (outside of the area of human rights or investor-state arbitration) litigation can only be brought by states (Bruce 2017). However, there have been active discussions about seeking an advisory opinion from the International Court of Justice (ICJ) on states' international obligations regarding the reduction of greenhouse gas emissions (Sands 2016; Wewerinke-Singh and Salili 2020), or bringing a case to the International Tribunal for the Law of the Sea on marine pollution harms caused by climate change (Boyle 2019). In September 2021 the Government of Vanuatu announced a campaign to seek an advisory opinion from the ICJ. The aim of climate litigation more generally is to supplement other regulatory efforts by filling gaps and ensuring that interpretations of laws and policies are aligned with climate mitigation goals (Osofsky 2010).

The overall impact of transnationally-organised civil society action and social movements for international cooperation on climate change mitigation has not been comprehensively evaluated in the literature. This may reflect the polycentric organisation of the movement, which poses challenges for coordinating between groups operating in different contexts, acting with different strategies and around multiple issues, and lobbying multiple decision-making bodies at various levels of government in a sustainable way (Tormos-Aponte and García-López 2018). There is some literature emerging on environmental defenders and their need for protection against violence and repression, particularly in the case of Indigenous environmental defenders who face significantly higher rates of violence (Scheidel et al. 2020). Scheidel et al. (2020) also find that combining strategies of preventive mobilisation, protest diversification and litigation can enhance rates of success for environmental defenders in halting environmentally destructive projects. In the area of climate litigation, commentators have noted the potential for activists and even researchers to suffer retaliation through the courts as a result of "strategic lawsuits against public participation" (SLAPP) and lawsuits against researchers brought by fossil fuel interests (Setzer and Byrnes 2019; Setzer and Benjamin 2020). Influence of social movements may be enhanced through taking advantage of 'movement spillover' (the involvement of activists in more than one movement) (Hadden 2014) and coordination of activities with a range of 'non-state governors,' including cities, sub-national governments, and investor groups (Gunningham 2019). Studies of general societal change suggest that once 3.5% of the population are mobilised on an issue, far-reaching change becomes possible (Gladwell 2002; Chenoweth and Belgioioso 2019) – a tipping point that may be approaching in the case of climate change (Gunningham 2019). As noted in Chapter 5, in the particular case of low-carbon technologies, 'if 10-30% of the population were to demonstrate commitment to low-carbon technologies, behaviours, and lifestyles, new social norms would be established.'

14.5.4 Transnational business and public-private partnerships and initiatives

Combined national climate commitments fall far short of the Paris Agreement's long term temperature goals. Similar political ambition gaps persist across various areas of sustainable development. Many therefore argue that actions by nonstate actors, such as businesses and investors, cities and regions, and nongovernmental organizations (NGOs), are crucial. However, nonstate climate and sustainability actions may not be self-reinforcing but may heavily depend on supporting mechanisms. Governance risk-reduction strategies can be combined to maximize nonstate potential in sustainable and climate-resilient transformations (Chan et al. 2019).

An important feature of the evolving international climate policy landscape of the recent years is the entrepreneurship of UN agencies such as UNEP and UNDP, as well as international organizations such as the World Bank in initiating public-private partnerships (PPPs). Andonova (2017) calls this 'governance entrepreneurship'. Such partnerships can be defined as 'voluntary agreements between public actors (IOs, states, or sub-state public authorities) and non-state actors (non-governmental organizations (NGOs), companies, foundations, etc.) on a set of governance objectives and norms, rules, practices, and/or implementation procedures and their attainment across multiple jurisdictions and levels of governance' (Andonova 2017). Partnerships may carry out different main functions: first, *policy development*, establishing new agreements on norms, rules, or standards among a broader set of governmental and non-governmental actors; second, *enabling implementation and delivery of services*, by combining resources from governmental and non-governmental actors; and, third, *knowledge production and dissemination*, to e.g. the evolution of relevant public policies.

An example of a prominent PPP in the area of climate mitigation is the Renewable Energy Network (REN21 2019), which is a global multi-stakeholder network focused on promoting renewable energy policies in support of the transition to renewable energy through knowledge, established 2004. It includes members from industry, NGOs, intergovernmental organizations, and science and academia. Another example is the Green Economy Coalition founded in 2009 to bring to bear the perspectives of workers, business, poor people, the environment community, and academics in the transition to greener and more sustainable economy. Another example is that in 2015 Peru in collaboration with France and the UNFCCC Secretariat launched the 'Non-State Actor Zone for Climate Action' (NAZCA), an online platform to showcase commitments to climate action by companies, cities, regions and investors (Chan et al. 2016; Bertoldi et al. 2018). More recently, the UNFCCC 'Race to Zero' initiative led by High-level Climate Champions Nigel Topping and Gonzalo Muñoz seeks to mobilize actors beyond national governments to join the Climate Ambition Alliance and pursue net zero CO_2 targets. Its membership includes 454 cities, 23 regions, 1,391 businesses, 74 of the biggest investors, and 569 universities.

PPPs may also be developed to assist with implementation and support of states' climate mitigation commitments. For instance, UNEP has initiated a number of PPPs for climate change finance. These are designed to increase financing for the purposes of disseminating low-carbon technologies to tackle climate change and promote clean energy in many parts of developing countries (UNEP 2018b; Charlery and Traerup 2019).

In the same vein, in 2010 FAO delivered the Framework for Assessing and Monitoring Forest Governance. The Framework draws on several approaches currently in use or under development in major forest governance-related processes and initiatives, including the World Bank's Framework for Forest Governance Reform. The Framework builds on the understanding that governance is both the context and the product of the interaction of a range of actors and stakeholders with diverse interests (FAO 2010). For example, UNFCCC and UN-REDD program focus on REDD+ and UNEP focus on TEEB (a global initiative focusing on the economics of ecosystems and biodiversity) institutional mechanisms have been conceptualized as a 'win-win-win' for mitigating climate, protecting biodiversity and conserving indigenous culture by institutionalizing payments on carbon sequestration and biodiversity conservation values of ecosystems services from global to local communities. These mechanisms include public-private partnership, and non-governmental organization participation. REDD+ and TEEB allocation policies will be interventions in a highly complex system, and will inevitably involve trade-offs; therefore, it is important to question the 'win-win-win' discourse (Zia and Kauffman 2018; Goulder et al. 2019). The initial investment and the longer periods of recovery of investment are sometimes barriers to private investment. In this sense, it is important to have government incentives and encourage public-private investment (Ivanova and Lopez 2013).

The World Bank has also established several partnerships since 2010, mainly in the field of carbon pricing. Prominent examples are the Networked Carbon Markets initiative (established 2013; spanning both governmental actors and experts; now entering a phase II) and the Carbon Pricing Leadership Coalition, established in 2015 and spanning a wide range of governmental and non-governmental actors, not least within business (World Bank 2018, 2019; Wettestad et al. 2021). These partnerships deal with knowledge production and dissemination and seek to enable implementation of carbon pricing policies. The leadership role of the international 'heavyweight' World Bank gives these partnerships additional comparative political weight, meaning also a potentially greater involvement of powerful finance ministries/ministers generally involved in Bank matters and meetings.

PPPs for cooperation on climate mitigation goals have emerged at multiple levels of governance beyond the realm of international organizations. For example, PPP funding for cities expanded rapidly in the 1990s and outpaced official external assistance almost tenfold. Most of the PPP infrastructure investment has been aimed at telecommunications, followed by energy. However, with the exception of the telecommunications sector, PPP investments have generally bypassed low-income countries (Ivanova 2017). It is therefore not surprising that PPPs have added relatively little to the financing of urban capital in developing countries over the past two decades (Bahl and Linn 2014). Liu and Waibel (2010) argue that the inherent risk of urban investment is the main obstacle to increasing the flow of private capital. Nevertheless, there have been cases where PPP investments have exceeded official external aid flows even for water and sanitation, and highly visible projects have been funded with PPPs in selected metropolitan areas of developing countries, including urban rail projects in Bangkok, Kuala Lumpur, and Manila (Liu and Waibel 2010).

Local governments are also creating cross-sector social partnerships (CSSPs) at the sub-national level; entities created for addressing social, economic, and/or environmental issues with partner organizations from the public, private and civil society sectors (Crane and Seitanidi 2014). In particular, with support from international networks such as ICLEI Local Governments for Sustainability, C40, Global Covenant of Mayors, and Global 100% Renewable Energy, local governments around the world are committing to aggressive carbon reduction targets for their cities (Ivanova et al. 2015; Clarke and Ordonez-Ponce 2017; Kona et al. 2018). Research on CSSPs implementing community sustainability plans shows that climate change is one of the four most common issues, after waste, energy and water (which are also highly relevant to climate mitigation) (MacDonald et al. 2017).

Community climate action plans consider all GHGs emitted within the local geographic boundaries, including from industry, home heating, burning fuel in vehicles, etc. It is these community plans that require large multi-stakeholder partnerships to be successful. Partners in these partnerships generally include the local government departments, other government departments, utilities, large businesses, Chamber of Commerce, some small and medium sized enterprises, universities, schools, and local civil society groups (Clarke and MacDonald 2016). Research shows that the partnership's structural features enable the achievement of plan outcomes, such as reducing GHG emissions, while also generating value for the partners (Austin and Seitanidi 2012; Clarke and MacDonald 2016; Clarke and Ordonez-Ponce 2017). Stua (2017b) explores the Mitigation Alliances (MAs) on the national level. The internal governance model of MAs consists of overarching authorities mandated to harmonize the overall organizational structure These authorities guarantee an effective, equitable and transparent functioning of the MA's pillars (the demand, supply, and exchange of mitigation outcomes), in line with the principles and criteria of the Paris Agreement. This hybrid governance model relies upon its unique links with international climate institutions (Stua 2017a).

Transnational business partnerships are a growing feature of the landscape of multi-level, multi-actor governance of climate change. Many business leaders embraced the ethos of ''business cannot succeed in societies that fail''. Examples of this line of reasoning are: poverty limits consumer spending, political instability disrupts business activity, and climate change threatens the production and distribution of goods and services. Such situations endanger MNE investments, global asset management funds, and the core business of international insurance companies and pension funds (van Tulder et al. 2021).

A leading example is the World Business Council on Sustainable Development (WBCSD), a global, CEO-led organization of over 200 leading businesses working together to accelerate the transition to a sustainable world. Member companies come from all business sectors and all major economies, representing a combined revenue of more than USD8.5 trillion and with 19 million employees. The WBCSD aims to enhance 'the business case for sustainability through tools, services, models and experiences'. It includes a Global Network of almost 70 national business councils across the globe. The overall vision is to create a world where more than 9 billion people are all living well and within the boundaries of our planet, by 2050. Vision 2050, released in 2010, explored what a sustainable world would look like 2050, how such a world could be realized, and the role that business can play in making that vision a reality. A few years later, Action2020 took that Vision and translated it into a roadmap of necessary business actions and solutions (WBCSD 2019). WBCSD focuses on those areas where business operates and can make an impact. They identify six transformation systems that are critical in this regard: Circular Economy, Climate and Energy, Cities and Mobility, Food and Nature, People and Redefining Value. All have an impact on climate. An important initiative launched in September of 2008 – the 'natural climate solutions', has the objective of leveraging business investment to capture carbon out of the atmosphere. This initiative has built strong cross-sectoral partnerships and is intended to tap into this immense emissions reduction solution potential through natural methods with the help of private investment.

The Global Methane Initiative is a multilateral partnership launched in 2010 by the United States Environmental Protection Agency along with thirty-six other countries to generate a voluntary, non-binding agenda for global collaboration to decrease anthropogenic methane releases. The GMI builds on the Methane to Market (M2M) Partnership, an international partnership launched in 2004. In addition to the GMI's own financial assistance, the initiative receives financial backing from the Global Methane Fund (GMF) for methane reduction projects. The GMF is a fund created by governments and private donors (Leonard 2014).

Another potentially influential type of transnational business partnership is investor coalitions or alliances formed for the purpose of pushing investee companies to adopt stronger measures for stranded asset management and climate change mitigation. MacLeod & Park (2011, p. 55) argue that these transnational groups 'attempt to re-orient and "regulate" the behaviour of business by holding corporations accountable via mechanisms of information sharing, monitoring of environmental impacts, and disclosure of activities related to the corporate climate footprint'. This favours a theory of active ownership (investor engagement with corporate boards) over capital divestment as the optimal pathway to shape the behaviour of corporate actors on climate risk (Kruitwagen et al. 2017; Krueger et al. 2020).

Transnational cooperative action by investors on climate mitigation has been facilitated by international standard-setting on issues of climate risk and disclosure. For example, in 2017 the Financial Stability Board's Taskforce on Climate-related Financial Disclosures (TCFD) adopted international recommendations for climate risk disclosure (TCFD 2017). These recommendations, which apply to all financial-sector organizations, including banks, insurance companies, asset managers, and asset owners, have received strong support from investor coalitions globally, including Climate Action 100+ (with 300 investors with more than USD33 trillion in assets under management), the Global Investor Coalition on Climate Change (a coalition of regional investor groups across Asia, Australia, Europe and North America) and the Institutional Investors Group on Climate Change (IIGCC). One of the key recommendations of the TCFD calls for stress-testing of investment portfolios taking into consideration different climate-related scenarios, including a 2° C or lower scenario. Broad adoption of the TCFD recommendations could provide a basis for decisions by investors to shift assets away from climate-risk exposed assets such as fossil fuel extraction projects (Osofsky et al. 2019). There is strong evidence showing the urgent need for scaling-up climate finance to mitigate greenhouse gases in line with pursuit of limiting the temperature increase to 1.5 °C above pre-industrial levels, and to support adaptation to safeguard the international community from the consequences of a changing climate. While public actors have a responsibility to deploy climate finance, it is clear that the contribution from the private sector needs to be significant (Gardiner et al. 2016).

As most of these partnerships are of recent vintage an assessment of their effectiveness is premature. Instead, partnerships can be assessed on the basis of the three main functions introduced earlier. Starting with policy development, i.e. establishing new agreements on norms, rules, or standards among a broader set of governmental and non-governmental actors, this is not the most prominent aspect of partnerships so far, although both the cities' networks and risk disclosure recommendations include some elements of this. The second element, enabling implementation and delivery of services, by combining resources from governmental and non-governmental actors, seems to be a more prominent part of the partnerships (Ivanova et al. 2020). Both UNEP financing, the World Business Council on Sustainable Development (WBCSD), the REDD+ and TEEB mechanisms, and PPP funding for cities are examples here. Finally, the third element, knowledge production and dissemination, for example, contributing to the evolution of relevant public policies, is the most prominent part of these partnerships, with the majority including such activities.

There is a relatively large volume of literature that assesses PPPs in general. Much of this applies to partnerships which, either by design or not, advance climate goals. This literature provides a good starting point for assessing these partnerships as they become operational. These can help assess whether such partnerships are worth the effort in terms of their performance and effectiveness (Liu et al. 2017b), their economic and social value added (Quélin et al. 2017), their efficiency (Estache and Saussier 2014) and the possible risks associated with them (Darrin, Grimsey and Mervyn 2002).

What is less common, but gradually growing, is an important and more relevant literature on criteria to assess sustainability and impact on climate and development goals. Michaelowa and Michaelowa assess 109 trans-national partnerships and alliances based on four design criteria: existence of mitigation targets; incentives for mitigation; definition of a baseline; and existence of a monitoring, reporting, and verification procedure (Michaelowa and Michaelowa 2017). About half of the initiatives do not meet any of these criteria, and not even 15% satisfy three or more. A recent study using a systematic review of business and public administration literature on PPPs concludes that research in the past rarely incorporates sustainability concepts. The authors propose a research agenda and a series of success factors that, if appropriately managed can contribute to sustainable development, and in so doing contribute to a more solid scientific evaluation of PPPs (Pinz et al. 2018). There is evidence that with the adoption of the Sustainable Development Goals (SDGs), many of which are directly linked to climate goals, PPPs will become even more prominent as they will be called upon to provide resources, knowledge, expertise, and implementation support in a very ambitious agenda. PPT in the developing world needs to take into account different cultural and social decision making processes, language differences, and unfamiliar bureaucracy (Gardiner et al. 2016). Having more evidence on what norms and standards in relation to sustainability are used and their governance is essential (Axel 2019). The issue of double counting should be revised. GHGs are accounted both at the national and sub-national level or company level (Schneider et al. 2014). Some recent studies aim to provide systems to assess the impact of PPPs beyond the much-used notion of value for money. One of these recent studies proposes a conceptual model that addresses six dimensions relevant to economic, social and environmental progress. These include resilience and environment, access of services to the population, scalability and replicability, economic impact, inclusiveness, and finally, degree of engagement of stakeholders (Berrone et al. 2019). These systems will most likely continue to evolve.

14.5.5 International co-operation at the sub-national and city levels

Local and regional governments have an important role to play in global climate action, something recognised by the Paris Agreement, and also assessed in Chapter 13 of this report, sections 13.3.2 and 13.3.4. There are several ways they can be useful. First, subnational governments can contribute insights and experience that provide valuable lessons to national governments, as well as offering needed implementation capacity (GIZ 2017; Leffel 2018). A great deal of policymaking has occurred at the level of city governments in particular. Cities have been responsible for more than 70% of global greenhouse gas (GHG) emissions and generate over 80% of global income (World Bank 2010), and many of them have started to take their own initiative in enacting and developing mitigation policies (CDP 2015). Most of these activities aim at the reduction of GHG emissions in the sectors of energy, transportation, urban land use and waste (Bulkeley 2010; Xuemei 2007), and are motivated by concerns not only over climate, but also a consideration of local co-benefits (Rashidi et al. 2017, 2019). Second, sub-national governments can fill the void in policy leadership in cases where national governments are ineffectual, even to the point of claiming leadership and authority with respect to foreign affairs (Leffel 2018). International cooperation plays a role in such action. Several international networks , such as C40, ICLEI, Mayors for Climate Protection, and the Covenant of Mayors have played an important role in defining and developing climate-policy initiatives at the city level (Fünfgeld 2015). While the networks differ from each other, they generally are voluntary and non-hierarchical, intended to support the horizontal diffusion of innovative climate policies through information sharing platforms linked to specific goals that member cities make (Kern and Bulkeley 2009). The literature has addressed the questions of why cities join the networks (Betsill and Bulkeley 2004; Pitt 2010), what recognition benefits cities can expect (Buis 2009; Kern and Bulkeley 2009), and how memberships can provide visibility to leverage international funding (Betsill and Bulkeley 2004; Heinrichs et al., 2013). Membership in the networks has been found to be a significant predictor of cities' adoption of mitigation policies, even when controlling for national-level policies that may be in place (Rashidi and Patt 2018). Kona et al. (2018) find that cities belonging to the Covenant of Mayors are engaging in emissions reductions at a rate consistent with achieving a 2°C global temperature target. Kona et al. (2021) document this trend continuing.

With respect to their role in formal international cooperation, however, it is unclear what authority, as a non-state actor, they actually have. Cities, for example, are members of transnational initiatives aimed at non-state actors, such as Global Climate Action, originally the Non-state Actor Zone for Climate Action, under the UNFCCC. While there is reason to believe that such membership can add value to mitigation efforts, one study suggests that the environmental effects have yet to be reliably quantified (Hsu et al. 2019a). By contrast, Kuramochi et al. (2020) provide evidence that non-state actors are leading to significant emission reductions beyond what countries would otherwise be achieving. In terms institutional strength, Michaelowa and Michaelowa (2017) suggest that few such networks fulfil governance criteria, and hence challenge their effectiveness. Several researchers suggest that their role is important in informal ways, given issues about the legitimacy of non-state actors (Nasiritousi et al. 2016; Chan et al. 2016). Bäckstrand et al. (2017) advance the concept of 'hybrid multilateralism' as a heuristic to capture this intensified interplay between state and non-state actors in the new landscape of international climate cooperation. The effectiveness of such non-state government actors should be measured not only by their contribution to mitigation, but also by their success to enhance the accountability, transparency and deliberative quality of the UNFCCC and the Paris Agreement (Busby 2016; Hale et al. 2016; Chan et al. 2015). In the post-Paris era, effectiveness also revolves around how to align non-state and intergovernmental action in a comprehensive framework that can help achieve low carbon futures (Chan et al. 2016). Stua (2017b) suggests that networks involving non-state actors can play an important role in enhancing transparency. Such effectiveness has to be complemented also by *normative questions*, applying a set of democratic values: participation, deliberation, accountability, and transparency (Bäckstrand and Kuyper 2017). Such concepts of polycentric governance offer new opportunities for climate action, but it has been argued that it is too early to judge its importance and effects (Jordan et al. 2015).

14.6 Synthesis

14.6.1 Changing nature of international cooperation

The main development since AR5 in terms of international climate cooperation has been the shift from the Kyoto Protocol to the Paris Agreement as the primary multilateral driver of climate mitigation policy worldwide (Section 14.3). Most *ex-post* assessments of the Kyoto Protocol suggest that it did lead to emissions reductions in countries with binding targets, in addition to changing investment patterns in low-carbon technologies. As noted earlier, the Paris Agreement is tailored to the evolving understanding of the climate mitigation challenge as well as shifting political imperatives and constraints. Whether the Paris Agreement will in fact be effective in supporting global action sufficient to achieve its objectives is contested, with competing arguments in the scientific literature supporting different views. To some extent these views align with the different analytic frameworks (Section 14.2.1): the Paris Agreement does not address the free-riding issue seen as important within the global commons framing, but may provide the necessary incentives and support mechanisms viewed as important under the political and transitions framings, respectively. The strongest critique of the Paris Agreement is that current NDCs themselves fail by a wide margin to add up to the level of aggregate emissions reductions necessary to achieve the objectives of holding global average warming well below 2°C, much less 1.5°C (see Section 14.3.3 and Figure 14.2), and that there is no legally binding obligation to achieve the NDCs. Arguments in support of Paris are that it puts in place the processes, and generates normative expectations, that nudge NDCs to become progressively more ambitious over time, including in developing countries. The growing number of countries with mid-century net zero GHG or CO_2 targets, consistent with Article 4 of Paris, lends support to this proposition, although there is as yet no empirical literature drawing an unambiguous connection. The collective quantified goal from a floor of USD100 billion a year in transfers to developing countries, the Green Climate Fund and other provisions on finance in the Paris Agreement have also been recognised as key to cooperation (Sections 14.3.2.8 and 14.4.1).

But then these arguments are met with counter arguments, that even with Paris processes in place, given the logic of iterative, rising levels of ambition over time, this is unlikely to happen within the narrow window of opportunity that exists to avert dangerous levels of global warming (Section 14.3.3). The degree to which countries are willing to increase the ambition and secure the achievement of their NDCs over time will be an important indicator of the success of the Paris Agreement; evidence of this was expected by the end of 2020, but the COVID-19 pandemic has delayed the process of updating NDCs.

An increasing role is also played by other cooperative agreements, in particular (potentially) under Article 6 (Sections 14.3.2.10 and 14.4.4), trans-national partnerships, and the institutions that support them. This fits both a transitions narrative that cooperation at the sub-global and sectoral levels is necessary to enable specific system transformations, and a recent emphasis in the public goods literature on club goods and a gradual approach to cooperation, also referred to as building blocks or incremental approach (Sections 14.2 and 14.5.1.4). There has been little analysis of whether these other agreements are of sufficient scale and scope to ensure that transformations happen quickly enough. This chapter, appraising them together, concludes that they are not. First, many agreements, such as those related to trade, may stand in the way of bottom-up mitigation efforts (Section 14.5.1.3). Second, many sectoral agreements aimed at decarbonisation – such as within the air travel sector – have not yet adopted targets comparable in scale, scope or legal character to those adopted under the Paris Agreement (Section 14.5.2.3). Third, there are many sectors for which there are no agreements in place. At the same time, there are some important bright spots, many in the area of trans-national partnerships. A growing number of cities have committed themselves to adopting urban policies that will place them on a path to rapid decarbonisation, while learning from each other how to implement successful policies to realise climate goals (Section 14.5.5). An increasing number of large corporations have committed to decarbonising their industrial processes and supply chains (Section 14.5.4). And, an ever-increasing number of non-state actors are adopting goals and initiating mitigation actions (Section 14.5.3). These goals and actions, some argue, could bridge the mitigation gap created by inadequate NDCs, although the empirical literature to date challenges this, suggesting that there is less transparency and limited accountability for such actions, and mitigation targets and incentives are also not clear (Sections 14.3.3 and 14.5).

14.6.2 Overall assessment of international cooperation

This section provides an overall assessment of international cooperation, taking into account the combined effects of cooperation within the UNFCCC process, other global agreements, as well as regional, sectoral, and transnational processes. Recent literature consistent with the transitions framing highlights that cooperation can be particularly effective when it addresses issues on a sector-by-sector basis (Geels et al. 2019). Table 14.4 below summarises the effects of international cooperation on mitigation efforts in each of the sectoral areas covered in Chapter 5 – 12 of this Assessment Report. As it indicates, there are some strong areas of sectoral-specific cooperation, but also some important weaknesses. Formal agreements and programs, both multilateral and bilateral, are advancing mitigation efforts in energy, AFOLU, and transportation, while transnational networks and partnerships are addressing issues in urban systems, industry, and buildings. Although many of the concerns relevant for buildings may be embedded in the energy sector with respect to their operation, and the industrial sector with respect to their materials, reinforcing the networks with more formal agreements could be vital to putting these sectors on a pathway to net zero GHG or CO_2 emissions. Several of the sectors have very little formal cooperation at the international level, and a common theme across many of them is a need for increased financial flows to achieve particular objectives.

Table 14.4 Effects of international cooperation on sectoral mitigation efforts

Sector	Key strengths	Key gaps and weaknesses
Demand, services, social aspects	Adoption of SDGs addressing social inequities and sustainable development in the context of mitigation.	Little international attention to demand-side mitigation issues.
Energy	Greater incorporation of climate goals into sectoral agreements and institutions; formation of new specialised agencies (e.g. IRENA, SE4All) devoted to climate-compatible energy.	Need for enhanced financial support to place low-carbon energy sources on an equal footing with carbon emitting energy in developing countries; investor-state dispute settlement mechanisms designed to protect the interests of companies engaged in high-carbon energy supply from national policies; ensuring just transition; and, addressing stranded assets.
AFOLU	Bilateral support for REDD+ activities; transnational partnerships disincentivising use of products from degraded lands.	Need for increased global finance for forest restoration projects and REDD+ activities; failure of national governments to meet internationally agreed upon targets with respect to deforestation and restoration; no cooperative mechanisms in place to address agricultural emissions
Urban systems	Transnational partnerships enhancing the capacity of municipal governments to design and implement effective policies.	Need for increased financial support for climate compatible urban infrastructure development.
Buildings	Transnational initiative aimed at developing regional roadmaps.	Need for formal international cooperation to enhance mitigation activities in buildings.
Transport	Sectoral agreements in aviation and shipping begin to address climate concerns.	Need to raise the level of ambition in sectoral agreements consistent with the Paris Agreement and complete decarbonisation, especially as emissions from international aviation and shipping continue to grow, unaccounted for in NDCs.
Industry	Transnational partnerships and networks encouraging the adoption of zero emission supply chain targets.	No formal multilateral or bilateral cooperation to address issues of decarbonisation in industry.
Cross-sectoral, including CDR and SRM	International agreements addressing risks of ocean-based CDR	Lack of cooperative mechanisms addressing risks and benefits of SRM; lack of cooperative mechanisms addressing financial and governance aspects of land- and technology-based CDR.

Table 14.5 provides examples of mechanisms addressing each of the assessment criteria identified in Section 14.2.3. The effects of different forms of international cooperation are separated out, including not only UNFCCC and other multilateral processes, but also sub-global and sectoral agreements. Several points stand out. First, the Paris Agreement has the potential to significantly advance the UN

climate regime's transformative potential. Second, the international market mechanisms under Article 6 – should an agreement on implementation deals be reached – allow a shift from projects and programs to policy-based and sectoral generation of emissions credits. Moreover, the sectoral agreement CORSIA also makes use of such credits. Third, there is a lack of attention to both distributive outcomes and institutional support within sectoral agreements, representing a serious gap in efforts to harmonise mitigation with equity and sustainable development. Fourth, there are transnational partnerships and initiatives, representing the actions of non-state actors, addressing each of the assessment criteria, with the exception of economic effectiveness.

Table 14.5 Illustrative examples of multi-level governance addressing criteria of effectiveness

	Environmental effectiveness	Transformative potential	Distributive Outcomes	Economic effectiveness	Institutional strength
UNFCCC	Stabilisation goal, and quasi-targets for industrialised countries	Financial mechanism; technology mechanism, provisions for capacity building	Financial mechanism, transfers from developed to developing; leadership role for industrialised countries listed in Annex 1		Reporting requirements; capacity building for national climate change offices.
Kyoto Protocol	Binding national targets for industrialised countries		Adaptation Fund; targets restricted to industrialised countries	Market-based mechanisms	Emissions accounting and reporting requirements, institutional capacity building
Paris Agreement	NDCs and the global stocktake	Mechanisms for capacity building and technology development and transfer	Furthering financial commitments under the UNFCCC, including enhanced transparency on finance	Voluntary cooperation	Mechanism for enhanced transparency
Other multilateral agreements (Montreal protocol, and SDG 7, etc)	Phase out of Ozone depleting substances (ODS) with high global warming potential - significant effects on GHG mitigation	Ozone Fund, technology transfer; development and sharing of knowledge and expertise	SDGs embedding mitigation in sustainable development		Processes for adjustment and amendment, reporting requirements

Multilateral and regional economic agreements and institutions	Harmonised lending practices of MDBs; mainstreaming climate change into IMF practices; liberalisation of trade in climate-friendly goods and services; negative effect from regulatory chill		Concessional financing agreements		Potentially negative results from dispute settlement processes
Sectoral agreements and institutions	Climate mitigation targets and actions in AFOLU, energy, and transport	Institutions devoted to developing and deploying zero-carbon energy technologies (e.g. IRENA).		Use of carbon offsets to reduce growth in emissions from aviation	
Transnational networks and partnerships	Youth climate movement raising mitigation and fossil fuel divestment on political agendas and in financial sector	Non-state actor commitments to renewable energy-based supply chains	Climate justice legal initiatives		City networks providing information exchange and technical support

14.7 Knowledge Gaps

Any assessment of the effectiveness of international cooperation is limited by the methodological challenge of observing sufficient variance in cooperation in order to support inference on effects. There is little in the way of cross-sectional variance, given that most of the governance mechanisms assessed here are global in their geographical coverage. One exception is with respect to the effects of the Kyoto Protocol, which we have reported. Time series analysis is also challenging, given that other determinants of climate mitigation, including technology costs and the effects of national and sub-national level policies, are rapidly evolving. Thus, this chapter primarily reviews scholarship that compares observations with theory-based counter-factual scenarios.

Many of the international agreements and institutions discussed in this chapter, in particular the Paris Agreement, are new. The logic and architecture of the Paris Agreement, in particular, breaks new ground, and there is limited evaluation of prior experience in the form of analogous treaties to draw on. Such instruments have evolved in response to geo-political and other drivers, that are changing rapidly, and will continue to shape the nature of international cooperation under it and triggered by it. The Paris Agreement is also, in common with other multilateral agreements, a 'living instrument' evolving through interpretative and operationalising rules, and forms of implementation, that parties continue to negotiate at conferences year on year. It is a constant 'work in progress' and thus challenging to assess at any given point in time. The Paris Agreement also engages a larger set of variables – given its privileging of national autonomy and politics, integration with the sustainable development agenda, and its engagement with actions and actors at multiple levels – than earlier international agreements, which further complicates the task of tracing causality between observed effects and international cooperation through the Paris Agreement.

Understanding of the effectiveness of international agreements and institutions is driven entirely by theory driven prediction of how the world will evolve, both with these agreements in place and without them. The former predictions in particular are problematic, because governance regimes are complex adaptive systems, making it impossible to predict how they will evolve over time, and hence what their effects will be. Time will cure this in part, as it will generate observations of the world with the new regime in place, which we can compare to the counterfactual situation of the new regime's being absent, which may be a simpler situation to model. But even here our modelling capacity is limited: it may simply never be possible to know with a high degree of confidence whether international cooperation, such as that embodied in the Paris Agreement, is having a significant effect, no matter how much data are accumulated.

Given the importance of theory for guiding assessments of the past and likely future impacts of policies, it is important to note that among the alternative theoretical frameworks for analysis, some have been much more extensively developed in the literature than others. This chapter has noted in particular the partial dichotomy between a global-commons framing of climate change and a transitions framing, which include different indicators to be used to evaluate the effectiveness of policies. The latter framing is particularly under-developed. Greater development of theories resting in social science disciplines such as economic geography, sociology, and psychology could potentially provide a more complete picture of the nature and effectiveness of international cooperation.

Frequently Asked Questions

FAQ 14.1: **Is international cooperation working?**

Yes, to an extent. Countries' emissions were in line with their internationally agreed targets: the collective Greenhouse Gas (GHG) mitigation target for Annex I countries in the UNFCCC to return to their 1990 emissions by 2000, and their individual targets in the Kyoto Protocol for 2008-12. Numerous studies suggest that participation in the Kyoto Protocol led to substantial reductions in national GHG emissions, as well increased levels of innovation and investment in low-carbon technologies. In this latter respect, the Kyoto Protocol set in motion some of the transformational changes that will be required to meet the temperature goal of the Paris Agreement. It is too soon to tell whether the processes and commitments embodied in the Paris Agreement will be effective in achieving its stated goals with respect to limiting temperature rise, adaptation, and financial flows. There is, however, evidence that its entry into force has been a contributing factor to many countries' adopting mid-century targets of net-zero GHG or CO_2 emissions.

FAQ 14.2: **What is the future role of international cooperation in the context of the Paris Agreement?**

Continued international cooperation remains critically important both to stimulate countries' enhanced levels of mitigation ambition, and through various means of support to increase the likelihood that they achieve these objectives. The latter is particularly the case in developing countries, where mitigation efforts often rely on bilateral and multilateral cooperation on low-carbon finance, technology support, capacity building, and enhanced South-South cooperation. The Paris Agreement is structured around nationally determined contributions (NDCs) that are subject to an international oversight system, and bolstered through international support. The international oversight system is designed to generate transparency and accountability for individual emission reduction contributions, and regular moments for stock-taking of these efforts towards global goals. Such enhanced transparency may instil confidence and trust, and foster solidarity among nations, with theory-based arguments that this will lead to greater levels of ambition. Together with other cooperative agreements at the sub-global and sectoral levels, as well as a growing number of transnational networks and initiatives, the implementation of all of these mechanisms are likely to play an important role in making political, economic, and social conditions more favourable to ambitious mitigation efforts in the context of sustainable development and efforts to eradicate poverty.

FAQ 14.3: **Are there any important gaps in international cooperation, which will need to be filled in order for countries to achieve the objectives of the Paris Agreement, such as holding temperature increase to 'well below 2°C' and pursuing efforts towards '1.5°C' above pre-industrial levels?**

While international cooperation is contributing to global mitigation efforts, its effects are far from uniform. Cooperation has contributed to setting a global direction of travel, and to falling greenhouse gas emissions in many countries and avoided emissions in others. It remains to be seen whether it can achieve the kind of transformational changes needed to achieve the Paris Agreement's long-term global goals. There appears to be a large potential role for international cooperation to better address sector-specific technical and infrastructure challenges that are associated with such transformational changes. Finalising the rules to pursue voluntary cooperation, such as through international carbon market mechanisms and public climate finance in the implementation of NDCs, without compromising environmental integrity, may play an important role in accelerating mitigation efforts in developing countries. Finally, there is room for international cooperation to more explicitly address transboundary issues associated with Carbon Dioxide Removal (CDR) and Solar Radiation Management (SRM).

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Chapter 15: Investment and Finance

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Date of Draft: 28/11/2021

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Executive summary

Finance to reduce net greenhouse gas (GHG) emissions and enhance resilience to climate impacts represents a critical enabling factor for the low carbon transition. Fundamental inequities in access to finance as well as its terms and conditions, and countries exposure to physical impacts of climate change overall result in a worsening outlook for a global just transition *(high confidence).* Decarbonising the economy requires global action to address fundamental economic inequities and overcome the climate investment trap that exists for many developing countries. For these countries the costs and risks of financing often represent a significant challenge for stakeholders at all levels. This challenge is exacerbated by these countries' general economic vulnerability and indebtedness. The rising public fiscal costs of mitigation, and of adapting to climate shocks, is affecting many countries and worsening public indebtedness and country credit ratings at a time when there were already significant stresses on public finances. The COVID-19 pandemic has made these stresses worse and tightened public finances still further. Other major challenges for commercial climate finance include: the mismatch between capital and investment needs, home bias[1] considerations, differences in risk perceptions for regions, as well as limited institutional capacity to ensure safeguards represent. {15.2, 15.6.3}

Investors, central banks, and financial regulators are driving increased awareness of climate risk. This increased awareness can support climate policy development and implementation *(high confidence).* Climate-related financial risks arise from physical impacts of climate change (already relevant in the short term), and from a disorderly transition to a low carbon economy. Awareness of these risks is increasing leading also to concerns about financial stability. Financial regulators and institutions have responded with multiple regulatory and voluntary initiatives by to assess and address these risks. Yet despite these initiatives, climate-related financial risks remain greatly underestimated by financial institutions and markets limiting the capital reallocation needed for the low-carbon transition. Moreover, risks relating to national and international inequity – which act as a barrier to the transformation – are not yet reflected in decisions by the financial community. Stronger steering by regulators and policy makers has the potential to close this gap. Despite the increasing attention of investors to climate change, there is limited evidence that this attention has directly impacted emission reductions. This leaves high uncertainty, both near-term (2021-30) and longer-term (2021-50), on the feasibility of an alignment of financial flows with the Paris Agreement (*high confidence*). {15.2, 15.6}

Progress on the alignment of financial flows with low GHG emissions pathways remains slow. There is a climate financing gap which reflects a persistent misallocation of global capital *(high confidence).* Persistently high levels of both public and private fossil-fuel related financing continue to be of major concern despite promising recent commitments. This reflects policy misalignment, the current perceived risk-return profile of fossil fuel-related investments, and political economy constraints (*high confidence*). {15.3}

Estimates of climate finance flows – which refers to local, national, or transnational financing from public, private, multilateral, bilateral and alternative sources, to support mitigation and adaptation actions addressing climate change – exhibit highly divergent patterns across regions and sectors and a slowing growth. {15.3}

When the perceived risks are too high the misallocation of abundant savings persists. Investors refrain from investing in infrastructure and industry in search of safer financial assets, even earning low or negative real returns. {15.2, 15.3}

FOOTNOTE [1] Most of climate finance stays within national borders, especially private climate flows (over 90%). Reasons are national policy support, differences in regulatory standards, exchange rate, political and governance risks, to information market failures.

Global climate finance is heavily focused on mitigation (more than 90% on average between 2017-2020). This is despite the significant economic effects of climate change's expected physical impacts, and the increasing awareness of these effects on financial stability. To meet the needs for rapid deployment of mitigation options, global mitigation investments are expected to need to increase by the factor of 3 to 6 (*high confidence*). The gaps represent a major challenge for developing countries, especially Least Developed Countries (LDCs), where flows have to increase by factor 4 to 8, for specific sectors like AFOLU, and for specific groups with limited access to-, and high costs of-, climate finance (*high confidence*). {15.4, 15.5}

The actual size of sectoral and regional climate financing gaps is only one component driving the magnitude of the challenge, with financial and economic viability, access to capital markets, appropriate regulatory frameworks and institutional capacity to attract and facilitate investments and ensure safeguards being decisive to scale-up financing. Financing needs for the creation and strengthening of regulatory environment and institutional capacity, upstream financing needs as well as R&D and venture capital for development of new technologies and business models are often overlooked despite their critical role to facilitate the deployment of scaled-up climate finance *(high confidence)*. {15.4.1, 15.5.2}

The relatively slow implementation of commitments by countries and stakeholders in the financial system to scale up climate finance reflects neither the urgent need for ambitious climate action, nor the economic rationale for ambitious climate action. *(high confidence).* Delayed climate investments and financing – and limited alignment of investment activity with the Paris Agreement – will result in significant carbon lock-ins, stranded assets, and other additional costs. This will particularly impact urban infrastructure and the energy and transport sectors *(high confidence)*. A common understanding of debt sustainability and debt transparency, including negative implications of deferred climate investments on future GDP, and how stranded assets and resources may be compensated, has not yet been developed *(medium confidence)*. {15.6}

The greater the urgency of action to remain on a 1.5°C pathway the greater need for parallel investment decisions in upstream and downstream parts of the value chain. Greater urgency also reduces the lead times to build trust in regulatory frameworks. Consequently, many investment decisions will need to be made based on the long-term global goals. This highlights the importance of trust in political leadership which, in turn, affects risk perception and ultimately financing costs *(high confidence).* {15.6.1, 15.6.2}

There is a mismatch between capital availability in the developed world and the future emissions expected in developing countries. This emphasizes the need to recognize the explicit and positive social value of global cross-border mitigation financing. A significant push for international climate finance access for vulnerable and poor countries is particularly important given these countries' high costs of financing, debt stress and the impacts of ongoing climate change *(high confidence).* {15.2, 15.3.2.3, 15.5.2, 15.6.1, 15.6.7}

Ambitious global climate policy coordination and stepped-up (public) climate financing over the next decade (2021–2030) can help address macroeconomic uncertainty and alleviate developing countries' debt burden post-COVID-19. It can also help redirect capital markets and overcome challenges relating to the need for parallel investments in mitigation and the up-front risks that deter economically sound low carbon projects. *(high confidence)* Providing strong climate policy signals helps guide investment decisions. Credible signalling by governments and the international community can reduce uncertainty for financial decision-makers and help reduce transition risk. In addition to indirect and direct subsidies, the public sector's role in addressing market failures, barriers, provision of information, and risk sharing (equity, various forms of public guarantees) can encourage the efficient mobilisation of private sector finance *(high confidence).* {15.2, 15.6.1, 15.6.2}

The mutual benefits of coordinated support for climate mitigation and adaptation in the next decade for both developed and developing regions could potentially be very high in the post-Covid era. Climate compatible stimulus packages could significantly reduce the macro-financial uncertainty generated by the pandemic and increase the sustainability of the world economic recovery. {15.2, 15.3.2.3, 15.5.2, 15.6.1, 15.6.7}

Political leadership and intervention remains central to addressing uncertainty as a fundamental barrier for a redirection of financial flows. Existing policy misalignments – for example in fossil fuel subsidies – undermine the credibility of public commitments, reduce perceived transition risks and limit financial sector action *(high confidence).* {15.2, 15.3.3, 15.6.1, 15.6.2, 15.6.3}

Innovative financing approaches could help reduce the systemic underpricing of climate risk in markets and foster demand for Paris-aligned investment opportunities. Approaches include de-risking investments, robust 'green' labelling and disclosure schemes, in addition to a regulatory focus on transparency and reforming international monetary system financial sector regulations *(medium confidence).* Green bond markets and markets for sustainable finance products have grown significantly since AR5 and the landscape continues to evolve. Underpinning this evolution is investors' preference for scalable and identifiable low-carbon investment opportunities. These relatively new labelled financial products will help by allowing a smooth integration into existing asset allocation models. *(high confidence)* Green bond markets and markets for sustainable finance products have also increased significantly since AR5, but challenges nevertheless remain, in particular there are concerns about 'greenwashing' and the limited application of these markets to developing countries. New business models (e.g. pay-as-you-go) can facilitate the aggregation of small-scale financing needs and provide scalable investment opportunities with more attractive risk-return profiles. Support and guidance for enhancing transparency can promote capital markets' climate financing by providing quality information to price climate risks and opportunities. Examples include sustainable development goals (SDG) and environmental, social and governance (ESG) disclosure, scenario analysis and climate risk assessments, including the Task Force on Climate-Related Financial Disclosures (TCFD). The outcome of these market-correcting approaches on capital flows cannot be taken for granted, however, without appropriate fiscal, monetary and financial policies. Mitigation policies will be required to enhance the risk-weighted return of low emission and climate resilient options, and - supported by progress in transparent and scientifically based projects' assessment methods - to accelerate the emergence and support for financial products based on real projects, such as green bonds, and phase out fossil fuel subsidies. Greater public-private cooperation can also encourage the private sector to increase and broaden investments, within a context of safeguards and standards, and this can be integrated into national climate change policies and plans. {15.1, 15.2.4, 15.3.1, 15.3.2, 15.3.3, 15.5.2, 15.6.1, 15.6.2, 15.6.6, 15.6.7, 15.6.8}.

The following policy options can have important long-term catalytic benefits *(high confidence).* (i) Stepped-up both the quantum and composition of financial, technical support and partnership in low-income and vulnerable countries alongside low-carbon energy access in low-income countries, such as Sub-Saharan Africa, which currently receives less than 5% of global climate financing flows; (ii) continued strong role of international and national financial institutions, including multilateral, especially location-based regional, and national development banks; (iii) de-risking cross-border investments in low-carbon infrastructure, development of local green bond markets, and the alignment of climate and non-climate policies, including direct and in-direct supports on fossil fuels, consistent with the climate goals; (iv) lowering financing costs including transaction costs and addressing risks through funds and risk-sharing mechanisms for under-served groups; (v) accelerated finance for nature-based solutions, including mitigation in the forest sector (REDD+), and climate-responsive social protection; (vi) improved financing instruments for loss and damage events, including risk-pooling-transfer-sharing for climate risk insurance; (vii) phasing-in carbon pricing and phasing out fossil fuel subsidies in a way that addresses equity and access; and (viii) gender-responsive and women empowered programs {15.2.3, 15.2.4, 15.3.1, 15.3.2.2, 15.3.3, 15.4.1, 15.4.2, 15.4.3, 15.5.2, 15.6, 15.6.2, 15.6.4, 15.6.5, 15.6.6, 15.6.7, 15.6.8.2}.

15.1 Introduction

15.1.1 Climate finance - key concepts and elements of scope

Finance for climate action (or climate finance), environmental finance (which also covers other environmental priorities such as water, air pollution and biodiversity), and sustainable finance (which encompasses issues relating to socio-economic impacts, poverty alleviation and empowerment) are interrelated rather than mutually exclusive concepts (UNEP Inquiry 2016a; ICMA 2020a). Their combination is needed to align mitigation investments with multiple SDGs, at a minimum, minimize the conflicts between climate targets and SDGs not being targeted. From a climate policy perspective, climate finance refers to finance "whose expected effect is to reduce net GHG emissions and/or enhance resilience to the impacts of climate variability and projected climate change" (UNFCCC 2018a). However, as pinpointed in the AR5, significant room for interpretation and context-specific considerations remain. Further, such definition needs to be put in perspective with the expectations of investors and financiers (see Box 15.2).

Specifying the scope of climate finance requires defining two terms: what qualifies as "finance" and as "climate" respectively. In terms of what type of finance to consider, options include considering investments or total costs (see Box 15.1), stocks or flows, gross or net (the latter taking into account reflows and/or depreciation), and domestic or cross-border, public or private (see Box 15.2). In terms of what may be considered as "climate", a key difference relates to measuring climate-specific finance (only accounts for the portion finance resulting in climate benefits) or climate-related finance (captures total project costs and aims to measure the mainstreaming of climate considerations). One should even consider the investments decided for reasons unrelated with climate objectives but contribute to these objectives (hydroelectricity, rail transportation).

'START BOX 15.1 HERE'

Box 15.1 Core Terms

This box defines some core terms used in this chapter as well as in other chapters addressing finance issues: cost, investment, financing, public and private. The chapter makes broad use of the *finance* to refer to all types of transactions involving monetary amounts. It avoids the use of the terms *funds* and *funding* to the extent possible, which should otherwise be understood as synonyms for *money* and *money provided*.

Cost, investment and financing: different but intertwined concepts. Cost encompass capital expenditures (CAPEX or upfront investment value leveraged over the lifetime of a project) operating and maintenance expenditures (OPEX), as well as financing costs. Note that some projects e.g. related to technical assistance may only involve OPEX (e.g. staff costs) but no CAPEX , or may not incur direct financing costs (e.g. if fully financed via own funds and grants).

Investment, in an economic sense, is the purchase of (or CAPEX for) a physical asset (notably infrastructure or equipment) or intangible asset (e.g. patents, IT solutions) not consumed immediately but used over time. For financial investors, physical and intangible assets take the form of financial assets such as bonds or stocks which are expecting to provide income or be sold at a higher price later. In practice, investment decisions are motivated by a calculation of risk-weighted expected returns that takes into account all expected costs, as well as the different types of risks, discussed in Section 15.6.1, that may impact the returns of the investment and even turn them into losses.

Incremental cost (or *investment*) accounts for the difference between the cost (or investment value) for a climate projects compared to the cost (or investment value) of a counterfactual reference project (or investment). In cases where climate projects and investments are more cost effective than the counterfactual, the incremental cost will be negative.

Financing refers to the process of securing the money needed to cover an investment or project cost. Financing can rely on debt (e.g. through bond issuance or loan subscription), equity issuances (listed or unlisted shares), own funds (typically savings or auto-financing through retained earnings), as well as on grants and subsidies

Public and private: statistical standard and grey zones. International statistics classify economic actors as pertaining to the public or private sectors. Households always qualify as private and governmental bodies and agencies as public. Criteria are needed for other types of actors such as enterprises and financial institutions. Most statistics rely on the majority ownership and control principle. This is the case for the Balance of Payment, which records transactions between residents of a country and the rest of the world (IMF 2009).

Such a strict boundary between public and private sectors may not always be suitable for mapping and assessing investment and financing activities. On the one hand, some publicly owned entities may have a mandate to operate on a fully- or semi-commercial basis, e.g. state-owned enterprises, commercial banks, and pension funds, as well as sovereign wealth funds. On the other hand, some privately owned or -controlled entities can pursue non-for profit objectives, e.g. philanthropies and charities. The present chapter considers these nuances to the extent made possible by available data and information.

'END BOX 15.1 HERE

In many cases, the scope of what may be considered as "climate finance" will also depend on the context of implementation such as priorities and activities listed in NDCs (UNFCCC 2019a) as well as national development plans more broadly targeting the achievement of SDGs. Hence, rather than opposing the different options listed above, the choice of one or the other depends on the desired scope of measurement, which in turn depends on the policy objective being pursued. The increasingly diverse initiatives and body of grey literature address a range of different information needs. They provide analyses at the levels of domestic finance flows (e.g. (UNDP 2015; Hainaut and Cochran 2018)), international flows (e.g. (OECD 2016; AfDB et al. 2018)), global flows (UNFCCC 2018a; Buchner et al. 2019)), the financial system (e.g. (UNEP Inquiry 2016a) or specific financial instruments such as bonds (e.g. (CBI 2018)). Common frameworks, reporting transparency are, however, necessary in order to identify overlaps, commonalities and differences between these different measurements in terms of scope and underlying definitions. In that regard, the developments of national and international taxonomies, definitions and standards can help, as further discussed in Section 15.6. and Chapter 17 in WGII (TSU please confirm).

'START BOX 15.2 HERE

Box 15.2 International climate finance architecture

International climate finance can flow through different bilateral, multilateral, and other channels, involving a range of different types of institutions both public (official) and private (commercial) with different mandates and focuses. In practice, the architecture of international public climate finance is rapidly evolving, with the creation by traditional donors of new public sources and channels of over the years (Watson and Schalatek 2019), as well as emergence of new providers of development co-operation, both bilateral (see (Benn and Luijkx 2017)) and multilateral (e.g. Asian Infrastructure Investment Bank), as well as of non-governmental actors such as philanthropies (OECD 2018a).

The operationalisation of the Green Climate Fund (GCF), which channels the majority of its funds via accredited entities, has notably attracted particular attention since AR5. Section 14.3.2 of Chapter 14 provides a further assessment of progress and challenges of financial mechanisms under the UNFCCC, such as the GCF, the Global Environment Facility (GEF) and the Adaptation Fund (AF).

The multiplication of sources and channels of international climate finance can help address growing climate-related needs, and partly results from increased decentralisation as well financial innovation, which in turn can increase the effectiveness of finance provided. There is, however, also evidence that increased complexity implies transaction costs (Brunner and Enting 2014), in part due to bureaucracy and intra-governmental factors (Peterson and Skovgaard 2019), which constitutes a barrier to low carbon projects and are often not accounted for in assessments of international climate finance. On the ground, activities by international providers operating in the same countries may overlap, with sub-optimal coordination and hence duplication of efforts, both on the bilateral and multilateral sides (Ahluwalia et al. 2016; Gallagher et al. 2018; Humphrey and Michaelowa 2019), as well as risks of fragmentation of efforts (Watson and Schalatek 2020) which slows down coordination with international providers, national development banks and other domestic institutions.

'END BOX 15.2 HERE'

Beyond the need to scale up levels of climate finance, the Paris Agreement provides a broad policy environment and momentum for a more systemic and transformational change in investment and financing strategies and patterns. Article 2.1c, which calls for "making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development", positions finance as one of the Agreement's three overarching goals (UNFCCC 2015). This formulation is a recognition that the mitigation and resilience goals cannot be achieved without finance, both in the real economy and in the financial system, being made consistent with these goals (Zamarioli et al. 2021). It has in turn contributed to the development of the concept of alignment (with the Paris Agreement) used in the financial sector (banks, institutional investors), businesses, and public institutions (development banks, public budgets). As a result, since AR5, in addition to measuring and analysing climate finance, an increasing focus has been placed on assessing the consistency or alignment, as well as respectively the inconsistency or misalignment, of finance with climate policy objectives, as for instance illustrated by the multilateral development banks joint framework for aligning their activities with the goals of the Paris Agreements (MDBs 2018).

Assessing climate consistency or alignment implies looking at all investment and financing activities, whether they target, contribute to, undermine or have no particular impact on climate objectives. This all-encompassing scope notably includes remaining investments and financing for high-GHG emission activities that may be incompatible with remaining carbon budgets, but also activities that may play a transition role in climate mitigation pathways and scenarios (see Section 15.3.2.3). As a result, any meaningful assessments of progress requires implies the use of different shades to assess activities based on their negative, neutral ("do no harm") or positive contributions, e.g. (CICERO 2015; Cochran and Pauthier 2019; Natixis 2019). Doing so in practice requires the development of robust definitions, assessment methods and metrics, an area of work and research that remained under development at the time of writing. A range of financial sector coalitions, civil society organisations as well as commercial services providers to the financial industry have developed frameworks, approaches and metrics, mainly focusing on investment portfolios (Raynaud et al. 2020; IIGCC 2021; TCFD Portfolio Alignment Team 2021; U.N.-Convened Net-Zero Asset Owner Alliance 2021),and, to a lesser extent for real economy investments (Micale et al. 2020; Jachnik and Dobrinevski 2021).

Key findings from AR5 and other IPCC publications

For the first time the IPCC in AR5 (Clarke et al. 2014) elaborated on the role of finance in a dedicated chapter. In the following year, the Paris Agreement (PA) (UNFCCC 2015) recognised the transformative role of finance, as a means to achieving climate outcomes, and the need to align financial flows with the long-term global goals even as implementation issues were left unresolved (Bodle and Noens 2018). AR5 noted the absence of a clear definition and measurement of climate finance flows, a difficulty that continues (see Sections 15.2 and 15.3) (Weikmans and Roberts 2019). The approach taken in AR5 was to report ranges of available information on climate finance flows from diverse sources, using a broad definition of climate finance, as in the Biennial Assessments in 2014 and again in 2018 (UNFCCC 2014a, 2018a) of the Standing Committee under the United Nations Framework Convention on Climate Change (UNFCCC): Climate finance is taken to refer to local, national or transnational financing – drawn from public, private and alternative sources of financing – that seeks to support mitigation and adaptation actions that address climate change (UNFCCC 2014b). For this chapter, while the focus is primarily on mitigation, adaptation, resilience and loss and damage financing needs cannot be entirely separated because of structural relationships, synergies, trade-offs and policy coherence requirements between these sub-categories of climate finance (Box 15.1).

'START BOX 15.3 HERE'

Box 15.3 Mitigation, adaptation and other related climate finance merit joint examination

Mitigation finance deals with investments that aim to reduce global carbon emissions, while adaptation finance deals with the consequences of climate change (Lindenberg and Pauw 2013). Mitigation affects the scale of adaptation needs and adaptation may have strong synergies and co-benefits as well as trade-offs with mitigation (Grafakos et al. 2019). If mitigation investments are inadequate to reducing global warming (as in last decade) with asymmetric adverse impacts in lower latitudes and low-lying geographies, the scale of adaptation investments has to rise and the benefits of stronger adaptation responses may be high (Markandya and González-Eguino 2019). If adaptation investments build greater resilience, they might even moderate mitigation financing costs. Similar policy coherence considerations apply to disaster risk reducing financing, the scale of which depends on success with both adaptation and mitigation (Mysiak et al. 2018). The same financial actors, especially governments and the private sector, decide at any given time on their relative allocations of available financing for mitigation, adaptation and disaster-risk from a constrained common pool of resources. The trade-offs and substitutability between closely-linked alternative uses of funds, therefore, make it essential for a simultaneous assessment of needs – as in parts of this chapter. Climate finance versus the financing of other Sustainable Development Goals (SDGs) faces a similar issue. A key agreement was that climate financing should be 'new and additional' and not at the cost of SDGs. Resources prioritising climate at the cost of non-climate development finance increases the vulnerability of a population for any given level of climate shocks, and additionality of climate financing is thus essential (Brown et al. 2010). Policy coherence is also the reason why mitigation finance cannot be separated from consideration of spending and subsidies on fossil fuels. Climate change may additionally cause the breaching of physical and social adaptation limits, resulting in climate-related residual risks (i.e. potential impacts after all feasible mitigation, adaptation, and disaster risk reduction measures, have been implemented) (Mechler et al. 2020). Because these residual losses and damages from climate-related risks are related to overall mitigation and adaptation efforts, the magnitude of potential impacts are related to the overall quantum of mitigation, adaptation, and disaster risk reduction finance available (Frame et al. 2020). All categories of climate finance thus need to be considered together in discussions around climate finance.

'END BOX 15.3 HERE'

The AR5 concluded that published assessments of financial flows whose expected effect was to reduce net greenhouse gas (GHG) emissions and/or to enhance resilience to climate change aggregated 343-385 billion USD yr^{-1} globally between 2010 and 2012 (*medium confidence*). Most (95% of total) went towards mitigation, which nevertheless underfinanced and adaptation even more so. Measurement of progress towards the commitment by developed countries to provide 100 billion USD yr^{-1} by 2020 to developing countries, for both mitigation and adaptation (Bhattacharya et al. 2020) – a narrower goal than overall levels of climate finance – continued to be a challenge, given the lack of clear definition of such finance, although there remain divergent perspectives (see Section 15.2.4). As against these flows, annual need for global aggregate mitigation finance between 2020 and 2030 was cited briefly in the AR5 to be about 635 billion USD (mean annual), both public and private, implying that the reported 'gap' in mitigation financing of estimated flows during 2010 to 2012 was slightly under one-half of that required (IPCC 2014).

More recent published data from the Biennial Assessments (UNFCCC 2018a) and the Special Report on Global Warming of 1.5°C (IPCC 2018) have revised upwards the needs of financing between 2020 and 2030 to 2035 to contain global temperature rise to below 2°C and 1.5°C respectively by 2100: 1.7 trillion USD yr^{-1} (mean) in the Biennial Assessment 2018 for the former, and for the latter, 2.4 trillion USD yr^{-1} (mean) for the energy sector alone (and three-times higher if transport and other sectors were to be included). The resulting estimated gaps in annual mitigation financing during 2014 to 2017, using reporting of climate financing from published sources was about 67% for 2015, and 76% for the energy sector alone in 2017 (*medium confidence*), and greater if other sectors were to be included. While the annual reported flows of climate financing showed some moderate progress (see Section 15.3), from earlier 364 billion USD (mean 2010/2011) to about 600 billion USD (mean 2017/2020), with a slowing in the most recent period 2014 to 2017, the gap in financing was reported to have widened considerably (see Section 15.4 and 15.5). In the context of policy coherence, it is also important to note that reported annual investments going into the fossil-fuel sectors, oil and gas upstream and coal mining, during the same period were about the same size as global climate finance, although the absence of alternative financing and access to low carbon energy is a complicating factor.

Adaptation financing needs, meanwhile, were rising rapidly. The Adaption Gap Report 2020 (UNEP 2021) reported that the current efforts are insufficient to narrow the adaptation finance gap, and additional adaptation finance is necessary, particularly in developing countries. The gap is expected to be aggravated by COVID-19 (*high confidence)*. It reaffirmed earlier assessments that by 2030 (2050) the estimated costs of adaptation ranges between 140-300 billion (280-500 billion). Against this, the reported actual global public finance flows for adaptation in 2019/2020 were estimated at 46 billion (Naran et al. 2021). The costs of climate disasters meanwhile continued to rise, affecting low-income developing countries the most. Climate natural disasters – not all necessarily attributable to climate change – caused some 300 billion USD yr^{-1} economic losses and well-being losses of about 520 billion USD yr^{-1} (Hallegatte et al. 2017).

15.2 Background considerations

The institutions under climate finance in this chapter refer to the set of financial actors, instruments and markets that are recognised to play a key role in financing decisions on climate mitigation and adaptation. For a definition of climate financial stock and flows see further Section 15.3 and the glossary. The issue of climate finance is closely related to the conversation on international cooperation and the question of how cross-border investments can support climate mitigation and adaptation in developing countries. However, the issue is also related to more general questions of how financial institutions, both public and private, can assess climate risks and opportunities from all investments, and what roles states, policy makers, regulators and markets can play in making them more sustainable. In particular, the question of the respective roles of the public and private financial actors has become important in deliberations on climate finance in recent years. The broader macroeconomic context is an important starting point. Four major events and macro trends mark the developments in climate finance in the previous five years and likely developments in the near-term.

- First, the 2015 Paris Agreement, with the engagement of the financial sector institutions in the climate agenda has been followed by a series of related developments in financial regulation in relation to climate change and in particular to the disclosure of climate related financial risk (*high confidence)* (see Section 15.2.1).

- Second, the last five years have been characterised by a series of interconnected "headwinds" (see Section 15.2.2), including rising private and public debt and policy uncertainty which work against the objective of filling the climate investment gap (*high confidence*).
- Third, the 2020 COVID-19 pandemic crisis has put enormous additional strain on the global economy, debt and the availability of finance, which will be longer-lasting (see Section 15.2.3). At the same time, while it is still too early to draw positive conclusions, this crisis highlights opportunities in terms of political and policy feasibility and behavioural change in respect of realigning climate finance (*medium confidence*).
- Fourth, the sharp rise in global inequality and the effects of the pandemic have brought into renewed sharp focus the need for a Just Transition (see Section 15.2.4) and a realignment of climate finance and policies that would be beneficial for a new social compact towards a more sustainable world that addresses energy equity and environmental justice (*high confidence*).

15.2.1 Paris Agreement and the engagement of the financial sector in the climate agenda

This is the first IPCC AR chapter on investment and finance since the 2015 Paris Agreement, which represented a landmark event for climate finance because for the first time the key role of aligning financial flows to climate goals was spelled out. Since then, the financial sector has recognised the opportunity and has stepped up to centre-stage in the global policy conversation on climate change. While before the Paris Agreement, only few financial professionals and regulators were acquainted with climate change, today climate change is acknowledged as a strategic priority in most financial institutions. This is a major change in the policy landscape from AR5. This is a major change in the policy landscape from AR5. However, this does not mean that finance necessarily plays an adequate enabling role for climate investments. On the contrary, the literature shows that without appropriate conditions, finance can represent a barrier to fill the climate investment gap (Hafner et al. 2020). Indeed, despite the enormous acceleration in policy initiatives (e.g. (NGFS 2020)) and coalitions of the willing in the private sectors, the effect in terms of closing the investment gap identified already in AR5 has been limited (see Section 15.5.2).

Financial investors have started to account for climate risk in some contexts but they do so only to a limited extent (Monasterolo and de Angelis 2020; Alessi et al. 2021; Bolton and Kacperczyk 2021) and the reasons for these remain unclear. Two aspects are relevant here. The first is the endogenous nature of climate financial risk and opportunities (with the term "risk" meaning here the potential for adverse financial impact whether, or not, the distribution of losses is known). Academics and practitioners in finance are aware that financial risk can in certain contexts be endogenous, i.e., the materialization of losses is affected by the action of financial players themselves. However, the standard treatment of risk both in financial valuation models and in asset pricing assumes that risk is exogenous. In contrast, endogeneity is a key feature of climate risk because today's perception of climate risk affects climate investment, which in turn affect directly the future risk. This endogeneity leads to the fact that multiple and rather different mitigation scenarios are possible (see Chapter 3). Moreover, the likelihood of occurrence of each alternative scenario is very hard to estimate. Further, the assessment of climate-related financial risk requires to combine information related to mitigation scenarios as well as climate impact scenarios, leaving open an important knowledge gap for the next years (see Section 15.6.1).

The second aspect is that the multiplicity of equilibria results in a coordination problem whereby the majority of investors wait to move and reallocate their investments until they can follow a clear signal. Despite the initial momentum of the Paris Agreement, for many investors, both public and private, the policy signal seems not strong enough to induce them to align their investment portfolios to climate goals.

Analyses of the dynamics of the low carbon transition suggest that it does not occur by itself and that it requires a policy signal credible enough in the perception of market players and investors (Battiston et al. 2021b). Credibility could require a policy commitment device (Brunner et al. 2012). The commitment would also need to be large enough (analogous to the "whatever it takes" statement by the European Central Bank during the 2011-12 European sovereign crisis (Kalinowski and Chenet 2020)). In principle, public investments in low carbon infrastructures (or private-public partnerships) as well as regulation could provide credible signals if their magnitude and time horizon are appropriate (past experiences with FiTs models across countries provide useful lessons).

15.2.2 Macroeconomic context

Entering 2020, the world already faced large macroeconomic headwinds to meeting the climate finance gap in the near-term – barring some globally coordinated action. While an understanding of the disaggregated country-by-country, sector-by-sector, project-by-project, and instrument-by-instrument approach to raising climate finances analysed in the later parts of this Chapter remains important, macroeconomic drivers of finance remain crucial in the near-term.

Near-term finance financial flows in aggregate often show strong empirically observed cycles over time, especially in terms of macroeconomic and financial cycles. By *near-term*, we mean here the likely cycle over the next five to ten years (2020–2025 and 2020–2030), as influenced by global macroeconomic real business cycles (output, investment and consumption), with periodic asymmetric downside impacts and crises (Gertler and Kiyotaki 2010; Borio 2014; Jordà et al. 2017; Borio et al. 2018). Financial cycles typically have strong co-movements (asset prices, credit growth, interest rates, leverage, risk factors, market fear, macro-prudential and central bank policies) (Coeurdacier and Rey 2013), They have large consequences for all types of financial flows such as equity, bond and banking credit markets, which in turn are likely to impact climate finance flows to all sub-sectors and geographies (with greater expected volatility in more risky and more leveraged regions). This is in contrast to *longer-term trend considerations* (2020–2050) that typically focus the attention on drivers of disaggregated flows of climate finance and policies. The upward trends of the cycles tend to favour speculative bubbles like real estates at the expenses of investment in production and infrastructures whereas the asymmetric downsides raise uncertainty and risks for longer-term investments on newer climate technologies, and favour a flight to near-term safety (e.g., lowest risk non-climate short-term treasury investments, highest creditworthy countries, and away from cross-border investments (see Section 15.5) – making the challenge of longer-term low-carbon transition more difficult. In this respect, the impact of financial regulation is unclear. On the one hand, it could be argued that the tighter bank regulations under Basel III, combined with an economic environment with higher uncertainty and flatter yield curve, can push banks to retrench from climate finance projects (Blended Finance Taskforce, 2018a), since banks tend to limit loan maturity to 5 or 8 years, while infrastructure projects typically require the amortisation of debt over 15-20 years (Arezki et al. 2016). On the other hand, other studies report that stricter capital requirements are not a driving factor for moving away from sustainability projects (CISL and UNEP FI 2014)

Four key aspects of the global macroeconomy, each slightly different, pointed in a cascading fashion towards a deteriorating environment for stepped-up climate financing over the next crucial decade (2020–2030), even before COVID-19. The argument is often made that there is enough climate financing available if the right projects and enabling policy actions ('bankable projects') present themselves (Cuntz et al. 2017; Meltzer 2018). The attention to 'bankability' does not however address access and equity issues (Bayliss and Van Waeyenberge 2018). Some significant gains in climate financing at the sectoral and microeconomic level were nevertheless happening in specific segments, such as solar energy financing and labelled green bonds (although how much of such labelled financing is incremental to unlabelled financing that might have happened anyway remains uncertain) (Tolliver et al. 2019). Issues of 'labelling' (Cornell 2020) apply even more to ESG (environmental, social and governance) investments which started to grow rapidly after 2016 (see Section 15.6.6. for more details). Overall, these increments for climate finance remained, however, small in aggregate relative to the size of the shifts in climate financing required in the coming decade. Annual energy investments in developing regions (other than China) which account for two-thirds of the world population, with least costs of mitigation per ton of emissions (one-half that in developed regions), and for the bulk of future expected global GHG emissions, saw a 20 percent decline in investments since 2016, and only a one-fifth share of global clean energy investment, reflecting persistent financing problems and costs of mobilizing finance towards clean energy transition, even prior to the pandemic (IEA 2021a). In the words of a macroeconomic institution, 'tangible policy responses to reduce greenhouse gas emissions have been grossly insufficient to date' (IMF 2020a). The reason is in part global macroeconomic headwinds, which show a relative stagnation since 2016 and limited cross-border flows in particular (Yeo 2019).

Slowing and more unstable GDP growth. The first headwind was more unstable and slowing GDP growth at individual country levels and in aggregate because of worsening climate change impact events (Donadelli et al. 2019; Kahn et al. 2019). As each warmer year keep producing more negative impacts – arising from greater and rising variability and intensity of rainfall, floods, droughts, forest fires and storms – the negative consequences have become more macro-economically significant, and worst for the most climate-vulnerable developing countries (*high confidence*). Paradoxically, while these effects should have raised the social returns and incentives to invest more in future climate mitigation, a standard public policy argument, these macroeconomic shocks may work in the opposite direction for private decisions by raising the financing costs now (Cherif and Hasanov 2018). With some climate tipping points, potentially in the near-term reach (see Chapter 4: Future global climate: scenario-based 1 projections and near-term information in WGI) the uncertainty with regard to the economic viability and growth prospects of selected macroeconomically critical sectors increases significantly (see Chapter 8 and Chapter 17 in WGII). Taking account of other behavioural failures, this was creating a barrier for pro-active and accelerated mitigation and adaptation action.

Public finances. The second headwind was rising public fiscal costs of mitigation and adapting to rising climate shocks affecting many countries, which were negatively impacting public indebtedness and country credit ratings (Cevik and Jalles 2020; Klusak et al. 2021) at a time of growing stresses on public finances and debt (Benali et al. 2018; Kling et al. 2018; Kose et al. 2020) (*high confidence*). Every climate shock and slowing growth puts greater pressures on public finances to offset these impacts. Crucially, the negative consequences were typically greater at the lower end of income distributions everywhere (Acevedo et al. 2018; Aggarwal 2019). As a result, the standard prescription of raising distributionally adverse carbon taxes and reducing fossil fuel subsidies to raise resources faced political pushback in several countries (Copland 2020; Green 2021), and low rates elsewhere. Reduced taxes on capital, by contrast, was viewed as a way to improve growth (Bhattarai et al. 2018; Font et al. 2018), and working against broader fiscal action. Progress with carbon pricing remained modest across 44 OECD and G20 countries, with 55-70% of all carbon emissions from energy use entirely unpriced as of 2018 (OECD 2021a). Climate vulnerable countries meanwhile faced sharply rising cost of sovereign debt. (Buhr et al. 2018). (Buhr et al. 2018) calculate the additional financing costs of Climate Vulnerable Forum countries of 40 billion USD on government debt over the past 10 years and 62 billion USD for the next 10 years. Including private financing cost the amount increases to 146–168 billion USD over the next decade.

Credit risks. The third headwind is rising financial and insurance sector risks and stresses (distinct from real 'physical' climate risks above) arising from the impacts of climate change, and systematically affecting both national and international financial institutions and raising their credit risks (Dafermos et al. 2018; Rudebusch 2019; Battiston et al. 2021a) *(high confidence)*. Central banks are beginning to take notice (Carney 2019; NGFS 2019). It is also the case that, even if at greater risk from stranded assets in the future, the large-scale financing of new fossil fuel projects by large global financial institutions rose significantly since 2016, because of perceived lower private risks and higher private returns in these investments and other factors than in alternative but perceived more risky low carbon investments.

Global growth. The fourth headwind entering 2020 was the sharply slowing global macroeconomic growth, and prospects for near-term recession (which occurred in the pandemic). During global real and financial cycle downturns (Jordà et al. 2019), the perception of general financial risk rises, causing financial institutions and savers to reallocate their financing to risk-free global assets *(high confidence)*. This 'flight to safety' was evident even before the recent pandemic, marked by an extraordinary tripling of financial assets to about 16.5 trillion USD in negative-interest earning 'safer' assets in 2019 in world debt markets – enough to have nearly closed the total financing gap in climate finance over a decade.

15.2.3 Impact of COVID-19 pandemic

The macroeconomic headwinds have worsened dramatically with the onset of COVID-19. Almost two years after the pandemic started, it is still too uncertain and early to conclude impacts of the pandemic until 2025-2030, especially as they affect climate finance. Multiple waves of the pandemic, new virus mutations, accumulating human toll, and growing vaccine coverage but vastly differing access across developed versus developing regions are evident. They are causing divergent impacts across sectors and countries, which combined with the divergent ability of countries and regions to mount sufficient fiscal and monetary policy actions imply continued high uncertainty on the economic recovery paths from the crisis. The situation remains more precarious in middle and low-income developing countries (IMF 2021a). While recovery is happening, the job losses have been large, poverty rates have climbed, public health systems are suffering long-term consequences, education gains have been set back, public debt levels are higher (5-10% of GDP higher), financial institutions have come under longer-term stress, a larger number of developing countries are facing debt distress, and many key high-contact sectors such as tourism and trade will take time to recover (Eichengreen et al. 2021). The implication is negative headwinds for climate finance with public attention focused on pandemic relief and recovery and limited (and divergent) fiscal headroom for a low carbon transition, with considerable uncertainties ahead (Hepburn et al. 2020b; Maffettone and Oldani 2020; Steffen et al. 2020).

The larger and still open public policy choice question that COVID-19 now raises is whether there is room for public policy globally and in respect of their individual economies to integrate climate more centrally to their growth, jobs and sustainable development strategies worldwide for ecological and economic survival. The outcomes will depend on the robustness of recovery from the pandemic, and the still evolving public policy responses to the climate agenda in the recovery process. Private equity and asset markets have recovered surprisingly rapidly during the pandemic (in response to the massive fiscal and central bank actions generating large excess savings with very low or negative yields boosting stock markets). On public spending, some early studies suggest that the immediate economic recovery packages were falling well short of being sufficiently climate sustainable (Gosens and Jotzo 2020; Kuzemko et al. 2020; O'Callaghan 2021) but several governments have also announced intentions to spend more on a green recovery, a 'build back better' and Just Transition efforts (see Section 15.2.4), although outcomes remain highly uncertain (Lehmann et al. 2021; Markandya et al. 2021).

An important immediate finding from the COVID-19 crisis was that the slowdown in economic activity is illustrating some of these choices: immediately after the onset, more costly and carbon-intensive coal use for energy use tumbled in major countries such as China and the USA, while the forced 'stay-at-home' policies adopted around the major economies of the world led to a -30-35% decline in individual country GDP, and was in turn been associated with a decrease in daily global CO_2 emissions by -26% at their peak in individual countries, and -17% globally (-11 to -25% for $\pm 1\sigma$) by early April 2020 compared with the mean 2019 levels, with just under half coming from changes in surface transport, city congestion and country mobility (Le Quéré et al. 2020). Along with the carbon emissions drop was a dramatic improvement in other parameters such as clean air quality. Moreover, longer-term behavioural impacts are also possible: a dramatic acceleration of digital technologies in communications, travel, retail trade and transport. The question however is whether the world might revert to the earlier carbon-intensive path of recovery, or to a different future, and the choice of policies in shaping this future. Studies generally suggest that the gains from long-term impacts of the pandemic on future global warming will be limited and depend more on the nature of public policy actions and long-term commitments by countries to raise their ambitions, not just on climate but on sustainable development broadly (Barbier 2020; Barbier and Burgess 2020; Forster et al. 2020; Gillingham et al. 2020; Reilly et al. 2021). The positive lesson is clear: opportunities exist for accelerating structural change, and for a re-orientation of economic activity modes to a low-carbon use strategy in areas such as coal use in energy consumption and surface transport, city congestion and in-country mobility, for which lower-cost alternatives exist and offer potentially dramatic gains (Hepburn et al. 2020b).

A new consensus and compact towards such a structural change and economic stimulus instruments may therefore need to be redrawn worldwide, where an accelerated low carbon transition is a priority; and accelerated climate finance to spur these investments may gain by becoming fully and rapidly integrated with near-term economic stimulus, growth and macroeconomic strategies for governments, central banks, and private financial systems alike. If that were to happen, COVID-19 may well be a turning point for sustainable climate policy and financing. Absent that, a return to 'business-as-usual' modes will mean a likely down-cycle in climate financing and investments in the near-term.

Expectations that the recovery package stimulus will increase economic activity rely on the assumption that increased credit investment will have a positive effect on demand, the so-called demand-led policy (Mercure et al. 2019). The argument for a green recovery also draws on the experience from the post Global Financial Crisis in 2008–2009 (GFC) recovery, in which large economies such as China, South Korea, the US and the EU observed that green investments propelled the development of new industrial sectors. Noticeably, this had a positive net effect on job creation when compared to the investment in traditional infrastructure (UKERC 2014; Vona et al. 2018; Jaeger et al. 2020). For a more in-depth discussion on macroeconomic-finance possible response see Section 15.6.3. Here, we conclude with the options for reviving a better globally coordinated macroeconomic climate action. The options are some combinations of five possible elements:

(a) Reaffirmation of a strong financial agenda in future Conference of Parties' meetings, and a new collective finance target, which will need to be undertaken by 2025. Given that the shortfalls in financing are likely to be acute for developing regions and especially the more debt-stressed and vulnerable (Dibley et al. 2021; Elkhishin and Mohieldin 2021; Laskaridis 2021; Umar et al. 2021), developed countries may wish to step up their collective support (Resano and Gallego 2021). One possibility is to expedite the new SDR issuance allocation rules for the 650 billion USD recently (2021) approved, most of which will go to increase the reserves of G-7 and other High-Income countries unless voluntarily reallocated towards the needs of the most vulnerable low-income countries, raising resources potentially 'larger than the Marshall Plan in today's money' (IMF 2021b; Jensen 2021; Obstfeld and Truman 2021), with decisions to be taken (Ameli et al. 2021a) note the climate investment trap of current high cost of finance that effectively lowers green electricity production possibilities in Africa for a cost optimal pathway. Other initiatives could also include G-7 and G-20 governments (especially with the lead taken by the developed members for cross-border support to avoid over-burdening public resources in developing countries) running coordinated fiscal deficits to accelerate the financing of low carbon investments ('green fiscal stimulus').

(b) introducing new actions, including regulatory, to take some of the risks off-the-table from institutional financial players investing in climate mitigation investment and insurance. This could include the provision of larger sovereign guarantees to such private finance, primarily from developed countries but jointly with developing countries to create a level-playing field (Dafermos et al. 2021) backed by explicit and transparent recognition of the 'social value of mitigation actions' or SVMAs, as fiscally superior (because of bigger 'multipliers' of such fiscal action to catalyse private investment than direct public investment) and the bigger social value of such investments (Article 108, UNFCCC) (Hourcade et al. 2018; Krogstrup and Oman 2019).

(c) facilitating and incentivizing much larger flows of cross-border climate financing which is especially crucial for such investments to happen in developing regions, where as much as two-thirds of collective investment may need to happen (IEA 2021a), and where the role of multilateral, regional and global institutions such as the IMF (including the expansion in availability of climate SDRs referred earlier) could be important.

(d) global central banks acting in coordination to include climate finance as intrinsic part of their monetary policy and stimulus (Carney 2019; Jordà et al. 2019; Hilmi et al. 2021; Schoenmaker 2021; Svartzman et al. 2021)

(e) an acceleration of Just Transition initiatives, outlined further below (Section 15.2.4).

15.2.4 Climate Finance and Just Transition

Climate finance in support of a Just Transition is likely to be a key to a successful low-carbon transition globally *(high confidence)*. Ambitious global climate agreements are likely to work far better by maximising cooperative arrangements (IPCC 2018; Gazzotti et al. 2021) with greater financing support from developed to developing regions in recognition of 'common but differentiated responsibilities and respective capabilities' and a greater ethical sense of climate justice (Khan et al. 2020; Sardo 2020; Warner 2020; Pearson et al. 2021). While Just Transition issues apply within developed countries as well (see later discussion), these are of relatively second-order significance to addressing climate justice issues between richer and poorer countries – given the scale of financing and existing social safety nets in the former and their absence in the latter. For example, over the past three decades drought in Africa has caused more climate-related mortality than all climate-related events combined from the rest of the world (Warner 2020). These issues can however serve both as a bridge and a barrier to greater cooperation on climate change. The key is to build greater mutual trust with clearer commitments and well-structured key decisions and instruments (Sardo 2020; Pearson et al. 2021).

The Just Transition discussion has picked up steam. It was explicitly recognised in the Paris Agreement and the 2018 Just Transition Declaration signed by 53 countries at COP24, which 'recognised the need to factor in the needs of workers and communities to build public support for a rapid shift to a zero-carbon economy.' Originally proposed by global trade unions in the 1980s, the recent discourse has become broader. It has coalesced into a more inclusive process to reduce inequality across all three areas of energy, environment and climate (McCauley and Heffron 2018; Bainton et al. 2021). It seeks accelerated public policy support to ensure environmental sustainability, decent work, social inclusion and poverty eradiation (Burrow 2017), widely shared benefits, and protection of indigenous rights, and livelihoods of communities and workers who stand to lose (including workers in fossil fuel sectors such as coal and oil and gas) (UNFCCC 2018b; EBRD 2020; Jenkins et al. 2020). Because the process involves 'climate justice' and equity within and across generations, it involves difficult political trade-offs (Newell and Mulvaney 2013). The implications for a Just Transition in climate finance are clear: expanding equitable and greater access to climate finance for vulnerable countries, communities and sectors, not just for the most profitable private investment opportunities, and a larger role for public finance in fulfilling existing finance commitments (Bracking and Leffel 2021; Kuhl 2021; Long 2021; Roberts et al. 2021) .

Large shocks, such as pandemics and slow-growing one such as climate are typically known to worsen inequality (IMF and World Bank 2020). Evidence from 133 countries between 2001–2018 suggests that such shocks can cause social unrest, and migration pressures, especially when starting inequality is high and social transfers are low (Saadi Sedik and Xu 2020). Additionally, climate policies are more politically difficult to implement, when the setting is one of high inequality but much less politically costly where incomes are more evenly distributed with stronger social safety nets (Furceri et al. 2021). A redrawn social compact incorporating climate (Beck et al. 2021) that would adopt redistributive taxes and lower carbon consumption, and strengthen state capacity to deliver safety nets, health, education with accelerated climate and environmental sustainability within and across countries is increasingly recognised as important. Countries, regions and coordination bodies of the larger countries (G-7, G-20) have already begun such as shift to financing of a Just Transition, but primarily focused on the developed countries, although gaps remain (Krawchenko and Gordon 2021).

Such a redrawing of a social compact has happened significantly in the past, for example, after the 1860s 'gilded age of capital' with the enlargement of the franchise in democratization waves in Europe and the Americas (Dasgupta and Ziblatt 2015, 2016). Not only was social conflict avoided but growth outcomes became more equitable and faster. Similarly, comprehensive modern social safety nets and progressive taxation, which started in the Great Depression and was extended in the post-war period, had both a positive pro-growth and lower inequality effects (Brida et al. 2020) .

There are three levels of at which policy attention on climate financing now may need to be focused. The first is the need for to addressing the global equity issues in climate finance in a more carefully constructed globally cooperative public policy approach. The second is to address issues appropriately with enhanced support, at the national level. The third is to work it down further, to addressing needs at local community levels. Because private investors and financing mostly deal with allocation to climate finance at a global portfolio level, then to allocation by countries, and finally to individual projects, the challenge for them is to refocus attention to Just Transition issues at the country level, but also globally as well as locally (in other words, at all three levels).

Climate finance will likely face greater challenges in the post-pandemic context (Hanna et al. 2020; Henry et al. 2020). Evidence from COVID-19 pandemic suggests that those in greatest vulnerability often had the least access to human, physical, and financial resources (Ruger and Horton 2020). It has also left in in its wake divergent prospects for economic recovery, with rising constraints on credit ratings and costly debt burden in many developing countries contrasted with the exceptionally low interest rate settings in developed economies driving the limited fiscal space in the former groups (Benmelech and Tzur-Ilan 2020). Similarly, monetary policies are likely to be much tighter in developing countries in part structurally because of the absence of 'exceptional privilege' of global reserve currencies in developed economies.

The result is a divergence in recovery prospects in the aftermath of the pandemic, with output losses (compared to potential) set to worsen in developing economies (excluding China) as compared to developed countries (IMF 2020b). In these circumstances, a coordinated and cooperative approach, instead of unilateralism, might work better (McKibbin and Vines 2020). In the case of climate, simulations clearly suggest the need and advantages of better coordinated climate action with stepped-up Paris Agreement envisaged transfers (IMF 2020b). Several options in international climate finance arrangements to support a Just Transition are both available and urgent.

As a first priority, measures might need to accelerate a mix of equitable financial grants, low-interest loans, guarantees and workable business models access across countries and borders, from developed countries to in low-income countries. A big push on low-carbon energy access globally, especially in large low-income regions such as Africa, with accelerated financial transfers makes sense (Boamah 2020). For about one billion people globally at the base of the pyramid without access to modern low-carbon energy access, such an action, with enormous immediate leap-frogging potential, would be a key pathway to achieve the SDGs, ensure that high-carbon energy use is avoided, such as the burning of biomass and forests for charcoal, and improve air quality and public health, especially women's health (van der Zwaan et al. 2018; Nathwani and Kammen 2019; Dalla Longa and van der Zwaan 2021; Michaelowa et al. 2021; Osabuohien et al. 2021).

A second priority is to accelerate the implementation of the 100 billion USD a year (and likely more given growing financing gaps) in climate finance commitments expressed in the Copenhagen Agreement Accord (and reiterated since) from developed to developing countries, and to build greater confidence by agreeing rapidly on key definitions. Shifting to a grant equivalent net flows definition of climate finance, which is now universally accepted for all other aid flows by all parties since 2014 and which took effect since 2019 on every other public international good finance provision (under the SDGs), with the sole exception of climate finance, would resolve many uncertainties: the disbursement of climate finance flows on a grant equivalent basis that is comparable across institutions, instruments and countries, and measurement with greater accuracy about the effective transfer of resources. The journey to get to a clear and precise definition of net Official Overseas Development Assistance (ODA) took time. The original proposal was first initiated in the 1960s (Pincus 1963) but it was not till MDB's and others laid out the compelling reasons why (Chang et al. 1998) that this was accomplished: especially to resolve decades of confusion and inconsistency between different types of financial flows and hence the perennial measurement problems and 'the compromise between political expediency and statistical reality' (Bulow and Rogoff 2005; Hynes and Scott 2013; Scott 2015, 2017).

A third related and increasingly crucial priority is to expedite the operational definition of blended finance and promote the use of public guarantee instruments. Private flows to accelerate the low-carbon transition in developing countries would benefit enormously, by gaining clearer access to public international funds and support defined on a grant equivalent basis, provided development and climate finance operational definitions and procedures were improved on an urgent basis (Blended Finance Taskforce 2018a; OECD-DAC 2021). When blended and supported by public finance and policy, the grant equivalency measure can easily and more accurately measure the value and benefit of blended public and private finance by comparing the effective interest cost (and volume) gain with such financing, against the benchmark costs without such blending. Here again, a pressing challenge is to improve the operational definitions of what counts as ODA within blended finance. Blended finance remains very poorly defined and accounted (Pereira 2017; Andersen et al. 2019; Attridge and Engen 2019; Basile and Dutra 2019). Guarantees are expressly not included in the definition of ODA (Garbacz et al. 2021), As a result, bilateral and multilateral agencies have no incentive or limited authority and basis to use such instruments, while multilateral development banks continue to approach guarantees with great caution because of the limits of their original charters (World Bank 2009) and require counter-indemnities by recipient countries, internal and historic agency inertia, perceived loss of control over the use of funds (compared to their preferred direct project-based lending) and employ restrictive accounting rules for capital provisioning of guarantees at 100% of their face value to maintain AAA ratings with credit rating agencies (Humphrey 2017; Pereira dos Santos and Kearney 2018a; Bandura and Ramanujam 2019; Hourcade et al. 2021a). Largely because of such official uncertainty the actual flows of blended finance and guarantees continue to remain a very small share (typically, less than 5%) of official and multilateral finance flows to lower project risks and costs, and hence the potential for large-scale accelerated low-carbon private investments in developing countries. Public guarantees can offer a fifteen times multiplier effect on the scale of low-carbon investments generated with such support, compared to a 1:1 ratio in direct financing (Hourcade et al. 2021a).

It makes sense to expedite these operational procedures (Khan et al. 2020) which cannot be otherwise explained except in terms of avoiding responsibilities, even where the benefits would be high (Klöck et al. 2018). It also causes (unnecessary) fragmentation and complexity and often 'strategic' ambiguity by many actors (Pickering et al. 2017), which worsens the possibilities for international cooperation, a critical requirement to achieve the Paris goals (IPCC 2018). The world would gain collectively if these issues were to be decided soon. The absence of such a collective decision continues to be exceptionally costly for the implementation of the Paris Agreement because of the fractious and seemingly insoluble negotiating climate and a breakdown of trust that this has created (Roberts and Weikmans 2017).

A fourth priority is on expanding jobs and dealing with job losses in the global low carbon transition (Carley and Konisky 2020; Crowe and Li 2020; Pai et al. 2020; Cunningham and Schmillen 2021; Hanto et al. 2021), especially in coal and other sectors, as well as land and other effects for indigenous communities (Zografos and Robbins 2020). Many countries, especially low-income countries, remain dependent on fossil fuels for their energy and exports and jobs, and support for their transition to a low-carbon future will be essential. Global recovery from the pandemic will take longer than initially envisaged (IMF 2021c; OECD 2021b) and an accelerated climate action for a Build Back Better global infrastructure plan with better and more resilient jobs might play a key role as part of the Just Transitions. Already, there is substantial evidence (Sulich et al. 2020; Dell'Anna 2021; Dordmond et al. 2021) that a more sustainable climate path would generate many more net productive jobs (with much higher employment multipliers and mutual gains from given spending) than would any other large-scale alternative. But this would nevertheless require a carefully managed transition globally, including access to much larger volumes of climate financing in developing economies (Muttitt and Kartha 2020). The multilateral finance institutions have generally played a supportive role, expanding their financing to developing countries during the pandemic (even as bilateral aid flows have fallen sharply), but have been hampered by the of constraints on their mandates and instruments (as noted earlier). Political leadership and direction will be again crucial to enhance their roles. The recent expansion of SDR quotas at the IMF similarly might help, but the current distributions of quota benefits flow primarily to the developed countries and does little to expand investment flows on a longer-term basis for a global expansion in growth and job opportunities in the low-carbon transition.

As a fifth priority, transformative climate financing options based on equity and global sustainability objectives may also need to consider a greater mix of public pricing and taxation options on the consumption side (Arrow et al. 2004; Folke et al. 2021). Two-thirds of global GHG emissions directly or indirectly are linked to household consumption, with average per capita carbon footprint of North America and Europe of 13.4 and 7.5 tCo_2-eq/capita, respectively, compared to 1.7 in Africa and Middle East (Gough 2020) and as high as 200tCO_2-eq/capita among the top 1% in some high-income geographies versus 0.1tCO_2-eq at the other end of the income distribution in some least-developed countries (Chancel and Piketty 2015). Globally, the highest-expenditure households account for eleven times the per capita emissions of lowest-expenditure households, with rising carbon income elasticities that suggest 'redistribution of carbon shares from global elites to global poor' as welfare efficient (Chancel and Piketty 2015; Hubacek et al. 2017). Within countries and regions, and within sectors, similar patterns hold. The top 10% of the population with the highest per capita footprints account for 27% of the EU carbon footprint, and the top 1% have a carbon footprint of 55tCO_2-eq/cap, with air transport the most elastic, unequal and carbon-intensive consumption (Ivanova and Wood 2020). Similarly, within sectors, there are large differences in carbon-intensity in the building sector in North America (Goldstein et al. 2020) and across cities where consumption-based GHG emissions vary widely across the world (ranging from 1.8 to 25.9 tCO_2-eq/capita).

Numerous options exist (Broeks et al. 2020; Nyfors et al. 2020) for such carbon consumption reduction measures, while potentially improving societal well-being, for example: (a) inner-city zoning restrictions on private cars and promoting walking/bicycle use and improved shared low-carbon transport infrastructure; (b) advertising regulation and carbon taxes and fees on high-carbon luxury status goods and services; (c) subsidies and exemptions for low-carbon options, higher value-added taxes on specific high-carbon products and services, subsidies for public low-carbon options such as commuter transport, and other behavioural nudges (Reisch et al. 2021); and (d) framing options (emphasizing total cost of car over life-times), mandatory smart metering, collective goods and services (leasing, renting, sharing options) and others. Finally, reducing subsidies on fossil fuels, raising the progressivity of taxes and raising overall wealth taxes on the richest households, which has been sharply falling (Scheuer and Slemrod 2021) even as global income and wealth has risen with regressive and falling overall taxes (Alvaredo et al. 2020; Saez and Zucman 2020) could effectively generate significant revenues (over 1% of GDP yr^{-1}, about the same size as the proposed global 50 USD per ton carbon price proposed and estimated by the IMF/OECD 2021 report to G20 (IMF and OECD 2021) to cover expected net interest costs on overall decarbonization initiatives and financing of green new deals (Schroeder 2021).

These five options identified above on near-term actions and priorities will however, require greater collective political leadership. A review of past crisis episodes suggests that collective actions to avoid large global or multi-country risks work well primarily when the problems are well-defined, a small number of actors are involved, solutions are relatively well-established scientifically, and public costs to address them are relatively small (Sandler 1998, 2015) (for example, dealing with early pandemic outbreaks such as Ebola, TB, and cholera; extending global vaccination programs such as smallpox, measles and polio; early warning systems and actions such as tsunamis, hurricanes/cyclones and volcanic disasters; Montreal Protocol for ozone depleting refrigerants, and renewables wind and solar energy development). They but do not appear to work as well for more complex global collective action problems which concern a number of economic actors, sectors, without inexpensive and mature technological options, and where political and institutional governance is fragmented. Greater political coordination is needed because the impacts are often not near-term or imminent, but diffuse, slow-moving and long-term, and where preventive disaster avoidance is costly even when these costs are low compared to the longer-term damages—till tipping points are reached of the need for reduced 'stressors' and increasing 'facilitators' (Jagers et al. 2020). But by then, it may be too late.

Private institutional investors equally might equally wish to pay greater attention to the Just Transition finance issues. It would be useful for investors to identify ways to support to such initiatives, and more clearly identifying the benefits of such transition measures envisaged by both countries and investment financing proposals, including incorporating Just Transition consideration in their support to broader ESG (environmental, social and governance) and green financing initiatives.

The second level of attention needed on Just Transitions has to do with inequities within a large country setting, developed or developing. The Just Transition issue exists within developed countries as well. As the ongoing pandemic illustrates, the first climate burden hit is often felt most acutely at the level of states and cities, with many smaller ones without enough fiscal capacity or ability to mount an adequate discretionary counter policy. Only national governments have ability to borrow more in their fiscal accounts to address large collective problems, whether pandemics or climate change. Therefore, it is important that national policies and funds be available for programs to address the Just Transition issues for larger sub-national states, cities and regions. This would be helped by countries including Just Transition initiatives in their NDCs for financing (as South Africa has recently done), and attention by external financing agencies and MDBs to large-scale adverse impacts in their climate policies and investments. For example, the EU Green Deal plans (Nae and Panie 2021) includes several initiatives (focusing on industries, regions and workers adversely affected with explicit programs to address them).

The third level of argument is for a shift in focus from an exclusive attention to financing of mitigation and low-carbon new investments projects to also better understanding and addressing the local adverse impacts of climate change on communities and people, who are vulnerable and increasingly dispossessed due to losses and damages from climate change or even those who are impacted by de-carbonization measures in the fossil fuel sectors, transportation, as well as those who are harmed by polluting sectors: indigenous men and women, minorities and generally the poor. It is evident that very few resources are available to countries, investors, civil society, and smaller development institutions seeking to achieve a just transition (Robins and Rydge 2020).

Finally, greater support is warranted for smaller towns and cities, local networks, SMEs, communities, local authorities and universities for projects, research ideas and proposals (Lubell and Morrison 2021; Moftakhari et al. 2021; Stehle 2021; Vedeld et al. 2021).

15.3 Assessment of current financial flows

15.3.1 Financial flows and stocks: orders of magnitude

Assessments of finance for climate action need to be placed within the broader perspective of all investments and financing flows and stocks. This section provides aggregate level reference points of relevance to the remainder of this Chapter, notably when assessing current levels of climate and fossil fuel-related investments and financing (Sections 15.3.2.3 and 15.3.2.4 respectively), as well as estimates investment and financing needed to meet climate objectives (Section 15.4).

Measures of financial flows and stocks provide complementary and interrelated insights into trends over time: the accumulation of flows, measured per unit of time, results in stocks, observed at a given point in time (IMF 2009; UN and ECB 2015). On the flows side, GDP, a System of National Accounts (SNA) statistical standard that measures the monetary value of final goods and services produced in a country in a given period of time. In 2020, global GDP represented above 70 trillion USD_{2015} (down from almost 80 trillion USD in 2019), out of which developed countries represented approx. 60% (Figure 15.1); a slowly decreasing share over the last years. The GDP metric is useful here as an indicator of the level of activity of an economy but gives no indication relating to human wellbeing or SDG achievements (Giannetti et al. 2015) counts positively activities that negatively impact the environment, without making deductions for the depletion and degradation of natural resources.

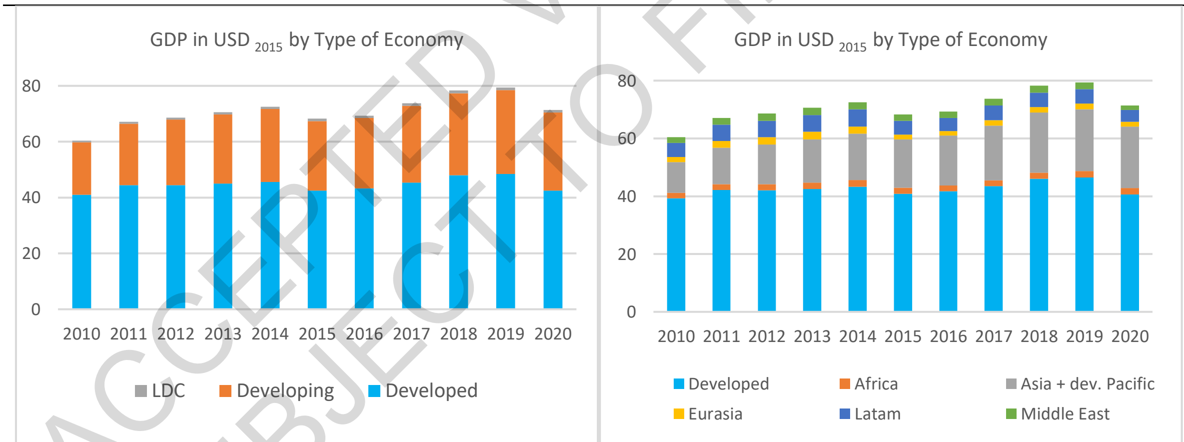


Figure 15.1 Financial flows – GDP (USD_{2015} tr.) by Type of Economy (left) and Region (right)

Note: Regional breakdown based on official UN country classification. GDP in USD_{2015} trillion. Source: World Bank Data (2020a). Numbers represent aggregated country data. Last updated data on 15 September 2021. CC BY-4.0

Gross-fixed capital formation (GFCF), another SNA standard that covers tangible assets (notably infrastructure and equipment) and intangible assets, is a good proxy for investment flows in the real economy. In 2019, global GFCF reached 23 trillion USD compared to 16.2 trillion USD in 2010, a 42% increase (Figure 15.2). Global GFCF represents about a quarter of global GDP, a relatively stable ratio since 2008. This share is, however, much higher for emerging economies, notably in Asia, which are building new infrastructure at scale. As analysed in Sections 15.4 and 15.5, infrastructure investment needs and gaps in developing countries are significant. How these are met over the next decade will critically influence the likelihood of reaching the Paris Agreement goals.

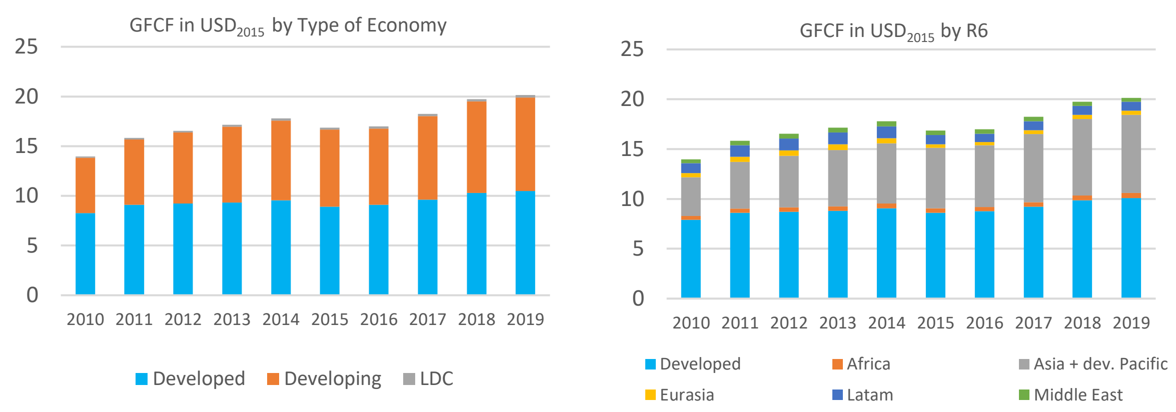


Figure 15.2 Financial flows – GFCF (USD_{2015} tr.) by Type of Economy (left) and Region (right)

Note: Regional breakdown based on official UN country classification. GDP in constant 2015 USD trillion USD_{2015}. Gross fixed capital formation (GFCF) includes land improvements (fences, ditches, drains, and so on); plant, machinery, and equipment purchases; and the construction of roads, railways, and the like, including schools, offices, hospitals, private residential dwellings, and commercial and industrial buildings. Source: World Bank Data (2020b). Data for 2020 not available. Last updated Data 15 September 2021. CC BY-4.0

One the stock side, an increasingly significant portion of the growing value of financial capital (stocks in particular) may be disconnected from the value of underlying productive capital in real economy (Igan et al. 2020). This trend, however, remains uneven between developed countries, most of which have relatively deep capital markets, and developing countries at different stages of development (Section 15.6.7). Bonds, a form of debt financing, represent a significant share of total financial assets. As of August 2020, the overall size of the global bond markets (amount outstanding) was estimated at approximately 128.3 trillion USD, out of which over two thirds from "supranational, sovereign, and agencies", and just under a third from corporations (ICMA 2020b). As discussed later in the Chapter, since AR5, an increasing number and volume of bonds have been earmarked for climate action but these still only represent less than 1% of the total bond market. As of end 2020, climate aligned bonds outstanding were estimated at 0.9 trillion (Giorgi and Michetti 2021), though already raising concerns in terms of both underlying definitions (Section 15.6.6) and risks of increased climate-related indebtedness (Section 15.6.1, 15.6.3).

From the perspective of climate change action, these orders of magnitude make it possible to highlight the relatively small size of current climate finance flows and relatively larger size of remaining fossil fuel-related finance flows (discussed in the following two sub-sections), as well as, more generally, the significant overall scale of financial flows and stocks that have to be made consistent with climate goals. These orders of magnitude further make it possible to put in perspective climate-related investment needs (Section 15.4) and gaps (Section 15.5).

15.3.2 Estimates of climate finance flows

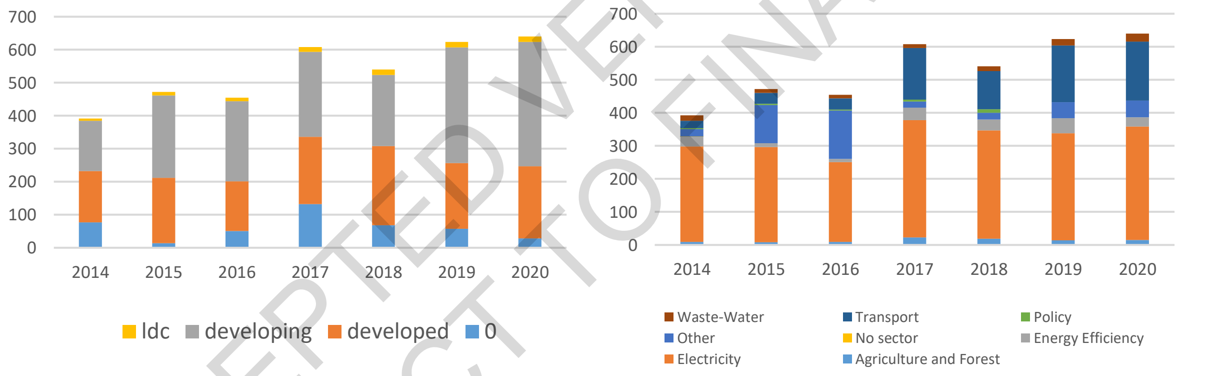
The measurement of climate finance flows continues to face similar definitional, coverage and reliability issues than at the time of AR5 and special report on the impacts of global warming of 1.5°C, despite progress made (more sources, greater frequency, and some definitional improvements) by a range of data providers and collators. Based on available estimates (Table 1 and Figure 3), flows of annual global climate finance are on an upward trend since AR5, reaching a high-bound estimate of 681 billion USD in 2016 (UNFCCC 2018a). Latest available estimates, indicate a drop in 2018 (Buchner et al. 2019) and a rebound in 2019 and 2020 (Naran et al. 2021) (*medium confidence*). Although not directly comparable in terms of scope, current climate finance flows remain small (approx. 3%)

compared to the GFCF reference point introduced in Section 15.3.1, as well as needs to be put in perspective with remaining fossil fuel financing (see Section 15.3.2.3) (*medium confidence*).

Table 15.1 Total climate finance flows between 2013 and 2020

Source (type)	2013	2014	2015	2016	2017	2018	2019	2020
UNFCCC SCF (total high)	687	584	680	681	Published after lit. cut-off		n/a	n/a
UNFCCC SCF (total low / CPI)	339	392	472	456	/608	/540	/623	/640

Note: Given the variations in numbers reported by different entities, changes in data, definitions and methodologies over time, there is low confidence attached to the aggregate numbers presented here. The higher bound reported in the SCF's Biennial Assessment reports includes estimates from the International Energy Agency on energy efficiency investments, which are excludes from the lower bound and CPI's estimates. Source: (UNFCCC 2018a; Buchner et al. 2019; Naran et al. 2021).



Type of Economy **Sector**

Figure 15.3 Available estimates of global climate finance between 2014 and 2020

Note: Numbers in billion USD. Type of Economy figure (left): Regional breakdown based on official UN country classification. "0" no regional mapping information available. Sectorial figure (right): *Policy*, incl. "Disaster Risk Management"; "Policy and national budget support & capacity building". *Transport*, incl. "Sustainable/Low Carbon Transport". Energy Efficiency, incl. "Industry, Extractive Industries, Manufacturing & Trade", "Low-carbon technologies", "Information and Communications Technology", "Buildings & Infrastructure". *Electricity*, incl. "Renewable energy generation", "Infrastructure, energy and other built environment", "Transmission and distribution systems", and "Energy Systems". *No sector*: no sector information available, or neglegting flows. *Other*, incl. Non-energy GHG reductions, Coastal protection. Source: Own calculations, based on (Naran et al. 2021).

At an aggregate level, in both developed and developing countries, the vast majority of tracked climate finance is sourced from domestic or national markets rather than cross-border financing (Buchner et al. 2019). This reinforces the point that national policies and settings remain crucial (Section 15.6.2), along with the development of local capital markets (Section 15.6.7).

Climate finance in developing countries remains heavily concentrated in a few large economies (*high confidence*), with Brazil, India, China and South Africa accounting for 25% to 43% depending on the year, a share similar to that represented by developed countries. Least-developed countries (LDCs), on the other hand, continue to represent less than 5% year-on-year (BNEF 2019; Buchner et al. 2019) (*medium confidence*). Further, the relatively modest growth of climate finance in developed countries is a matter of concern given that economic circumstances are, in most cases, relatively more amenable to greater financing, savings and affordability than in developing countries.

At a global level, the majority of tracked climate finance is assessed as coming from private actors (Buchner et al. 2019), although, as discussed in Box 15.2, the boundaries between private and public finance include significant grey zones, which implies that different definitions could lead to different conclusions (for instance see (Yeo 2019; Weikmans and Roberts 2019)). However, private investments in climate projects and activities often benefit from public support in the form of co-financing, guarantees or fiscal measures. In terms of financial instruments and mechanisms, debt as well as balance sheet financing (which can rely on both own resources and further debt) and project financing (combining a large debt portion and smaller equity portion) represent the lion's share. In this context, the rapid rise of climate-related bond issuances since AR5 (Giorgi and Michetti 2021) represents an opportunity for scaling up climate finance but also poses underlying issues of integrity (Nicol et al. 2018a; Shishlov et al. 2018) and additionality (Schneeweiss 2019), as further discussed in Section 15.6.6, as well as needs to be considered in the context of overall indebtedness and debt sustainability (Sections 15.6.1, 15.6.3).

Mitigation continues to represent the lion's share of global climate finance (between 90% and 95% between 2017 and 2020), and in particular renewable energy, followed by energy efficiency and transport (UNFCCC 2018a; Buchner et al. 2019) (*high confidence*). While capacity additions on the ground kept rising, falling technology costs in certain sectors (e.g. solar energy) has had a negative impact on the year-on-year trend that can be observed in terms of volumes of climate finance (IRENA 2019a; BNEF 2019). However, such cost reduction could free up investment and financing capacities for potential use in other climate-related activities.

Tracking adaptation finance continues to pose significant challenges in terms of data and methods. Notably, the mainstreaming of resilience into investments and business decisions makes it difficult to identify relevant activities within financial datasets (Agrawala et al. 2011; Averchenkova et al. 2016) (Brown et al. 2015). Despite these limitations, evidence shows that finance for adaptation remains fragmented and significantly below rapidly rising needs (Section 15.4 and WG2, TSU please confirm). Further, there is increasing awareness about the need to better understand and address the interlinkages between climate change adaptation and disaster-risk-reduction (DRR) towards achieving resilience (OECD 2020a). (Watson et al. 2015) however, notes that between 2003 and 2014 of the 2 billion USD that flowed through dedicated climate change adaptation funds, only 369 million USD explicitly went to DRR activities (Climate Funds Update 2014; Nakhooda et al. 2014a,b; Watson et al. 2015). For the private sector, insurance and reinsurance remain the dominant way to transfer risk, as discussed in Section 15.6.4).

More generally, significant gaps remain to track climate finance comprehensively at a global level:

- Available estimates are based on a good coverage of investments in renewable energy and, where available, energy efficiency and transport, while other sectors remain more difficult to track, such as industry, agriculture and land use (UNFCCC 2018a; Buchner et al. 2019). (*high confidence*)
- In contrast to international public climate finance, domestic public finance data remain partial despite initiatives to track domestic climate finance (e.g. (Hainaut and Cochran 2018)) and public expenditures (for instance based on the UNDP's Climate Public Expenditure and Institutional Review approach). (*high confidence*)

Data on private and commercial finance remains very patchy, particularly for corporate financing (including debt financing provided by commercial banks), for which it is difficult to establish a link with activities and projects on the ground. (*high confidence*). Further, as individual source of aggregate reporting (UNFCCC 2018a; Buchner et al. 2019; FS-UNEP Centre and BNEF 2020) tend to rely on the same main data sources (notably the BNEF commercial database for renewable energy investments) as well as to cross-check numbers against similar other sources, there is a potential for 'group-think' and bias.

Such data gaps as well as varying definitions of what qualifies as "climate" (or more broadly as "green" and "sustainable") not only pose a measurement challenge. They also result in a lack of clarity for investors and financiers seeking climate-related opportunities. Such uncertainty can lead both to reduced climate finance as well as to a lack of transparency in climate-related reporting (further discussed in Section 15.6.1), which in turn further hinders reliable measurement.

In terms of finance provided and mobilised by developed countries for climate action in developing countries, while accounting scope and methodologies continue to be debated (see Box 15.4), progress has been achieved on these matters in the context of the UNFCCC (UNFCCC 2019b). A consensus, however, exists, on a need to further scale up public finance and improve its effectiveness in mobilising private finance (OECD 2020b), as well as to further prioritise adaptation financing, in particular towards the most vulnerable countries (Carty et al. 2020). The relatively low share of adaptation in international climate finance to date may in part due to a low level of obligation and precision in global adaptation rules and commitments (Hall and Persson 2018). Further, providers of international climate finance may have more incentive to support mitigation over adaptation as mitigation benefits are global while the benefits of adaptation are local or regional (Abadie et al. 2013).

'START BOX 15.4 HERE'

Box 15.4 Measuring progress towards the 100 billion USD yr^{-1} **by 2020 goal - issues of method**

In 2009, at COP15, Parties to the UNFCCC agreed the following: "In the context of meaningful mitigation actions and transparency on implementation, developed countries commit to a goal of mobilizing jointly 100 billion USD dollars a year by 2020 to address the needs of developing countries. This goal is further embedded as a target under SDG 13 Climate Action Such finance may come from a wide variety of sources, public and private, bilateral and multilateral, including alternative sources of finance." (UNFCCC 2009). While the parameters for what and how to count were not defined when the goal was set, progress in this area has been achieved under the UNFCCC (UNFCCC 2019b) and via a UN-driven independent expert review (Bhattacharya et al. 2020).

There remains well documented interpretations and debates on how to account for progress (Clapp et al. 2012; Stadelmann et al. 2013; Jachnik et al. 2015; Weikmans and Roberts 2019). Different interpretations relate mainly to the type and proportion of activities that may qualify as "climate" on the one hand, and to how to account for different types of finance (and financial instruments) on the other hand. As an example, there are different points at which financing can be measured, e.g. pledges, commitments, disbursements. There can be significant lags between these different points in time, e.g. disbursements may spread over time. Further, the choice of point of measurement can have an impact on both the volumes and on the characteristics (geographical origin, labelling as public or private) of the finance tracked. The enhanced transparency framework under the Paris Agreement may lead to improvements and more consensus in the way climate finance is accounted for and reported under the UNFCCC. Available analyses specifically aimed at assessing progress towards the 100 billion USD goal remain rare, e.g. the UNFCCC SCF Biennial Assessments do not directly address this point (UNFCCC 2018a). Dedicated OECD reports provide figures based on accounting for gross flows of climate finance based on analysing activity-level data recorded by the UNFCCC (bilateral public climate finance) and the OECD (multilateral public climate finance, mobilised private climate finance and climate-related export credits) (OECD 2015a, 2019a, 2020b). For 2018, the OECD analysis resulted in a total of 78.9 billion USD, out of which 62.2 billion USD of public finance, 2.1 billion USD of export credits and 14.5 billion USD of private finance mobilised. Mitigation represented 73% of the total, adaptation 19% and cross-cutting activities 8%.

Reports by Oxfam provide a complementary view on public climate finance, building on OECD figures and underlying data sources to translate gross flows of bilateral and multilateral public climate finance in grant equivalent terms, while also, for some activities, applying discounts to the proportion considered as climate finance (Carty et al. 2016; Carty and Le Comte 2018 and Carty et al 2020). The resulting annual averages for 2015– 2016 and 2017–2018range between 32% (low bound) and 44% (high bound) of gross public climate finance. The difference with OECD figures stems from the high share represented by loans, both concessional and non-concessional, in public climate finance, i.e. 74% in 2018 2018 (OECD 2020b).

A point of method that attracts much attention relates to how to account for private finance mobilised. The OECD, through its Development Assistance Committee, established an international standard to measure private finance mobilised by official development finance, which consists in methods tailored to different financial mechanisms. These methods taking into account the role of, risk taken, and/or amount provided by all official actors involved in a given project, including recipient country institutions, thereby also avoiding risks of double counting. (OECD 2019b). MDBs apply a different method (World Bank 2018a) in their joint climate finance reporting (AfDB et al. 2020)., which neither correspond to the geographical scope of the 100 billion USD goal, nor address the issue of attribution to the extent required in that context.

Notwithstanding methodological discussions under the UNFCCC, there is still some distance from the 100 billion USD a year commitment being achieved, including in terms of further prioritising adaptation. While the scope of the commitment corresponds to only a fraction of the larger sums needed (Section 15.4), its fulfilment can both contribute to climate action in developing countries as well as to trust building in international climate negotiations. Combined with further clarity on geographical and sectoral gaps, this can, in turn, facilitate the implementation of better-coordinated and cooperative arrangements for mobilising funds (Peake and Ekins 2017).

'END BOX 15.4 HERE'

15.3.3 Fossil fuel-related and transition finance

As called for by Article 2.1c of the Paris Agreement and introduced in Section 15.3.1, achieving the goal of the Paris Agreement of holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels requires making all finance consistent with this goal. Data on investments and financing to high GHG activities remain very partial and difficult to access, as relevant actors currently have little incentive or obligations to disclose such information compared to reporting on and communicating about their activities contributing to climate action. Further, the development of methodologies to assess finance for activities misaligned with climate mitigation goals, for hard- and costly-to-abate sectors such as heavy industries, as well as for activities that eventually need to be phased out but can play a transition role for given period, remain work in progress. This results in limited empirical evidence to date.

Scenarios compatible with a 1.5°C warming, however, make it clear that the share of fossil fuels in energy supply has to decrease. For instance, the International Energy Agency (IEA) Net Zero by 2050 scenario relies on halting sales of new internal combustion engine passenger cars by 2035, rapid and steady decrease of the production of coal (minus 90%), oil (minus 75%) and natural gas (minus 55%) by 2050, and phasing out all unabated coal and oil power plants by 2040 (IEA 2021b). To avoid locking GHG emissions incompatible with remaining carbon budgets, this implies a rapid scaling down of new fossil fuel-related investments, combined with a scaling up of financing to allow energy and infrastructure systems to transition (*high confidence*).

The IEA provides comprehensive analyses of global energy investments, estimated at about 1.8 trillion USD a year over 2017–2019 (IEA 2019a, 2020a), and expected to reach that level again in 2021 after a drop to about 1.6 trillion in 2020 (IEA 2021c). Energy investments represent about 8% of global GFCF (Section 15.3.2.1). In the power sector, fossil fuel-related investments reached an estimated 120 billion USD yr^{-1} on average over 2019–2020, which remains well above the level that underpin the IEA's own Paris-compatible Sustainable Development Scenario (SDS) and Net Zero scenarios. The IEA observes a similar inconsistency with for supply side new investments: in 2019-2020 on average yr^{-1}, an estimated 650 billion USD were invested in oil supply and close to 100 billion USD in coal supply. These estimates also result in fossil fuel investments remaining larger in aggregate than the total tracked climate finance worldwide (Section 15.3.2.2). For oil and gas companies, which are amongst the world largest corporations and sometimes government owned or backed, low-carbon solutions are estimated to represent less than 1% of capital expenditure (IEA 2020b). As discussed in the remainder of this Chapter, shifting investments towards low-GHG solutions requires a combination of conducive public policies, attractive investment opportunities, as well as the availability of financing to finance such a transition.

In terms of financing provided to fossil fuel investments, available analyses point out to a still significant role played by commercial banks and export credit agencies. Commercial banks provide both direct lending as well as underwriting services, the latter facilitating capital raising from investors in the form of bond or share issuance. Available estimates indicate that lending and underwriting extended over 2016 –2019 by 35 of the world's largest banks to 2,100 companies active across the fossil fuel life cycle, reached USD 687 billion yr^{-1} on average (Rainforest Action Network et al. 2020). Official export credit agencies, which are owned or backed by their government, de-risk exports by providing guarantees and insurances or, less often, loans. In 2016–2018, available estimates indicate the provision of about 31 billion USD yr^{-1} worth of fossil fuel-related official export credits, out of which close to 80% for the oil and gas, and over 20% for coal DeAngelis and Tucker 2020).

Finance for new fossil fuel-related assets lock in future GHG emissions that may be inconsistent with remaining carbon budgets and, as discussed above, with emission pathways to reach the Paris Agreement goals. This inconsistency exposes investors and asset owners to the risk of stranded assets, which results from potential sharp strengthening climate public policies, i.e. transition risk. As a result, a growing number of investors and financiers are assessing climate-related risks with the aim to disclose information about their current level of exposure (to both transition and physical climate-related risks), as well as to inform their future decisions (TCFD 2017). Reporting to date is, however, inconsistent across geographies and jurisdictions (CDSB and CDP 2018; Perera et al. 2019), with also a wide variety of metrics, methodologies, and approaches developed by commercial providers that contribute to disparate outcomes (Kotsantonis and Serafeim 2019; Boffo and Patalano 2020). Further, as developed in Sections 15.6.1, there is currently not enough evidence in order to conclude whether climate-related risk assessments result in increased climate action and alignment with the goals of the Paris Agreement(e.g. 2° Investing Initiative (The 2°Investing Initiative and Wuest Partner 2020)).

As developed in Section 15.6.3, the insufficient level of ambition and coherence of public policies at national and international level remains the root cause of the still significant misalignment of investment and financing compared to pathways compatible with the Paris Agreement temperature goal (UNEP 2018). Such lack of coherence includes low pricing of carbon and of environmental externalities more generally, as well as misaligned policies in non-climate policy areas such as fiscal, trade, industrial and investment policy, and financial regulation (OECD 2015b), as further specified in the sectoral Chapters 6 to 12.

The most documented policy misalignment relates to the remaining very large scale of public direct and indirect financial support for fossil fuel-related production and consumption in many parts of the world (Bast et al. 2015; Coady et al. 2017; Climate Transparency 2020). Fossil fuel subsidies are embedded across economic sectors as well as policy areas, e.g. from a trade policy perspective, in most countries, import tariffs and non-tariff barriers are substantially lower on relatively more CO_2 intensive industries (Shapiro 2020). Available inventories of fossil fuel subsidies (in the form of direct budgetary transfers, revenue forgone, risk transfers, or induced transfers), covering 76 economies, indicate a rise to USD 340 billion in 2017, a 5% increase compared to 2016. Such trend is due to slowed down progress in reducing support among OECD and G20 economies in 2017 (OECD 2018b) and to a rise in fossil-fuel subsidies for consumption in several developing economies (Matsumura and Adam 2019), which, in turn, reduces the efficiency of public instruments and incentives aimed at redirecting investments and financing towards low-GHG activities.

As a result, the demand for fossil fuels, especially in the energy production, transport and buildings sectors, remain high, and the risk-return profile of fossil fuel-related investments it still positive in many instance (Hanif et al. 2019). Political economy constraints of fossil fuel subsidy reform continue to be a major hurdle for climate action (Schwanitz et al. 2014; Röttgers and Anderson 2018), as further discussed in Section 15.5.2. and Chapter 13.

15.4 Financing needs

15.4.1 Definitions of financing needs

Financing needs are discussed in various contexts, only one being international climate politics and finance. Also, financing needs are used as an indicator for required system changes (when compared to current flows and asset bases) and an indicator for near- to long-term investment opportunities from the perspective of investors and corporates. Investment needs are widely used as an indicator focusing on initial investments required to realise new infrastructure. It compares relatively well with private sector flows dominated by return-generating investments but lacks comparability and explanatory power regarding the needs in the context of international climate cooperation where considerations on economic costs play a more substantial role. Chapter 12 elaborates on global economic cost estimates for various technologies. This indicator includes both costs and benefits of options, of which investment-related costs make up only one component. . Both analyses offer complementary insights. There are financing needs not directly related to the realisation of physical infrastructure and which are not covered in both, investment and cost estimates. For instance, the need for building institutional capacity facilitating to achieve social and economic goals underpinning knowledge, skills, notional and international cooperation might not be significant, but an enabling environment for future investments would not be established without satisfying it. Moreover, comprehending financial needs for addressing economic losses due to climate change can hardly be measured in terms of the indicators introduced before.

Understanding the magnitude of the challenge to scale-up finance in sectors and regions requires a more comprehensive (and qualitative) assessment of the needs. For finance to become an enabler of the transition, domestic and international public interventions can be needed to ensure enough supply of finance across sectors, regions and stakeholders. The location of financing needs and vicinity to capital matter given home bias (Fuchs et al. 2017; OECD 2017a; Ito and McCauley 2019) (prioritizing own country or regions), transaction costs and risk considerations (see also 15.2). Most of the finance is mobilised domestically but the depth of capital markets is substantially greater in developed countries, increasing the challenges to mobilise substantial volumes of additional funding for many developing countries. The same applies to various stakeholders with limited connections into the financial sector. In addition, governments' enabling financial market frameworks, guidelines and supportive infrastructure is crucial for inclusive finance for the bottom of the pyramid (BoP), especially disadvantaged and economically marginalised segments of society.

The attractiveness of a sector and region for capital markets depend on several factors. Some essential elements are the duration of loan and profile as long term loans and heavily heterogeneous returns represent challenges in financing mitigation technologies and policies. After the financial crisis and restricted access to long-term debt, capital intensity of technologies and resulting long payback periods of investment opportunities for mitigation technologies have been a crucial challenge (Bertoldi et al. 2021). Also, implicit discount rates applied during the investment decision process vary depending on the payback profile, with research mainly covering the difference between the financing of assets generating revenues versus costs (Jaffe et al. 2004; Schleich et al. 2016). In addition, a low correlation between the climate projects and dominating asset classes might provide an opportunity in climate action by satisfying the appetite of institutional investors, which tend to manage portfolios with consideration of the Markowitz modern portfolio theory (optimizing return and risk of a portfolio through diversification) (Marinoni et al. 2011). Transaction cost is a significant barrier to the diffusion and commercialization of low-carbon technologies and business models and adaptation action. High transaction costs, attributed to various factors, such as complexity and limited standardisation of investments, limited pipelines, complex institutional and administrative procedures, create significant opportunity costs of green investments comparing with other standard investments (IRENA 2016; Nelson et al. 2016; Feldman et al. 2018). For example, transaction costs are commonly observed in small-scale, dispersed independent renewable energy systems, especially in rural areas, and energy efficiency projects (Hunecke et al. 2019). A more robust standardisation and alignment of Power Purchase Agreement (PPA) terms with best practices globally has led to a substantially increased interest in capital markets in developing countries (WBCSD 2016; Schmidt et al. 2019; World Bank 2021). Notably, Power Purchase Agreement (PPA) significantly increases the probability of more balanced investment and development outcomes and ultimately more sustainable independent power projects in developing countries. Therefore, lowering transaction costs would be essential for creating investor appetite. The role of intermediaries bundling demand for financing has been demonstrated to reduce transaction costs and to reach investors' critical size. In addition, new innovative approaches, such as fintech and blockchain (see Section 15.6.8), have been discussed for providing new opportunities in the energy sector.

Economic viability of investments – ideally not relying on the pricing of positive externalities – has been a critical driver of momentum in the past. The falling technology costs and the competitiveness of renewable technologies, especially solar PV and wind, have accelerated the deployment of renewable technologies over the past years. renewable energy technologies now often competitive, even become the cheapest, in many countries, even without financial support, (FS-UNEP Centre and BNEF 2015, 2016, 2017, 2018, 2019; IEA 2020c; IRENA 2020a) and without pricing of the avoided carbon emissions. In contrast, the dependency on regulatory interventions and public financial support to create financial viability has provided a source of volatile investor appetite. The annual volume of renewable investment by country is often volatile reflecting ending and new regulations and policies (IEA 2019a).

For example, the recent Chinese policy direction towards tougher access to and a substantial cut in FiT in 2018 led to a significant drop in renewable investment and new capacity addition in China (FS-UNEP Centre and BNEF 2019; Hove 2020). However, the significant bouncing back of newly installed capacity (72 GW wind power and 47 GW solar power in 2020) shows the strong development of zero carbon power generation driven by lower cost and policies to support them by energy revolution strategies in China. Investors had proven to be willing to work with transparent support mechanisms, such as with the Clean Development Mechanism (CDM), which stimulated emission reductions and allowed industrialised countries to implement emission-reduction projects in developing countries to meet their emission targets (Michaelowa et al. 2019). However, the collapse of carbon markets and prices, especially of the EU ETS, led to the continuous decline of Certified Emission Reductions (CER) issuances from CDM in the past years (World Bank Group 2020). Also, the dependency on regulatory intervention to ensure fair market access only has proven to burden investor appetite.

A significant share of investment needs in heavily regulated sectors, such as electricity, public transport, and telecom, emphasises the importance of regulatory intervention, such as ownership and market access (OECD 2017b). For instance, energy-system developments require effective and credible commitments and action by policy-maker to ensure an efficient capital allocation aligned with climate targets (Bertram et al. 2021).

There are a lot of discussion about the regulated ownership of the private sector (European Commission 2017) and the restructuring of electricity market contributed to low level of investment in baseline electricity capacity and in investment research and innovation. This changes create uncertainty of investment, and barriers to market entry and exit also potentially limit the competition in the market and restrict the entrance of new investment (Finon 2006; Joskow 2007; Grubb and Newbery 2018). This is also the case in developing countries (Foster and Rana 2020).

The positive development in the energy sector has benefitted from the evident stand-alone character of renewable energy generation projects. First movers realised these projects with investors and developers acting from conviction (Steffen et al. 2018). Such action is not possible to this extent in energy efficiency with related investment rather representing an add-on component and consequently requiring the support of decision-makers used to business-as-usual projects. Despite the benefits that improvement of energy efficiency has in contributing to curbing energy consumption, mitigating greenhouse gas emissions, and providing multiple co-benefits (IEA 2014a), investment in energy efficiency is at a low priority for firms, and the financial environment is not favourable due to lacking awareness of energy efficiency by financial institutions, existing administrative barriers, lack of expertise to develop projects, asymmetric information, and split incentives (UNEP DTU 2017; Cattaneo 2019). While Energy Service Companies (ESCO) business models are expected to facilitate the investment in energy efficiency by sharing a portion of financial risk and providing expertise, there has been limited progress made with ESCO business models, and only slightly over 20% of projects used financing through ESCOs (UNEP DTU 2017).

The investment needs and existing challenges differ by sector. Each sector has different characteristics along the arguments listed above making the supply of finance by commercial investors an enabling factor or barrier. In the transport sector, transformation towards green mobility would provide significant co-benefits for human health by reducing transport-related air pollution, so the transport sector cannot achieve such transformation in isolation with other sectors. However, a considerable involvement of the public sector in many transportation infrastructure projects is given, and the absence of a standard solution increases transaction costs (including bidding package, estimating, drawing up a contract, administering the contract, corruption, and so on). Financial constraints, including access to adequate finance, pose a significant challenge in the agriculture sector, especially for SMEs and smallholder farmers. The distortion created by government failure and a lack of effective policies create barriers to financing for agriculture. The inability to manage the impact of the agriculture-related risks, such as seasonality, increases uncertainty in financial management. Moreover, inadequate infrastructure, such as electricity and telecommunication, makes it difficult for financial institutions to reach agricultural SMEs and farmers and increases transaction costs (World Bank 2016). Low economies of scale, low bargaining power, poor connectivity to markets, and information asymmetry also lead to higher transaction cost (Pingali et al. 2019). In the industrial manufacturing and residential sector, gaining energy efficiency remains one of the critical challenges. Investment in achieving energy efficiency encounters some challenges when it may not necessarily generate direct or indirect benefits, such as increase in production capacity or productivity and improvement in product quality. Also, early-stage, high upfront cost and future, stable revenue stream structure suggest the needs for a better enabling environment, such as a robust financial market, awareness of financial institutions, and regulatory frameworks (e.g., stringent building codes, incentives for ESCOs) (IEA 2014a; Barnsley et al. 2015).

15.4.2 Quantitative assessment of financing needs

Multiple stakeholders prepare and present quantitative financing needs assessments with methodologies applied to vary significantly representing a major challenge for aggregation of needs (i.e. (Osama et al. 2021) for African countries), most of them with a focus on scenarios likely to limit warming to 2°C or lower. The differences relate to the scope of the assessments regarding sectors, regions and periods, top-down versus bottom-up approaches, and methodological issues around boundaries of climate-related investment needs, particularly full vs incremental costs and the exclusion or inclusion of consumer-level investments. Information on investment needs and financing options in NDCs mirror this challenge and is heavily heterogeneous (Zhang and Pan 2016).

In particular, for global approaches, modelling assumptions are often heavily standardised, focusing on technology costs. Only limited global analysis is available on incremental costs and investments, reflecting the reality of developing countries, also considering the interplay with significant infrastructure finance gaps, and can hardly serve as a robust basis for negotiations about international public climate finance. The focus on investment irrespective of uncertainty as well as other qualitative aspects of needs does not allow for a straightforward analysis of the need for public finance to leverage private sector financing and of the country heterogeneity in terms of investment risks and access to capital (Clark et al. 2018).

One source of uncertainty about the investment estimates for the power sector is the evolution of the levelized cost of technical options in the future for example the continuation of the observed declining trend of renewable energy (IRENA 2020b) which has been underestimated in many modelling exercises. The learning by doing processes and economies of scale might be at least partially outweighted, in all countries and more specifically in SIDS and other developing countries because of different risk factors, scales of installations, accessibility, and others (Lucas et al. 2015; van der Zwaan et al. 2018). These parameters, together with transaction costs/soft costs (see Section 15.5), financing costs and the level of technical competences need to be better represented in the future to represent the "climate investment trap" in many developing countries (IDB 2019). This "climate investment trap", as flagged by (Ameli et al. 2021b) is created by existing and expected physical effects of climate change, higher financing costs and resulting lower investment levels in developing countries. Applying significantly standardised assumptions can consequently not provide robust insights for specific country groups. This will require progress in the spatiotemporal granularity of the models (Collins et al. 2016).

Another source of uncertainty about the financing needs is the interplays between a) the baseline economic growth rates, b) the link between economic growth and energy demand, including rebound effects of energy efficiency gains c) the evolution of microeconomic parameters such as fossil fuel prices, interest rates, currency exchange rates d) the level of integration between climate policies and sectoral policies and their efficacy and e) the impact of climate policies on growth and the capacity of fiscal and financial policies to offset their adverse effect (see (IPCC 2018) and AR5 (IPCC 2014, 2018)). Integrated assessment models (IAMs) try to capture some to these interplays even though they typically do not capture the financial constraints and the structural causes of the infrastructure investment gap. Many of them rely on growth models with full exploitation of the means of production (labour and capital). They nevertheless provide useful indications of the orders of magnitude at play over the long run, and the determinants of their uncertainty. Global yearly average low-carbon investment needs until 2030 for electricity, transportation, AFOLU and energy efficiency measures incl. industry and buildings are estimated between 3% and 6% of the world's GDP according to the analysis in section 15.5. The incremental costs of low carbon options are less than that and their funding could be achieved without reducing global consumption by reallocating 1.4% to 3.9% of global savings, 2.4% on average (see Box 4.8 of (IPCC 2018)) currently flow towards real estate, land and liquid financial vehicles. For the short term decisions, the major information they give is the uncertainty range because this is an indicator of the risks decision-makers need.

While the IAMs database provides good transparency with regard to technology costs for electricity generation, assumptions driving in particular investments in energy efficiency are rarely made available in both, IAM based assessments but also other studies. Taking into account the much broader range of tested and untested technologies the confidence levels, in particular for 2050 estimates, remains low but can provide an initial indication. Also, the ranges allow for a rough indication on possible "green" investment volumes and respective asset allocation for financial sector stakeholders.

Using global scenarios assessed in Chapter 3 for assessing investment requirements
Tables 15.2 and 15.3 present the analysis of investment requirements in global mitigation pathways assessed in Chapter 3 for key energy sub-sectors for scenarios likely to limit warming to 2°C or lower. These pathways explore the energy, land-use, and climate system interactions and thus help identify required energy sector transformations to reach specific long-term climate targets. However, reporting of investment needs outside the energy sector was scarce, reducing the explanatory power of total in the context of overall investment needs (Bertram et al. 2021)(Ekholm et al. 2013; McCollum et al. 2018); and Box 4.8 in (IPCC 2018)). The modelling of these scenarios is done with a variation of scenario assumptions along different dimensions (inter alia policy, socio-economic development and technology availability), as well as with different modelling tools which represent different assumptions about the structural functioning of the energy-economy-land-use system (see "Annex III: Scenarios and modelling methods" for details). Tables 15.2 and 15.3 focus on the near-term (2023–2032) investment requirements in the energy sector and how this differs depending on temperature category (Figure 3.36 and 3.37 in Chapter 3) presents the data for the medium-term (2023-2052)). The results highlight both requirements for increased investments and a shift from fossil towards renewable technologies and efficiency for more ambitious temperature categories. The substantial ranges within each category reflect multiple pathways, differentiated by socio-economic assumptions, technology etc. It is necessary to open up these extra dimensions and contrast them with national and sub-regional analysis to understand how investment requirements depend on particular circumstances and assumptions within a country for a specific technology. Limiting peak temperature to levels of 1.5°C–2°C requires rapid decarbonization of the global energy systems, with the fastest relative emission reductions occurring in the power generation sector (Hirth and Steckel 2016; Luderer et al. 2018).

Table 15.2 Global average yearly investments from 2023–2032 for Electricity supply in billion USD_{2015}.

Category	Fossil	Nuclear	Storage	T&D	Non-Biomass Renewables	Thereof Solar	Thereof Wind
C1	53 [50]	127 [52]	221 [39]	549 [50]	1190 [52]	498 [52]	390 [52]
(Range)	(34;115)	(85;165)	(88;295)	(422;787)	(688;1430)	(292;603)	(273;578)
C2	78 [100]	116 [92]	57 [66]	489 [81]	736 [96]	312 [96]	237 [96]
(Range)	(50;129)	(61;150)	(37;139)	(401;620)	(482;848)	(181;385)	(174;328)
C3	75 [221]	96 [190]	28 [129]	389 [157]	639 [207]	220 [207]	266 [207]
(Range)	(52;129)	(50;122)	(8;155)	(326;760)	(432;820)	(167;345)	(137;353)

Note: Global average yearly investments from 2023-2032 in USD_{2015}). Electricity subcomponents are not exhaustive, hydro, geothermal, biomass and others are not shown, as these are shown to be of smaller magnitude (Chapter 3). Difference between non-biomass renewables and solar/wind represents hydro and in some scenarios geothermal, tidal, and ocean. Scenarios are grouped into common AR6 categories (vertical axis, C1-C3). The numbers represent medians across all scenarios within one category, and rounded brackets indicate inter-quartile ranges, while the numbers in squared brackets indicate number of scenarios. C6, C7, and C8 not shown in Table 15.2. Reference C5 category for T&D is 364bn (294bn to 445bn) [111] used for calculation of incremental needs in Figure 4.

This requires fast shifts of investment as infrastructures in the power sector generally have long lifetimes of few decades. In the scenarios limiting warming to below 1.5°C, investments into non-biomass renewables (especially solar and wind, but also including hydro, geothermal, and others not shown in Table 15.2) increase to over 1 trillion USD yr^{-1} in 2030, increasing by more than factor 3 over the values of around 250–300 billion USD yr^{-1} that has been relatively stable over the last decade (IEA 2019a). Overall, electricity generation investments increase considerably, reflecting the higher relevance of capital expenditures in decarbonised electricity systems. While decreasing technology costs have substantially reduced the challenge of high capital intensity, still remaining relative disadvantages in terms of capital intensity of low-carbon power technologies can especially create obstacles for fast decarbonization in countries with high interest rates, which decrease the competitiveness of those technologies (Iyer et al. 2015; Hirth and Steckel 2016; Steckel and Jakob 2018; Schmidt et al. 2019). CCS as well as nuclear will not drive investment needs until 2030, given considerably longer lead-times for these technologies, and the lack of a significant project pipeline currently.

Table 15.3 Regional average yearly investments from 2023–2032 for Electricity supply in billion USD2015.

	Africa	East Asia	Europe	South Asia	Latin America	Middle East	North America	Asia-Pacific Developed	East. Eur. W.C. Asia	South East Aisa
Non-Biomass Renewables										
C1	41 [39]	302 [41]	130 [41]	120 [41]	69 [41]	67 [41]	177 [41]	37 [41]	48 [41]	85 [41]
(Range)	(36;66)	(188;356)	(101;150)	(83;164)	(55;97)	(31;90)	(149;222)	(28;39)	(35;65)	(59;141)
C2	32 [77]	179 [87]	95 [87]	69 [87]	55 [87]	28 [87]	106 [87]	19 [87]	17 [87]	63 [87]
(Range)	(27;42)	(124;255)	(64;104)	(35;84)	(27;73)	(19;43)	(73;134)	(12;29)	(10;37)	(35;78)
C3	17 [170]	166 [185]	91 [185]	53 [182]	53 [185]	22 [182]	119 [185]	22 [179]	15 [185]	38 [182]
(Range)	(12;47)	(108;200)	(42;118)	(35;80)	(25;81)	(11;32)	(71;167)	(12;30)	(11;30)	(22;67)
Thereof Solar										
C1	16 [39]	134 [41]	43 [41]	53 [41]	22 [41]	33 [41]	81 [41]	11 [41]	20 [41]	33 [41]
(Range)	(8;24)	(89;147)	(38;55)	(37;82)	(14;34)	(16;40)	(75;95)	(10;16)	(10;25)	(17;56)
C2	10 [77]	83 [87]	34 [87]	37 [87]	16 [87]	15 [82]	44 [87]	7 [80]	5 [81]	20 [87]
(Range)	(6;14)	(54;125)	(19;47)	(17;41)	(8;21)	(10;23)	(18;69)	(4;10)	(1;12)	(9;33)
C3	7 [170]	53 [185]	28 [184]	23 [182]	12 [184]	12 [164]	32 [185]	9 [157]	8 [164]	14 [182]
(Range)	(3;14)	(42;83)	(17;36)	(17;39)	(5;25)	(9;20)	(21;74)	(4;11)	(3;12)	(7;27)
Thereof Wind										
C1	10 [39]	133 [41]	59 [41]	45 [41]	19 [41]	22 [41]	58 [41]	20 [41]	17 [41]	28 [41]
(Range)	(4;30)	(86;164)	(29;86)	(23;71)	(15;26)	(13;39)	(44;122)	(12;25)	(10;23)	(17;52)
C2	5 [77]	63 [87]	41 [83]	23 [87]	15 [87]	8 [81]	31 [87]	8 [87]	4 [81]	19 [87]
(Range)	(4;14)	(44;102)	(9;59)	(14;30)	(7;18)	(3;16)	(19;75)	(5;12)	(2;12)	(6;23)
C3	3 [170]	64 [185]	59 [169]	21 [182]	12 [184]	10 [160]	52 [184]	10 [179]	4 [164]	10 [182]
(Range)	(2;15)	(40;93)	(12;65)	(12;37)	(7;22)	(5;13)	(19;86)	(6;13)	(2;10)	(5;32)
Storage										
C1	3 [27]	68 [32]	46 [32]	27 [32]	7 [29]	13 [30]	56 [30]	4 [32]	3 [24]	15 [30]
(Range)	(0;8)	(30;80)	(9;54)	(24;45)	(2;11)	(3;19)	(30;62)	(2;6)	(0;4)	(1;30)
C2	2 [36]	19 [60]	18 [52]	10 [57]	3 [42]	3 [31]	13 [44]	1 [43]	0 [20]	3 [41]
(Range)	(0;4)	(6;36)	(7;35)	(4;17)	(1;8)	(0;4)	(11;34)	(1;2)	(0;0)	(2;13)
C3	4 [78]	20 [106]	22 [92]	9 [107]	9 [85]	4 [78]	29 [81]	1 [90]	0 [78]	9 [83]
(Range)	(Range)	(Range)	(Range)	(Range)	(Range)	(Range)	(Range)	(Range)	(Range)	(Range)
Transmission and Distribution										
C1	24 [39]	147 [39]	67 [39]	51 [39]	40 [39]	27 [39]	87 [39]	16 [39]	24 [39]	64 [39]
(Range)	(13;39)	(96;250)	(61;105)	(46;97)	(29;62)	(22;40)	(70;120)	(13;19)	(18;35)	(26;94)
C2	24 [77]	132 [77]	60 [77]	49 [77]	36 [77]	33 [77]	70 [77]	14 [77]	26 [77]	36 [77]
(Range)	(14;30)	(84;175)	(48;79)	(43;56)	(28;45)	(27;37)	(53;92)	(8;19)	(17;34)	(28;61)

C3	14 [150]	93 [153]	61 [153]	46 [150]	26 [153]	25 [150]	70 [153]	14 [147]	23 [153]	26 [150]
(Range)	(10;37)	(74;190)	(52;86)	(38;86)	(21;62)	(17;40)	(52;90)	(11;16)	(17;27)	(17;87)
C5	13 [109]	81 [110]	55 [110]	41 [109]	25 [110]	23 [109]	58 [110]	14 [109]	23 [110]	25 [109]
(Range)	(9;13)	(67;160)	(46;59)	(22;46)	(19;28)	(15;28)	(51;67)	(12;16)	(16;26)	(17;29)

Note: Average yearly investments from 2023-2032 for Electricity generation capacity, by aggregate regions (in billion USD_{2015}). Further notes see Table 15.2. Reference C5 category for T&D shown in Table 2 as it is used for calculation of incremental needs for Figure 4. Vertical axis vertical axis, C4-C8 except T&D not shown. Reference C5 category for T&D shown because it is used for calculation of incremental needs for Figure 4.

What is apparent is that the bulk of investment requirements corresponds to medium- and low-income countries such as Asia, Latin America and the Middle East and Africa, as these still have growing energy demand and it is still considerably lower than the global average. This illustrates a vital opportunity to ensure the build-up of sustainable energy infrastructures in these regions and constitutes a risk of additional carbon lock-in if investments into fossil infrastructures, especially coal-fired power plants and uncontrolled urban expansion, continue.

Investment needs in electrification derived from IAMs do not include systematically investments in end-use equipment and distribution (See Box 4.8 in IPCC 1.5°C (IPCC 2018)). Model-based estimates of investment needs don't have the regional granularity to single out LDCs, as model regions typically are defined based on geographic proximity and therefore aggregate LDCs and other countries. With the average electricity consumption per capita in Africa increasing to 0.68-0.87 (1.43-2.92) MWh in 2030 (2050) yr-1 and remaining at the very low end of the global range [0.46 in Africa compared to the upper end of 12.02 in North America, MWh per capita and year in 2020], the targeted full electrification until 2030 appears unrealistic across all scenarios. SEforAll and IEA estimate assume investment needs to decentralised end-user electrification to come in around 40 billion USD on average until 2030 (SEforALL and CPI 2020; IEA 2021d).

Quantitative analysis of investment needs in energy generation based on IRENA and IEA data and comparison to AR6 scenario database output.

According to IRENA, the government plans in place today call for investing at least 95 trillion USD in energy systems over the coming three decades (2016–2050) (IRENA 2020c). Redirecting and increasing investments to ensure a climate-safe future (Transforming Energy Scenario) would require reaching on average around 1 USD trillion yr^{-1} (average until 2030) for electricity generation as well as grids and storage, increasing to above 2 USD trillion yr^{-1} (average until 2030) in the 1.5 scenario (IRENA 2021). IEA's respective SDS and NZE scenarios come in at average annual investments between 1.1 USD trillion yr^{-1} and 1.6 USD trillion yr^{-1} (average until 2030) (IEA 2021b). These additional data points for the C1 and C3 category underpin the range presented in the IAM database for needs until 2032 despite the slightly varying periods.

In contrast to the IAMs, IRENA and IEA assessments do not allow for an analysis of mitigation-driven investment needs in transmission and distribution which likely results in an overestimation of the mitigation driven investment needs in their analysis.

It is worth highlighting that driven by technology cost assumptions IRENA forecasts falling average annual investments needs for energy, but also energy efficiency, for the period 2030-2050 compared to 2020-2030. In the 1.5-S scenario the total annual investment needs excluding fossils and nuclear decrease from 5.0 trillion USD until 2030 yr^{-1} to 3.8 trillion USD yr^{-1} for 2030-2050 (IRENA 2021).In IAM scenarios of Category C1, Electricity supply investments (incl. generation, T&D, and storge) remain flat at 2.2 trillion USD yr^{-1} through the coming three decades in absolute terms. Given rising GDP, the complementary methods and sources thus consistently point to a peak in electricity supply investments as a percentage of GDP in mitigation scenarios in the coming decade. This reflects the fact that the coming decade requires low-carbon power generation investments to both cover the demand increase and (partly premature) replacement of fossil generation capacities, both concentrated in emerging and developing countries. Relative investment numbers for electricity measured against GDP then decrease towards 2050, as they only need to cover natural replacement and increasing demands (which due to electrification will also pick up in developed countries), and due to further declining technology costs. Investments for low-carbon fuel supply like hydrogen and synthetic fuels, and for direct electrification equipment (heat pumps, electric vehicles, etc.) scale up from much lower levels and will likely continue to grow as a share of GDP until mid-century, though uncertainties and accounting is still much more uncertain. (Bertram et al. 2021).

Quantitative analysis of investment needs in other sectors. As described above investment needs in non-energy sectors tend to be ignored in many integrated assessment models with studies for individual countries or regions providing a more fragmented picture only. However, the quality of estimates is likely not to be less robust given the drawbacks of integrated assessment models.

Energy efficiency Estimates on energy investment needs vary significantly with a low level of transparency with regard to underlying technology cost assumptions burdening the confidence levels.

IRENA only selectively reports financing needs for EE in buildings and industry as separate categories. For the 1.5-S average yr^{-1} needs until 2050 come in at 963 billion USD for buildings, 102 billion USD for heat pumps, and 354 billion USD for industry. Applying the relative share of these categories on higher total needs until 2030, around 1.8 trillion USD yr^{-1} in buildings and 1.7 trillion USD yr^{-1} in industry are needed in the 1.5-S and TES scenario. For the TES total EE investment needs until 2030 are stated at 29 trillion USD translating into an yearly average of around 1.8 trillion USD yr^{-1}. IEA estimates come in at a much lower level at 0.6 and 0.8 billion USD yr^{-1} on average between 2026-2030 for their SDS and NZE scenarios.

Transportation For the transportation sector, OECD has presented the most comprehensive assessment of financing needs in the AR6 database based on IEA data with the annual average coming in at 2.7 trillion USD in the 2°C (66%) scenario between 2015 and 2035. The assessment comprises road, rail and airports/ports infrastructure with only rail infrastructure being considered in our analysis amounting to 0.4 trillion USD on average until 2030.

On a regional level, (Oxford Economics 2017) shows, that annual infrastructure investments between 2016 and 2040 vary widely. For all available countries (n=50) estimates counts close to 0.4 trillion USD, including 0.2 trillion USD for China. Based on available data for 9 African countries, investments in rail infrastructure range from 0.1 billion USD in Senegal to 1.6 billion USD in Nigeria. (Osama et al. 2021) highlights a 4.7 billion USD financing gap for African countries in the transport sector. In Latin America the report identifies Brazil as frontrunner of required rail investments with 8.3 billion USD, followed by Peru with 2.3 billion USD. Totally, developed countries mounting up to 117 billion USD yr^{-1} (n=14, mean=8.35bn USD) for rail infrastructure funding needs, succeeded by developing countries (excl. LDCs) with 26 billion USD yr^{-1} (n=28, mean=0.93bn USD, excluding China).

Fisch-Romito and Guivarch (2019) show, by endogenizing the impact of urban infrastructure policies on mobility needs and modal choices that transportation investment needs globally might be lower in low-carbon pathways compared with baselines, with lower investments in road and air infrastructure. This does mean that higher investments are not needed over the following two decades; this means, this is confirmed by (Rozenberg and Fay 2019) that strong policy integration between urban, transportation and energy policies reduce the total investment gap..

IRENA as well as IEA have presented estimates for energy efficiency investments in the transport sector. For the 1.5-S scenario, IRENA indicates average investment needs of 0.2 trillion USD yr^{-1} for electric vehicle infrastructure, 0.2 trillion USD yr^{-1} for transport energy efficiency and 0.3 trillion USD yr^{-1} for EV batteries (IRENA 2020d) (average until 2030). IEA indicates a total of around 0.6 and 0.8 trillion USD yr^{-1} for transport energy efficiency in the SDS and IEA scenario for the 2026-2030 period (IEA 2021c). Many investment categories relating to mitigation options in particular with regard to behavioural change and transport mode changes (see Chapter 10, Figure SPM.8) are neglected in these analyses despite their significant mitigation potential.

AFOLU The Food and Land use Coalition estimates additional investment needs for ten critical transitions for the global food and land use systems to achieve the LTGG and SDGs. Additional annual investment needs until 2030 add up to 300-350 billion USD. Considering the change in global diets as well as the land-based nature-based solutions only, annual investment needs would come in between 110–135 billion USD. Chapter 7 stresses the importance of opportunity costs for AFOLU mitigation options, in particular for afforestation projects [cross-reference], and derives average yearly investment needs of around 278 billion USD yr^{-1} until 2030 and 431 USD billion yr^{-1} in the next several decades, including opportunity costs. The estimate is based on an assumption of emission reductions consistent with pathways C1-C4, leading to average abatement of 9.1 $GtCO_2$ yr^{-1} (median range 6.7 – 12.3 $GtCO_2$ yr^{-1}) from 2020-2050 and marginal costs of 100 USD per ton CO_2, excluding investments in BECCS and changes in food consumption and food waste (see Section 7.4). The largest investments are projected to occur in Latin America, Southeast Asia, and Africa, constituting 61% of total expenditure. The implied change of land use might trigger negative effects on other SDGs which need to be addressed to offer robust safeguards and labelling for investors.

However, given the strong interlinkage of the presented transitions and accumulated effects, climate change related investments can hardly be separated (The Food and Land Use Coalition 2019). (Shakhovskoy et al. 2019) present an overview of financing needs of small-scale farmers globally, however, without focusing on the required climate related investments. According to their assessment 270 million smallholder farmers in South/South-East Asia, sub-Sahara Africa and Latin America face approximately 240 billion USD of financing needs, thereof 100 billion USD short-term agricultural needs, 88 billion USD long-term agricultural needs and 50 billion USD non-agricultural needs (Shakhovskoy et al. 2019). These numbers can only provide "an indication of the magnitude of the climate investments required in small-scale agriculture" (CPI 2020). The following table summarises the studies used as well as adjustments made to determine needs for the gap discussion in Section 15.5.2.

Table 15.4 Sector studies to determine average financing needs.

Sector	Studies	Global ranges tr USD yr^{-1} - *Confidence Level*		Regional breakdown		Comment
Energy	IAM database, SEforAll (SEforALL and CPI 2020), IRENA 1.5-S and TES scenarios (IRENA 2021), IEA SDS and NZE scenarios (IEA 2021b)	0.7-1.6	*High confidence*	Detailed breakdown for R10 possible for IAM database and applied to the derived range	*Medium confidence*	Wide ranges primarily driven by varying assumptions with regard to grid investments relating to the increased RE penetration.
Energy Efficiency	IRENA 1.5-S and TES scenarios, IEA SDS and NZE scenarios	0.6-1.8	*Medium confidence*	Adjustments required to regional categorization by IEA and IRENA	*Low-medium confidence*	Medium confidence levels due to missing transparency with regard to underlying assumptions on technology costs. Low-to-medium confidence level

						on regional allocations due to required adjustments.
Transport	OECD/IEA (OECD 2017b) and Oxford Economics (Oxford Economics 2017) on rail investment data, IRENA 1.5-S and TES scenarios, IEA SDS and NZE scenarios for transport (energy efficiency) and electrification	1.0-1.2	*Medium confidence*	Adjustments required to regional categorization by IEA and IRENA	*Low-medium confidence*	Needs including battery costs, not total costs, of EVs, likely underestimation of needs due to missing data points on rail infrastructure.
AFOLU	Chapter 7 analysis, Section 7.4; The Food and Land use Coalition (Shakhovskoy et al. 2019)	0.1-0.3	*High confidence*	Breakdown for R10 possible for chapter 7 analysis	*Medium confidence*	Upper end of range incl. opportunity costs as these likely increase costs of investment of land.

Note: Total range 2,4 trillion to 4.8 trillion USD yr^{-1}.

Adaptation financing needs.

Financing needs for adaptation are even more difficult to define than those of mitigation because mobilizing specific adaptation investments is only part of the challenge since ultimately improving societies' adaptive capacities depends on the SDGs' fulfilment (Hallegatte et al. 2016). Bridging the investment gap on irrigation, water supply, healthcare, energy access, and quality buildings is an essential enabling condition for adapting to climate change. The scenario analysis conducted by (Rozenberg and Fay 2019) show that fulfilling the SDGs to improve the adaptive capacity of low and middle income countries would require investments in water supply, sanitation, irrigation and flood protection that would account for about 0.5% of developing countries GDP in a baseline scenario to 1,85% and 1% with a strong and anticipatory policy integration (USD 664 billion and 351 billion on average by 2030).

Most studies choose to assess public sector projects ignoring household level investments as well as private sector adaptation (UNEP 2018; Buchner et al. 2019). UNEP 2016 Adaptation Gap Report estimates adaptation financing needs amounting to 140–300 billion USD yr^{-1} by 2030 and 280–500 billion USD yr^{-1} by 2050 (UNEP 2016, 2018, 2021). Over 100 countries included adaptation components in their intended NDCs (INDCs) and approximately 25% of these referenced national adaptation plans (NAPs) (GIZ 2017a) but estimates of the financing required for NAP processes is not available (NAP Global Network 2017). These NAPs, as formally agreed under the UNFCCC in 2010 are iterative, continuous processes that have multiple stages with a developmental phase that requires country specific financing of primarily packages domestic sources, grants, bond issuance or debt conversion (NDC Partnership 2020). At the same time, multilateral climate funds such as the Green Climate Fund and the GEF/LDCF offer ‘readiness and preparatory support’ and implementation for the NAPs and adaptation planning process (GCF 2020a; GEF 2021a,b). There has been no significant updating of adaptation cost estimates since (UNEP 2016, 2018). The Global Commission on Adaptation makes the case that investing USD 1.8 trillion in early warning system, climate resilient infrastructure, global mangrove and resilient water resources would generate about USD1.7 trillion in benefits due to avoided cost and non-monetary and social resources (Verkooijen 2019; UNEP 2021).

There is increasing recognition of rising adaptation challenges and associated costs within and across Developed countries. Undoubtedly many developed countries are spending more on wide range of adaptation issues both as preventive measures and building resilience (greening infrastructure, climate proofing major projects and managing climate related risks) against the impacts of climate change extreme weather events (USGCRP 2018). Developed countries climate change adaptation spending covers areas such as federal insurance programmes, federal, state and local property and infrastructure, supply chains, water systems.

15.5 Considerations on financing gaps and drivers

15.5.1 Definitions

The analysis of financing gaps in climate action, which is used to measure implementation action and mitigation impact (FS-UNEP Centre and BNEF 2019) cannot be carried out as a pure demand-side challenge, in isolation from the analysis of barriers to deploy funds (e.g. (Ramlee and Berma 2013)) and to take investment initiatives. These barriers are friction that prevents socially optimal investments from being commercially attractive' (Druce et al. 2016). They are at the root of the "microeconomic paradox" of a deficit of infrastructure investments despite a real return between 4% and 8% (Bhattacharya et al., 2016), of the low share of carbon saving potentials tapped by dedicated policies such as energy renovation programmes (Ürge-Vorsatz et al. 2018), and, more generally of a demand for climate finance lower than the volume of economically viable projects(de Gouvello and Zelenko 2010; Timilsina et al. 2010)..

A few exercises tried and assess the consequences of the perpetuation of these drivers on the magnitude of the financing gap. They suggest, comparing the evolution of the infrastructure investment trends (beyond energy) by comparison with what they should be in an optimal scenario, a cumulative deficit between 15.9% in 2035 (Oxford Economics 2017) and 32% (Arezki et al. 2016). The volume of this gap is of the same order of magnitude than the incremental infrastructure investments (energy and beyond) for meeting a 1.5°C target, 2.4 % of the world GDP on average, (Box 4.8, IPCC 1.5°C 2018 (IPCC 2018)) calculated by exercises assuming no pre-existing investment gap. This figure is consistent with the 1.5% to 1.8% assessed by (European Commission 2020) for Europe and the 2% of the (IMF 2021d) for the G20 which do not encompass many developing countries of which economic take-off is today fossil fuels dependent. For low and middle income economies, (Rozenberg and Fay 2019) results suggest to increase the infrastructure investments by 2.5 to 6 percentage points of the GDP to cover both the reduction of the structural investment gap and the specific additional costs for bridging it with low carbon and climate resilient options. These assessments indicate the challenge at stake but do not exist at very disaggregated sectoral and regional levels for sectors other than energy.

The below quantitative analysis does not differentiate between financing gaps driven by barriers within or outside the financial sector given that the IAM models as well as most other studies used do not incorporate actual risk ranges depending on policy strength and coherence and institutional capacity, low-carbon-policy-risks, lack of long-term capital, cross-border currency fluctuation, and pre-investment costs and barriers within the financial sector that are discourage private sector funding. They comprise short-termism (e.g. (UNEP Inquiry 2016b)), high perceived risks for mitigation relevant technologies and/or regions (information gap through incomplete/ asymmetric information, e.g. (Clark et al. 2018)), lack of carbon pricing effects (e.g. (Best and Burke 2018)), home bias (results in limited balancing for regional mismatches between current capital and needs distribution, e.g. (Boissinot et al. 2016)), and perceived high opportunity and transaction costs (results from limited visibility of future pipelines and policy interventions; SME financing tickets and the missing middle, e.g. (Grubler et al. 2016)). In addition, barriers outside the financial sector will have to be addressed to close future financing gaps. The mix and dominance of individual barriers might vary significantly across sectors and regions and is analysed below

The interpretation of the quantitative analysis thus needs to be performed, taking into account the qualitative needs assessment in Section 15.4.1 and the evolution of parameters that determine the risk-weighted relative attractiveness low carbon and climate resilient investments compared to other investment opportunities. With some institutions having announced climate finance commitments and/or targets (see also Box 15.4 Measuring progress towards the 100 billion USD yr^{-1} by 2020 goal: issues of method), the actual asset allocation of commercial financial sector players including sectoral and regional focus will respond to tangible and financially viable investment opportunities available in the short-term. Robust long-term pathways to create such conditions for a significant private sector involvement do rarely exist and expectations on private sector involvement in some critical sectors/regions might be too high (Clark et al. 2018).

15.5.2 Identified financing gaps for sector and regions

The following section compares current climate finance flows as reported by CPI and IEA to needs derived in section 15.4 ignoring the slight mismatch in time horizons. The analysis ignores interlinked gaps in particular infrastructure investment gaps and other SDG-related investment gaps, which need to be addressed in parallel to reach the LTGG but also at least partially to facilitate green investments.

Total investments in mitigation need to increase by around 3 and 6 times with significant gaps existing across sectors and regions *(high confidence)*. The findings on still significant gaps and limited progress over the past few years to some extent seem to contradict the massive increase in commitments by financial institutions. As discussed in section 15.6 the investment gap is not due to global scarcity of funds.

However, these investment gaps have any little explanatory power in terms of the magnitude of the challenge to mobilise funding. In addition to measurement challenges from different definitions and data gap, sectors and regions offer highly divergent financial risk-return profiles and economic costs as well as standardization, scalability and replicability of investment opportunities as basis for private sector investment appetite. Moreover, soft costs and institutional capacity for enabling environment that can be prerequisite for addressing financing gap are ignored when focusing on investment cost needs.

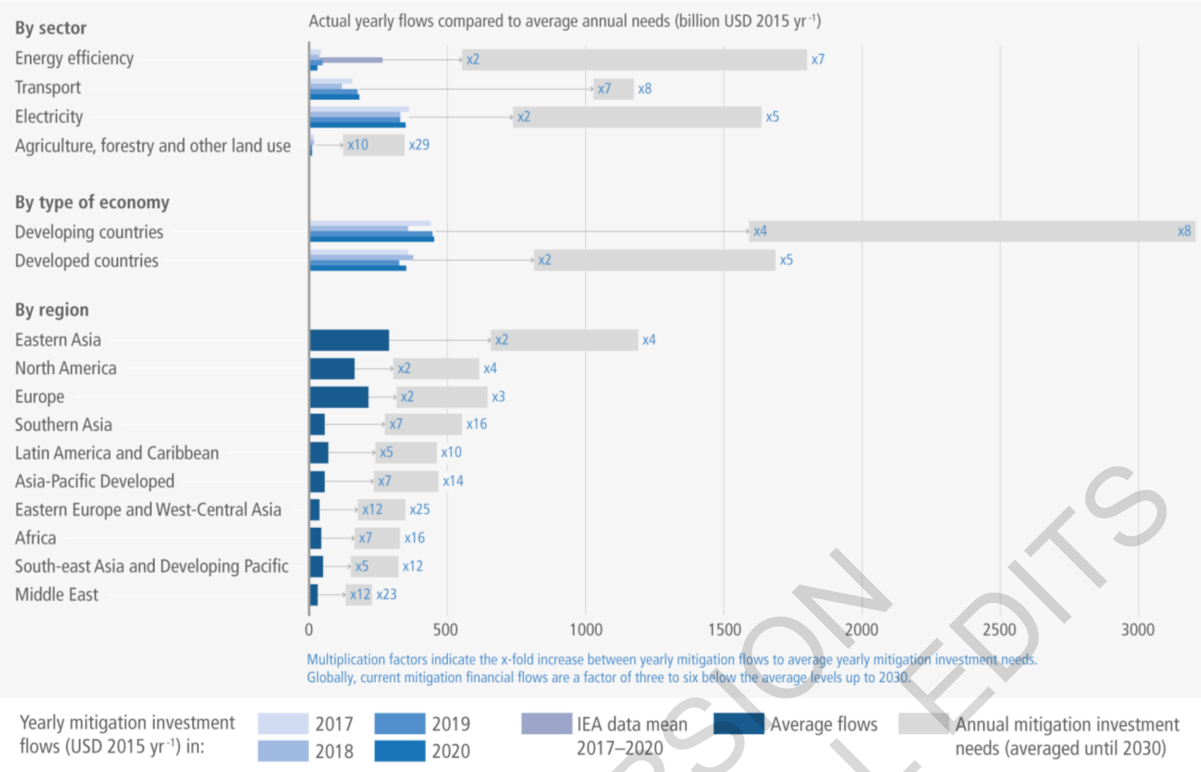


Figure 15.4 Breakdown of average investment flows and needs until 2030
Flows: Yearly CPI data for the *Agriculture and Forest*, *Electricity*, *Energy Efficiency*, and *Transport*. Adaptation pegged transactions are excluded. Technical assistance (i.e. Policy and national budget support or capacity building) and other non-technology deployment financing excluded from analysis. Small differences between sector and regional breakdowns due to non-regional/sectoral allocatable flows. In addition, 2017-2020 yearly average for IEA *End-use Energy Efficiency* are considered (WEI 2021). Minor adjustments to match IEA and IPCC regions applied based on CPI pro-rata allocation. Total Needs: See Table 15.4. Regional breakdown of needs: For *Electricity* based on IAM output for Non-Biomass renewable (mean C1:C3) plus incremental investment needs for T&D and Storage (mean C1:C3 less mean C5:C7) (see Table 15.2, 15.3., except C6 and C7). For *Energy Efficiency* based on IRENA Transforming Energy Scenario (TES) and adjusted to IPCC regional categories based on GDP. *Agriculture and Forestry* based on chapter 7.4 analysis and additional needs based on GDP. *Transport* investments for rail investment based on GIO rail investment needs per country and IRENA regional breakdown for total energy efficiency for needs for EV charging infrastructure, transport energy efficiency, and costs of batteries of EVs with adjustments to IPCC regional categories based on Energy Efficiency pro rata.

Sectoral considerations. The renewable energy sector attracted the highest level of funding in absolute and relative terms with business models in generation being proven and rapidly falling technology costs driving the competitiveness of solar photovoltaic and on-shore wind even without taking account the mitigation component (FS-UNEP Centre and BNEF 2019; IRENA 2020a). This investment activity comes in line with the first generation of NDCs and their heavy focus on mitigation opportunities in the renewable energy sector (Pauw et al. 2016; Schletz et al. 2017). Still, the investment gap tends to remain stable with flows over the past years not showing an upward trend.

Comparing annual average total investments in global fuel supply and the power sector of approximately 1.61 trillion USD yr^{-1} in 2019 (IEA 2020a) to the investment in the Stated Policies Scenario (approximately 1.84 trillion USD yr^{-1}) and the Sustainable Development Scenario (approximately 1.91 trillion USD yr^{-1}) in 2030 underlines the required shift of existing capital investment from fossil to renewables even more than the need to increase sector allocations (Granoff et al. 2016; McCollum et al. 2018).

Ensuring access to the heavily regulated electricity markets is a key driver for an accelerated private sector engagement (IFC 2016; FS-UNEP Centre and BNEF 2018; REN21 2019) with phasing out of support schemes and regulatory uncertainty being a major driver for reduced investment volumes in various regional markets in the past years (FS-UNEP Centre and BNEF 2015, 2016, 2017, 2018, 2020). Strategic investors and corporate investments by utilities dominate the investment activity in developed countries and countries in transition (BNEF 2019) based on the competitiveness of renewable energy sources. Reasonable auction results based on a substantial private-sector competition for investments have also been achieved in selected developing countries driven by rather standardised contract structures and the increased availability of risk mitigation instruments addressing political/regulatory risks and home bias constraints (FS-UNEP Centre and BNEF 2019; IRENA 2020a). DFI climate portfolios tend to be driven by concessional loans for renewable energy generation assets with equity often being provided by (semi-) commercial investors (see Section 15.3) which will have to change to accelerate renewable energy investment activity.

Given the wide range of estimates on current investment flows into energy efficiency, substantial uncertainty exists with regard to the magnitude of the investment gaps. While CPI publishes investment levels of 44 billion in 2019 and 26 billion in 2020) for energy efficiency, counting majorly international flows, IEA results come in at a much higher level of more than annually 250bn USD between 2017 and 2020 (IEA 2021c) and (IRENA 2020c) estimates energy efficiency investments in buildings between 2017-2019 at an average of 139 bn USD yr^{-1}.

Public sector investments in the transport sector have increased significantly in the past years reflecting the increased interest of capital markets in renewable energy and the efficient and corresponding reallocation of public funding. Provision of funding by capital markets for public transport infrastructure among others heavily depend on suitable financing vehicles and increased funding for development of projects with a low level of standardization (OECD, 2015a).

Both IRENA and IEA include only incremental costs of EVs in their estimates on needs while CPI, when measuring actual flows, includes those at full costs. Total private flows for EVs included in CPI numbers amount to 41bn USD in 2018 (Buchner et al. 2019), representing more than 80% of private sector finance into the transport sector around one third of total, public and private, funding to the transport sector in 2018. This likely results in an underestimation of the financing gap – in addition to the fact that estimates for investment needs for rail infrastructure are only available for selected countries.

Current funding of land-based mitigation options is less than 1 billion USD yr^{-1} representing only 2.5% of climate mitigation funding, significantly below the potential proportional contribution (Buchner et al. 2019). A stronger focus on deforestation-free value chain, including a stronger reflection in taxonomies and financial sector investment decision processes are necessary to *ensure* an alignment of financial flows with the LTGG. Taking into account the specifics of land-based mitigation (in particular long investment horizons, strong dependency on the monetization of mitigation effects, strong public sector involvement) a significant scale-up of commercial funding to the sector can hardly be expected in absence of strong climate policies (Clark et al. 2018). Agriculture is likely to develop more potential to mobilise private finance than the forest sector given its strong linkage to food security and hunger and shorter payback periods. The significant gap in land-based mitigation finance also indicates the crucial lack of finance to the bottom of the pyramid.

Agricultural support is an important source of distortions to agricultural incentives in both rich and poor countries (Mamun et al. 2019) ranging from largest component of the support, market price supports, increased gross revenue to farmers as a result of higher prices due to market barriers created by government policies, to production payments and other support including input subsidy (e.g. fertilizer subsidy) (Searchinger et al. 2020). 600 billion USD of annual governmental support for agriculture in the OECD database contributes only modestly to the related objectives of boosting crop yields and just transition (Searchinger et al. 2020). A review of (NDCs of 40 developing countries which submitted a NDC to the UNFCCC Interim NDC Registry by April 2017, and include within their NDC efforts to REDD+ via support from the UN-REDD Programme and/or World Bank Forest Carbon Partnership Facility) indicates that none of the countries reviewed mention fiscal policy reform of existing finance flows to agricultural commodity production or other publicly supported programmes that affect the direct and underlying drivers of land use conversion (Kissinger et al. 2019).

Analysis by region and type of economy. The analysis of gaps by type of economy illustrates the challenge for developing countries. Estimated mitigation financing needs as percentage of current GDP (USD_{2015}) comes in at around 2-4% for developed countries, and around 5-10% for developing countries (see Figure 15.4) (*high confidence*). Climate finance flows have to increase by factor 4-8 in developing countries and 2-5 in developed countries. This disparity is further exacerbated when considering adaptation, infrastructure and SDG related investment needs (Hourcade et al. 2021a) (*high confidence*). However, differences across developing countries are significant. Flows to Eastern Asia, with its average flows of 269 billion USD being dominated by China (more than 95% of total mitigation flows to Eastern Asia), would have to increase by a factor of 2-4, a comparable level to developed countries. Section 15.6.2 elaborates on outlooks with regard to fiscal space and ability to tap capital markets, in particular for developing countries. In particular, attention must accelerate on low-income Africa. This large continent currently contributes very little to global emissions, but its rapidly rising energy demands and renewable energy potential versus its growing reliance on fossil fuels and 'cheap' biomass (especially fuelwood for cooking and charcoal with impacts on deforestation) amid fast-rising urbanization makes it imperative that institutional investors and policy-makers recognise the very large 'leap-frog' potential for the renewable energy transition as well as risks of lock-in effects in infrastructure more general in Africa that is critical to hold the global temperatures rise to well below 2°C in the longer-term (2020–2050). Overlooking this transition opportunity, rivalling China, India, US and Europe, would be costly. Policies centred around the accelerated development of local capital markets for energy transitions - with support from external grants, supra-national guarantees and recognition of carbon remediation assets - are crucial options here, as in other low-income countries and regional settings. Notably, climate finance flows to African countries might have even decreased by about one fifth for mitigation technology deployment (stagnated for adaptation between 2017 and 2020), widening the finance gap in African countries in the recent years *(high confidence).*

Over 80% of climate finance is reported to originate and stay within borders, and even higher for private climate flows (over 90%) (Boissinot et al. 2016). There are multiple reasons for such 'home bias' in finance - national policy support, differences in regulatory standards, exchange rate, political and governance risks, as well as information market failures. The extensive home bias means that even if national actions are announced and intended to be implemented unilaterally and voluntarily, the ability to implement them requires access to climate finance which are constrained by the relative ability of financial and capital markets at home to provide such financing, and access to global capital markets that requires supporting institutional policies in source countries. 'Enabling' public policies and actions locally (cities, states, countries and regions), to reduce investment risks and boost domestic climate capital markets financing, and to enlarge the pool of external climate financing sources with policy support from source capital countries thus matter at a general level. The biggest challenge in climate finance is likely to be in developing countries, even in the presence of enabling policies and quite apart from any other considerations such as equity and climate justice (Klinsky et al. 2017) or questions about the equitable allocations of future 'climate budgets' (Gignac and Matthews 2015). The differentiation between developed and developing countries matter most on financing. Most developed countries have already achieved very high levels of incomes, have the largest pool of capital stock and financial capital (which can be more easily redeployed within these countries given the 'home bias' of financial markets), the most well-developed financial markets and the highest sovereign credit-ratings, in addition to starting with very high levels of per capita carbon consumption - factors that should allow the fastest adjustment to low carbon investments and transition in these countries from domestic policies alone. The financial and economic circumstances are the opposite for virtually all developing countries, even within a heterogeneity of circumstances across countries. The dilemma, however, is that the fastest rates of the expected increase in future carbon emissions are in developing countries. The biggest challenge of climate finance globally is thus likely to be the constraints to climate financing because of the opportunity costs and relative under-development of capital markets and financing constraints (and costs) at home in developing countries, and the relative availability or absence of adequate financing policy support internationally from developed countries. The Paris Agreement and commitment by developed countries to support the climate financing needs of developing countries thus continue to matter a great deal.

Soft costs / Institutional capacity (Osama et al. 2021). Most funding needs assessments focus on technology costs and ignore the cascade of financing needs as outlined above. International grant funding or national budget allocations for soft costs like the creation of a regulatory environment can be prerequisite for the supply of commercial financing for the deployment of technologies. Such critical funding needs might represent a small share of overall investment needs but current (relatively small) gaps in funding of policy reforms can hinder/delay deployment of large volumes of funding in later years. The role, as well as the approximate volumes of such required timely international grant funding or national budget allocations, appear underestimated in research. The numbers available for the creation of an enabling environment for medium-sized RE projects in Uganda (GET FiT Uganda) are illustrative only and cannot be transferred as assumptions to other countries without taking into account potentially varying starting points in terms of institutional readiness, pipelines as well as the general business environment. GET FiT Uganda supported 170 MWp of medium-scale RE capacity triggering investments of 453 million USD (GET FiT Uganda 2018), international results-based incremental cost support amounted to 92 million USD and project preparation, technical assistance, as well as implementation support, required 8 million USD excluding support from national agencies.

There is strong evidence of the correlation between institutional capacity of countries and international climate finance flows towards those economies (Adenle et al. 2017; Stender et al. 2019) and a strong need for robust institutional capacity to manage the transformation in a sustainable and human rights based way (Duyck et al. 2018). One example to consider unaddressed social concerns, is the ongoing call for feedback by the European Commission and its platform on sustainable finance. It argues for a social taxonomy, that can support the identification of financing opportunities of economic activities contributing to social objectives (European Commission 2021b). SEforAll has highlighted the issue of investments not going to the countries with the greatest need, also partly driven by institutional capacity levels (SEforALL and CPI 2020). Also, most of the developing countries NDCs are conditional upon international support for capacity building (Pauw et al. 2020). The Climate Technology Centre and Network (CTCN) was created as an operational arm of the UNFCCC Technology Mechanism with the mandate to respond to requests from developing countries. Initial evaluations of the mechanism underpin its importance and value for developing countries but stress long lead times and predictability of future international public funding to maintain operations as key challenges (UNFCCC 2017; DANIDA 2018). While limited pipelines, limited absorptive capacities as well as restricted institutional capacity of countries being often stated as challenge for an accelerated deployment of funding (Adenle et al. 2017), the question remains on the role of international public climate finance to address this gap and whether a concrete current financing gap exists for patient institutional capacity building. While current short-term, mostly project-related capacity building often fails to meet needs but alternative, well-structured patient interventions and funding could play an important role (Saldanha 2006; Hope 2011) accepting other barriers than funding playing a role as well. One reason why international public climate funding is not sufficiently directed to such needs might be the complexity in measuring intangible, direct outcomes like improved institutional capacity (Clark et al. 2018).

Early stage/Venture capital funding/Pilot project funding Early-stage companies in impact investment sectors with business solutions can contribute positively to climate impact. Figure SPM.8 highlights the need for new business models facilitating parts of the behavioural change. Also, SE4All has underpinned the need for an expansion of available business models to achieve universal access (SEforALL and CPI 2020). Further research and development needs range from resource efficiency of proven technologies and next generation technologies but also new technologies (see Chapter 16). Access to early stage funding remains critical with performance in in recent years being weak (Gaddy et al. 2016). This historically weak performance of clean tech start-ups burdens the interest of investors in the sector on the one hand and discourage experienced executive talent (Wang and Yee 2020). Besides that, the concentration of VC markets in the US, Europe and India represents a major challenge (FS-UNEP Centre and BNEF 2019; Statistica 2021). With regard to commercial-scale demonstration projects, IEA estimates a need of 90 USD billion of public sector funding before 2030 having around 25 billion USD already planned by governments to 2030 (IEA 2021c).

Need parallel rather than sequential investment decisions. The needs and gaps assessment does not include upstream investment needs required to facilitate the technology deployment as foreseen in the scenarios presented above. For example, for their transforming energy scenario IRENA estimates the number of EVs to increase from around 8m units in 2019 to 269m units in 2030 (IRENA 2020c). This would require investments in battery factories amounting to approximately 207 USD billion with further investment requirements in the value chain (IRENA 2020d). This illustrates the extent of parallel investments based on goals rather than concrete regulatory interventions and/or demand and poses a problem of up-front investment risks for each industry in the chain in the absence of certainty of the presence of parallel decisions in the upstream and downstream links in the chain. This is a typical element of the 'valley of the death' of innovation (Scherer et al. 2000; Åhman et al. 2017). It discourages risk-taking and slows-down the learning-by-doing processes, economies of scale and increasing returns to adoption needed for lowering the costs of systemic technical change (Kahouli-Brahmi 2009; Weiss et al. 2010). Implications on risk perception, financing costs as well as investment decision making processes and ultimately on feasibility are rarely considered.

Finance for adaptation and resilience. As explained early the reduction of the infrastructure gap to increase the societies' resilience and the implementation of the NAPs of will require more and higher levels of sustained financing. Activities mobilized for adaptation and resilience are often non marketable and their funding will continue coming from the public sector noted by (Murphy and Parry 2020) and, at the international level from grants based technical assistance or through budgetary support or basket funding for large projects/program or sector wide approaches or multilateral funding under (Non-)UNFCCC[2] are also anticipate supporting NAP implementation - particularly those involved incremental costs and co-benefits, which will include sectoral approach such as water, energy, infrastructures, food production. According to the UNFCCC, 'in 2015–2016, 3 per cent of international public adaptation finance flows was supplied by multilateral climate funds, while 84 per cent came from development finance institutions and 13 per cent from other government sources' (UNFCCC 2019c). Comprehensive reporting on adaptation finance by (Murphy and Parry 2020) and (Buchner et al. 2019) argues that flows of finance for adaptation action in developing countries in 2017 and 2018 were estimated to be approximately USD 30 billion; this plus an additional estimated flow of USD 12 billion for dual adaptation and mitigation actions totalled USD 42 billion accounting for 7.25% of the total estimated international public and private flows of climate finance (Buchner et al. 2019). They are far below the financing needs given in 15.4. To date, the private sector has limited involvement in NAPs

FOOTNOTE[2] Those under the UNFCCC such as the GCF through its 3 million USD per country readiness and preparatory support programme, the LDCF and the SCCF and the PPCR and ASAP are focused on supporting the preparatory process of the NAPs. But the Adaptation Fund will support the implementation of concrete projects up to 10 million USD per country.

and adaptation projects and planning but can be involved through public-private partnership (discussed in section 15.6.2.1) and other incentives provided by governments (Schmidt-Traub and Sachs 2015; Koh et al. 2016; Druce et al. 2016; UNEP 2016; NAP Global Network 2017; Murphy and Parry 2020) and innovative private financing mechanisms such as green and blue bonds. However, adaptation financing is only about 2% of the share of green bond financing raised up to June 2019 (UNFCCC 2019c)[3] , whereas it is about 10% of sovereign green bonds raised (UNFCCC 2019d). (Tuhkanen 2020a), in a detailed review of green bond issuance in the Environmental Finance Data base 2019, found that between March 2010 to April 2019, '5% of all green bonds issued were categorized as adaptation and that 'the private sector accounts for a significant proportion of adaptation-related green bond issuances' (p.11). However, citing (GIZ 2017b; Nicol et al. 2017, 2018a) (Tuhkanen 2020b) highlights that there is scepticism about this stream of funding for adaptation due to the factors that has thus far limited the private sector's involvement in adaptation: lack of resilience-related revenue streams, the small-scale of some adaptation projects and the overall "intangibility" of funding adaptation projects,' (p.9). (Larsen et al. 2019)

Financing for resilience is limited unpredictable, fragmented and focused on few projects or sectors and short term as opposed to programmatic and long-term (10–15 years) funding to build resilience (ISDR 2009, 2011; Kellett and Peters 2014; Watson et al. 2015). Market-based mechanisms are available but not equally accessible to all developing countries, particularly SIDS and LDCs and such mechanisms can undermine debt sustainability (OECD and World Bank 2016).. While resilience financing is mainly grant-funding, concessional loans are increasing substantially and are key sources of financing for disaster and resilience, particularly for upper-middle-income countries (OECD and World Bank 2016). The combination of these trends can contribute to greater levels of indebtedness among many developing countries many of who are already at or approaching debt distress.

Social protection systems can be linked with a number of the instruments already considered: reserve funds, insurance and catastrophe bonds, regional risk-sharing facilities, contingent credit, in addition to traditional international aid and disaster response. (Hallegatte et al. 2017) recommend combining adaptive social protection with financial instruments in a consistent policy package, which includes financial instruments to deliver adequate liquidity and contingency plans for the disbursement of funds post-disaster. Challenges related to financing residual climate-related losses and damages are particularly high for developing countries. Financing losses and damages from extreme events requires rapid pay-outs; the cost of financing for many developing countries is already quite high; and the expense of risk financing is expected to increase as disasters become more frequent, intense and more costly not only due to climate change but also due to higher levels of exposure. Addressing both extreme and slow onset climate impacts requires designing adequate financial protection systems for reaching the most vulnerable. Moreover, some fraction of losses and damages, both material and non-material, are not commonly valued in monetary terms [non-economic loss] and hence financing requirements are hard to estimate. These non-market-based residual impacts include loss of cultural identity, sacred places, human health and lives (Paul 2019; Serdeczny 2019).

15.6 Approaches to accelerate alignment of financial flows with long-term global goals

Near-term actions to shift the financial system over the next decade are critically important and possible with globally coordinated efforts. Taking into account the inertia of the financial system as well as the

FOOTNOTE[3] According to climate bonds initiative, total green bond finance raised in 2018 was 168.5 billion USD across 44 countries (UNFCCC 2019c).

magnitude of the challenge to align financial flows with the long-term global goals, fast action is required to ensure the readiness of the financial sector as an enabler of the transition *(high confidence)*. The following subsections elaborate on key areas which can have a catalytic effect in terms of addressing existing barriers – besides political leadership and interventions discussed in other Chapters of AR6.

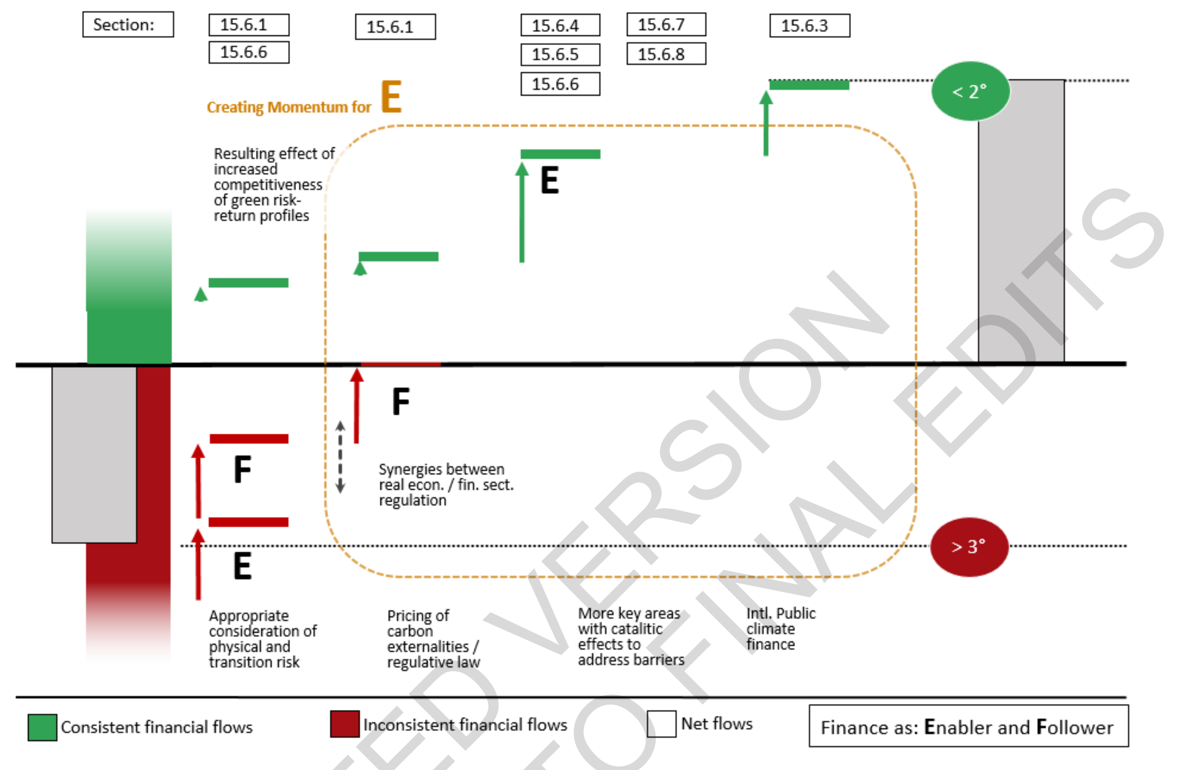


Figure 15.5 Visual abstract to address financing gaps in Section 15.6

Addressing knowledge gaps with regard to climate risk analysis and transparency will be one key driver for more appropriate climate risk assessment and efficient capital allocation (15.6.1), efficient enabling environments support the reduction of financing costs and reduce dependency on public financing (15.6.2), a revised common understanding of debt sustainability, including also negative implications of deferred climate investments on future GDP, particularly stranded assets and resources to be compensated, can facilitate the stronger access to public climate finance, domestically and internationally (15.6.3), climate risk pooling and insurance approaches are a key element of financing of a just transition (15.6.4), the supply of finance to a widened focus on relevant actors can ensure transformational climate action at all levels (15.6.5), new green asset classes and financial products can attract the attention of capital markets and support the scale up of financing by providing standardised investment opportunities which can be well integrated in existing investment processes (15.6.6), a stronger focus on the development of local capital markets can help mobilizing new investor groups and to some extent mitigate home bias effects (15.6.7), new business models and financing approaches can help to overcome barriers related to transactions costs by aggregating and/or transferring financing needs and establish supply of finance for needs of stakeholder groups lacking financial inclusion (15.6.8).

15.6.1 Address knowledge gaps with regard to climate risk analysis and transparency

Climate change as a source of financial risk. Achieving climate mitigation and adaptation objectives requires ambitious climate finance flows in the near-term, i.e. 5-10 years ahead. However, knowledge gaps in the assessment of climate-related financial risk are a key barrier to such climate finance flows. Therefore, this section discusses the main knowledge gaps that are currently being addressed in the literature and those that remain outstanding

Climate-related financial risk is meant here as the potential adverse impact of climate change on the value of financial assets. A recent but remarkable development since AR5 is that climate change has been explicitly recognised by financial supervisors as a source of financial risk that matters both for financial institutions and citizens' savings (Bolton et al. 2020). Previously, climate change was mostly regarded in the finance community only as an ethical issue. The reasons why climate change implies financial risk are not new and are discussed more in detail below. What is new is that climate enters now as a factor in the assessment of financial institutions' risk (e.g. such as the European Central Bank or the European Banking Authority) and credit rating (see also Section 15.6.3) and, going forward, into stress-test exercises. This implies changes in incentives of the supervised financial actors, both public and private, and thus changes in the landscape of mitigation action by generating a new potential for climate finance flows. However, critical knowledge gaps remain. In particular, the underestimation of climate-related financial risk by public and private financial actors can explain that the current allocation of capital among financial institutions is often inconsistent with the mitigation objectives (Rempel et al. 2020). Moreover, even a correct assessment of risk, which could provide incentives for divesting from carbon-intensive activities, does not necessarily lead to investing in the technical options needed for deep decarbonisation. Therefore, understanding the dynamics of the low carbon transition require to fill in at the same time gaps about risk and gaps about investments in enabling activities in a broader sense.

Physical risk. On the one hand, unmitigated climate change implies an increased potential for adverse socio-economic impacts especially in more exposed economic activities and areas *(high confidence)*. Accordingly, *physical risk* refers to the component of financial risk associated with the adverse physical impact of hazards related to climate change (e.g., extreme weather events or sea level rise) on the financial value of assets such as industrial plants or real estate. In turn, these losses can translate into losses on the values of financial assets issued by exposed companies (e.g., equity/bonds) and or sovereign entities as well as losses for insurance companies. The assessment of climate financial physical risks poses both challenges in terms of data, methods and scenarios. It requires to cross-match scenarios of climate-related hazards at granular geographical scale, with the geolocation and financial value of physical assets. The relationship between the value of physical assets (such as plants or real estate) and the financial value of securities issued by the owners of those assets is not straightforward. Further, the repercussion of climate related hazards on sovereign risk should also be accounted for.

Transition risks and opportunities. On the other hand, the mitigation of climate change, by means of a transition to a low-carbon economy, requires a transformation of the energy and production system at a pace and scale that implies adverse impacts on a range of economic activities, but also opportunities for some other activities *(high confidence)*. If these impacts are factored in by financial markets, they are reflected in the value of financial assets. Thus, *transition risks and opportunities* refer to the component of financial risk (opportunities) associated with negative (positive) adjustments in assets' values resulting directly or indirectly from the low-carbon transition.

The concepts of *carbon-stranded assets* (see e.g.(Leaton and Sussams 2011), and *orderly* vs. *disorderly transition* (Sussams et al. 2015) emerged in the NGO community, have provided powerful metaphors to conceptualise transition risks and have evolved into concepts used also by financial supervisors (NGFS 2019) and academics. The term carbon stranded assets refer to fossil-fuel-related assets (fuel or equipment) that become unproductive. An *orderly transition* is defined here as a situation in which market players are able to fully anticipate the price adjustments that could arise from the transition. In this case, there would still be losses associated with stranded assets, but it would be possible for market players to spread losses over time and plan ahead. In contrast, a *disorderly transition* is defined here as a situation in which a transition to a low carbon economy on a 2C° path is achieved (i.e., by about 2040), but the impact of climate policies in terms of reallocation of capital into low-carbon activities and the corresponding adjustment in prices of financial assets (e.g. bonds and equity shares) is large, sudden and not fully anticipated by market players and investors. Note the impact could be unanticipated even if the date of the introduction is known in advance by the market players. There are several reasons why such adjustments could occur. One simple argument is that the political economy of the transition is characterised by forces in different directions, including opposing interests within the industry, mounting pressure from social awareness of unmitigated climate risks. Politics will have to find a synthesis and the outcome could remain uncertain until it suddenly unravels. Note also that, in order to be relevant for financial risk, the disorderly transition does not need to be a catastrophic scenario in terms of the fabric of markets. It also does not automatically entail systemic risk, as discussed further down. Knowledge gaps in this area are related to emerging questions, including: What are, in detail, the transmission channels of physical and transition risk? How to assess the magnitude of the exposure to these risks for financial institutions and ultimately for people's savings? How do transition risk and opportunities depend on the future scenarios of climate change and climate policies? How to deal with the intrinsic uncertainty around the scenarios? To what extent, an underestimation of climate-related financial risk, could feed back on the alignment of climate finance flows and hamper the low-carbon transition? Should climate risk be explicitly accounted for in regulatory frameworks for financial institutions, such as Basel III for banks and national frameworks for insurance? What lessons from the 2008 financial crisis are relevant here, regarding moral hazard and the trustworthiness of credit risk ratings? The attention of both practitioners and the scientific community to these questions has grown since the Paris Agreement. In the following we review some of the findings from the literature, but the field is relatively young and many of the questions are still open.[4] Nordic countries (FinansNorge et al. 2013). Damages from climate change are expected to escalate dramatically in Europe (Forzieri et al. 2018) and in some EU countries there is already some evidence that banks, anticipating possible losses on the their loan books, lend proportionally less to

Assessment of physical risk. There is a literature on estimates of economic losses on physical assets (see respective chapter in WGII). Here we discuss some figures and mechanisms that are relevant for the financial system. Significant cost increases have been observed related to increases in frequency and magnitude of extreme events (see Section 15.4.2) *(high confidence)*. At the global level, the expected 'climate value at risk' (climate VaR) of financial assets has been estimated to be 1.8% along a business-as-usual emissions path (Dietz et al. 2016), with however, a concentration of risk in the tail (e.g. 99th VaR equals to 16.9%, or 24.2 trillion USD, in 2016). Climate-related impacts are estimated to increase the frequency of banking crises (up over 200% across scenarios) while rescuing insolvent banks could increase the ratio of public debt to gross domestic product by a factor of 2 (Lamperti et al. 2019). Further assessments of physical risk for financial assets (Mandel 2020), accounting in particular for the propagation of losses through financial networks, estimate global yearly GDP losses at 7.1% (1.13%) in 2080, without adaptation (with adaptation), the former corresponding to a 10-fold increase with respect to the current yearly losses (0.76% of global GDP). Finally, climate physical risk can

FOOTNOTE[4] In the context, while belonging to grey literature, reports from financial supervisors or non-academic stakeholders, can be of interest, for what they document in terms of changes in perception and incentives among the market players and hence of the dynamics of climate finance flows.

impact on the value of sovereign **bonds** (one of the top asset classes by size), in particular for vulnerable countries (Volz et al. 2020).

Insurance payouts for catastrophes have increased significantly over the last 10 years, with dramatic cost spikes in years with multiple major catastrophes (such as in 2018 with hurricanes Harvey, Irma, and Maria). This trend is expected to continue. The indirect costs of climate-related flooding event can be up to 50% of the total costs, the majority of which is not covered by insurance (Alnes et al. 2018) (see chapter 15.6.4). The gap between total damage losses and insurance payouts has increased over the past 10 years (Swiss Re Institute 2019). Indeed, the probability of 'extreme but plausible' scenarios will be progressively revised upwards in the 'value at risk' (VaR). As a result it becomes more difficult to find financial actors willing to provide insurance as it was observed for real estate in relation to flood and wildfires in California (Ouazad and Kahn 2019). This progressive adjustment would keep the financial system safe (Climate-Related Market Risk Subcommittee 2020; Keenan and Bradt 2020), but transfer to taxpayers the onus of damage compensation and the funding of adaptation investments (OECD 2021c) as well as build up latent liabilities.

Assessment of transition risk

Carbon stranded assets. Fossil fuel reserve and resource estimates exceed in equivalent quantity of CO_2 with virtual certainty the carbon budget available to reach a 1.5°C and 2°C targets (Meinshausen et al. 2009; McGlade and Ekins 2015; Millar et al. 2017) *(high confidence)*. In relative terms, stranded assets of fossil-fuel companies amount to 82% of global coal reserves, 49% of global gas reserves and 33% of global oil reserves (McGlade and Ekins 2015). This suggests that only less than the whole quantity of fossil fuels currently valued (either currently extracted, waiting for extraction as reserves or assets on company balance sheets) can yield economic return if the carbon budget is respected. The devaluation of fossil fuel assets imply financial losses for both the public sector (see Section 15.6.8) and the private sector (Coffin and Grant 2019). Global estimates of potential stranded fossil fuel assets amount to at least 1 trillion, based on ongoing low-carbon technology trends and in the absence of climate policies (cumulated to 2035 with 10% discount rate applied; 8 trillion USD without discounting (Mercure et al. 2018a). With worldwide climate policies to achieve the 2°C target with 75% likelihood, this could increase to over 4 trillion USD (until 2035, 10% discount rate; 12 trillion USD without discounting). Other estimates indicate 8–15 trillion USD (until 2050, 5% discount rate, (Bauer et al. 2015)) and 185 trillion USD (cumulated to year 2115 using combined social and private discount rate; (Linquiti and Cogswell 2016). However the geographical distribution of potential stranded fossil fuel assets (also called 'unburnable carbon') is not even across the world due to differences in production costs (McGlade and Ekins 2015). In this context, a delayed deployment of climate funding and consequently limited alignment of investment activity with the Paris Agreement tend to strengthen carbon and thus to increase the magnitude of stranded assets.

Assets directly and indirectly exposed to transition risk. In terms of types of assets and economic activities, the focus of estimates of carbon stranded assets, tend to be on physical reserves of fossil fuel (e.g., oil fields) and sometimes financial assets of fossil-fuel companies (see (van der Ploeg and Rezai 2020)). However, a precondition for a broader analysis of transition risks and opportunities is to go beyond the narrative of stranded assets and to consider a classification of sectors of all the economic activities that could be affected (Monasterolo 2020). This, in turn depends on their direct or indirect role in the GHG value chain, their level of substitutability with respect to fossil fuel and their role in the policy landscape. Moreover, such a classification needs to be replicable and comparable across portfolios and jurisdictions. One classification that meets these criteria is the Climate Policy Relevant Sectors (CPRS) (Battiston et al. 2017) which has been used in several studies by financial supervisors (EIOPA 2018; ECB 2019; EBA 2020; ESMA 2020). The CPRS classification builds on the international classification of economic activities (ISIC) to map the most granular level (4 digits) into a small set of categories characterised by differing types of risk: fossil-fuel (i.e. all activities whose revenues depends mostly and directly on fossil-fuel, including concession of reserves and operating industrial plants for extraction and refinement); electricity (affected in terms of input but that can in principle diversify they energy sources); energy intensive (e.g. steel or cement production plants, automotive manufacturing plants), which are affected in terms of energy cost but not in terms of the main input); transport and buildings (affected in terms of both energy sources and specific policies). All financial assets (e.g. bonds, equity shares, loans) having as issuers or counterparties firms whose revenues depends significantly on the above activities are thus potentially exposed to transition risks and opportunities. Further, investors' portfolios have to be part of the analysis since changes in financial assets values affect the stability of financial institutions and can thus feed back into the transition dynamics itself (e.g. through cost of debt for firms and through costs for assisting the financial sector).One outstanding challenge for the analysis of investors' exposure to climate risks is the difficulty to gather granular and standardised information on the breakdown of non-financial firms' revenues and capex in terms of low/high-carbon activities *(high confidence)*.

Several financial super visors have conducted assessments of transition risk for the financial system at the regional level. For instance, the European Central Bank (ECB) reported preliminary estimates of aggregate exposures of financial institutions to CPRS relative to their total debt securities holdings, as ranging between 1% for banks to about 9% for investment funds (ECB 2019). The European Insurance and Occupational Pensions Authority (EIOPA) reported aggregate exposures to CPRS of EU insurance companies at about 13% of their total securities holdings (EIOPA 2018). Further analyses on the EU securities holdings indicate that among financial investments in bonds issued by non-financial corporations, EU institutions hold exposures to CPRS ranging between 36.8%for investment funds to 47.7% for insurance corporations; analogous figures for equity holdings range from 36.4% for banks to 43.1% for pension funds (Alessi et al. 2019). Another study indicates that losses on EU insurance portfolios of sovereign bonds could reach up to 1%, in conservative scenarios (Battiston et al. 2019).

Given the magnitude of the assets that are potentially exposed, reported in the previously cited studies, a delayed or uncoordinated transition risk can have implications for financial stability not only at the level of individual financial institutions, but also at the macro-level. The possible systemic nature of climate financial risk has been highlighted on the basis of general equilibrium economic analysis (Stern and Stiglitz 2021).

Some financial authorities recognize that Climate change represents a major source of systemic risk, particularly for banks with portfolios concentrated in certain economic sectors or geographical areas (de Guindos 2021). Specifically, the concern that central banks would have to act as "climate rescuers of last resort" in a systemic financial crisis stemming from some combination of physical and transition risk has been raised in the financial supervisor community (Bolton et al. 2020). The systemic nature of climate risk is reinforced by the possible presence of moral hazard. Indeed, if many enough financial actors have an incentive to downplay climate-related financial risk, then systemic risk builds up in the financial system eventually materialising for tax payers (Climate-Related Market Risk Subcommittee 2020). While such type or risk may go undetected to standard market indicators for a while, it can materialise with a time delay, similarly to the developments observed in the run up of the 2008 financial crisis.

These considerations are part of an ongoing discussion on whether the current financial frameworks, including Basel III, should incorporate explicitly climate risk as a systemic risk. In particular, the challenges in quantifying the extent of climate risk, reviewed in this section, especially if risk is systemic, raise the question whether a combination of quantitative and qualitative restrictions on banks' portfolios could be put in place to limit the build-up of climate risks (Baranović et al. 2021).

Endogeneity of risk and multiplicity of scenarios. One fundamental challenge is that climate-related financial risk is endogenous *(high confidence)*. This means that the perception of the risk changes the risk itself, unlike most contexts of financial risk. Indeed, transition risk depends on whether governments and firms continue on a business-as-usual pathway (i.e. misaligned with the Paris Agreement targets) or engage on a climate mitigation pathway. But the realisation of the transition pathway depends itself on how, collectively, society, including financial investors and supervisors, perceive the risk of taking / not taking the transition scenario. The circularity between perception of risk and realisation of the scenario simplifies first of all those multiple scenarios are possible, and that which scenario is ultimately realised can depend on policy action. The coordination problem associated also with low-carbon investments opportunities increases the uncertainty. Further, not all low-carbon activities are directly functional to the transition (e.g. investments in pharmaceutical, IT companies, or financial intermediaries), thus not all reallocations of capital lead to the same path.

In this context, probabilities of occurrence of scenarios are difficult to assess and this is important because risk vary widely across the different scenarios. In this context a major challenge is the fat-tail nature of physical risk. One the one hand, forecasts of climate change and its impact on humans and ecosystems imply tail events (Weitzman 2014) and tipping points which cannot be overcome by model consensus (Knutti 2010). On the other hand, everything else the same, costs and benefits vary substantially with assumptions on agents' utility, productivity, and intertemporal discount rate, which ultimately depend on philosophical and ethical considerations (see (Nordhaus 2007; Nicholas Stern 2008; Pindyck 2013). Thus, more knowledge is needed on the interaction of climate physical and transition risk, the possible reinforcing feedbacks and transmission channels to the economy and to finance. Moreover, models need to account for compound risk, i.e. the interaction of climate physical and/ or transition risk with other sources of risk such as pandemics, as the COVID-19.

Challenges for climate transition scenarios. The endogeneity of risk and its associated deep uncertainty implies that the standard approach to financial risk consisting of computing expected values and risk based on historical values of market prices, is not adequate for climate risk (Bolton et al. 2020) *(high confidence)*. To address this challenge, a recent stream of work has developed an approach to make use of climate policy scenarios to derive risk measures (e.g. expected shortfall) for financial assets and portfolios, conditioned to scenarios of disorderly transition (Battiston et al. 2017; Monasterolo and Battiston 2020; Roncoroni et al. 2020). In particular, climate policy shocks on the output of low/high carbon economic activities are calculated based on trajectories of energy technologies as provided by large- scale Integrated Assessment Models (Kriegler et al. 2015; McCollum et al. 2018) conditioned to the introduction of specific climate policies over time. This approach allows to conduct climate stress-test both at the level of financial institutions and at the level of the financial system of a given jurisdiction.

In a similar spirit, recently, the community of financial supervisors in collaboration with the community of climate economics has identified a set of climate policy scenarios, based on large-scale IAM, as candidate scenarios for assessing transition risk (Monasterolo and Battiston 2020). These scenarios have been used for instance, in an assessment of transition risk conducted at a national central bank (Allen et al. 2020). This development is key to mainstreaming the assessment of transition risk among financial institutions, but the following challenges emerge *(high confidence)*. First, a consensus among financial supervisors and actors on scenarios of transition risk that are too mild could lead to a systematic underestimation of risk. The reason is that the default probability of leveraged financial institutions is sensitive to errors in the estimation of the loss distribution and hence sensitive on the choice of transition scenarios (Battiston and Monasterolo 2020). This in turn could lead to an allocation of capital across low/high carbon activities that is insufficient to cater for the investment needs of the low-carbon transition.

Second, IAM do not contain a description of the financial system in terms of actors and instruments and make assumptions on agents' expectations that could be inconsistent with the nature of a disorderly transition (Espagne 2018; Pollitt and Mercure 2018a; Battiston et al. 2020b). In particular, IAMs solve for least cost pathways to an emissions target in 2100 (AR4 WGIII SPM Box 3), while the financial sector's time horizon is much shorter and risk is an important factor in investment decision.

Third, the current modelling frameworks used to develop climate mitigation scenarios, which are based on large-scale IAM, assume that the financial system acts always as an enabler and do not account for the fact that, under some condition (i.e. if there is underestimation of climate transition risk) can also act as a barrier to the transition (Battiston et al. 2020a) because it invests disproportionately more in high carbon activities.

Macroeconomic implications of the technological transition. Global macroeconomic changes that may affect asset prices are expected to take place as a result of a possible reduction in growth or contraction of fossil fuel demand, in scenarios in which climate targets are met according to carbon budgets, but also following ongoing energy efficiency changes ((Mercure et al. 2018a); see also (Clarke et al. 2014)) *(high confidence)*. A review of the economic mechanisms involved in the accumulation of systemic risk associated to declining industries, with focus on fossil fuels, is given by (Semieniuk et al. 2021). An example is the transport sector, which uses around 50% of oil extracted (IEA 2018; Thomä 2018). A rapid diffusion of electric vehicles (and other alternative vehicle types), poses an important risk of as it could lead to oil demand peaking before 2050 far before mid-century (Mercure et al. 2018b; Mercure et al. 2021). New technologies and fuel switching in aviation, heavy industry and shipping could further displace liquid fossil fuel demand (IEA 2017). A rapid diffusion of solar photovoltaic could displace electricity generation based predominantly on coal and gas (Sussams and Leaton 2017). A rapid diffusion of household and commercial indoor heating and cooling based on electricity could further reduce the demand for oil, coal and gas (Knobloch et al. 2019). Parallels can be made with earlier literature on great waves of innovation, eras of clustered technological innovation and diffusion between which periods of economic, financial and social instability have emerged (Freeman and Louca 2001; Perez 2009).

Due to the predominantly international nature of fossil fuel markets, assets may be at risk from regulatory and technological changes both domestically and in foreign countries *(medium confidence)*. Fossil-fuel exporting nations with lower competitiveness could lose substantial amounts of industrial activity and employment in scenarios of peaking or declining demand for fossil fuels. In scenarios of peaking oil demand, production is likely to concentrate towards the Middle-East and OPEC countries (IEA 2017). Since state-owned fossil fuel companies tend to enjoy lower production cost, privately-owned fossil fuel companies are more at risk (Thomä 2018). Losses of employment may be directly linked to losses of fossil-related industrial activity or indirectly linked through losses of large institutions, notably of government income from extraction royalties and export duties. A multiplier effect may take place making losses of employment spill out of fossil fuel extraction, transformation and transportation sectors into other supplying sectors (Mercure et al. 2018a).

Main regulatory developments and voluntary responses to climate risk. Framing climate risk as a financial risk (not just as an ethical issue) is key for it to become an actionable criteria for investment decision among mainstream investors (TCFD 2019) *(high confidence)*. Since 2015 financial supervisors and central banks (e.g. the Financial Stability Board, the G20 Green Finance Study Group, and the Network for Greening the Financial System (NGFS)) have played a central role in raising awareness and increase transparency of the potential material financial impacts of climate change within the financial sector (Bank of England 2015, 2018; TCFD 2019). The NGFS initiative have engaged in particular in the elaboration of climate financial risk scenarios, as mentioned earlier.

Although disclosure has increased since the TCFD recommendations were published, the information is still insufficient for investors and more clarity is needed on potential financial impacts and how resilient corporate strategies are under different scenarios (TCFD 2019). Several efforts to provide guidance and tools for the application of the TCFD recommendations have been made (using SASB Standards and the CDSB Framework to Enhance Climate-Related Financial Disclosures in Mainstream Reporting TCFD Implementation Guide (UNEP FI 2018; CDSB and SASB 2019). Results of voluntary reporting have been mixed, with one study pointing to unreliable and incomparable results reported by the US utilities sector to the CDP (Stanny 2018).

There have been also similar initiatives at the national level (U.S. GCRP 2018; DNB 2017)(UK Government 2017). In particular, France was the first country to mandate climate risk disclosure from financial institutions (via Article 173 of the law on energy transition). However, disclosure responses have been so far mixed in scope and detail, with the majority of insurance companies not reporting on physical risk (Evain et al. 2018). In the UK, mandatory GHG emissions reporting for UK-listed companies has not led to substantial emissions reductions to date but could be laying the foundation for future mitigation (Tang and Demeritt 2018).

A key recent development is the EU Taxonomy for Sustainable Finance (TEG 2019), which provides a classification of economic activities that (among other dimensions) contribute to climate mitigation or can be enabling for the low-carbon transition. Indirectly, such classification provides useful information on investors' exposure to transition risk (Alessi et al. 2019; ESMA 2020). Finally, many consultancies have stepped forward offering services related to climate risk. However, the methods are typically proprietary, non-transparent, or based primarily on carbon foot printing, which is a necessary but insufficient measure of climate risk. Further, ESG (environmental, social and governance) metrics can useful but are, alone, inadequate to assess climate risk.

Illustrative mitigation pathways and financial risk for end-users of climate scenarios

Decision makers in financial risk management make increasingly use of climate policy scenarios, in line with the TCFD guidelines and the recommendations of the NGFS. In order to reduce the number of scenarios to consider, Illustrative Mitigation Pathways (IMPs, Chapter 3), have been elaborated to illustrate key features that characterise the possible climate (policy) futures. The following considerations can be useful for scenario end-users who carry out risk analyses on the basis of the scenarios described in Chapter 3. It is possible to associate climate policy scenarios with levels of physical and/or transition risk, but these are not provided with the scenario data themselves.

On the one hand, each scenario is associated with a warming path, which in turn, on the basis of the results from WGII, implies certain levels of physical risk (see WGII Chapter 16). However, climate impacts are not accounted for in the scenarios. Moreover, levels of risk may vary with the Reason for Concern (RFC, ibidem) and with the speed in the implementation of adaptation. On the other hand, while mitigation can come with transition risk, in the case of lack of coordination among the actors, as discussed earlier in this section, this is not modelled explicitly in the trajectories, since the financial sector is not represented in underlying models. The scientific state of the art in climate-related financial risk offers an analysis that is not yet comprehensive of both the physical and transition risk dimensions in the same quantitative framework. However, decision makers can follow a mixed approach where they can combine quantitative risk assessment for transition risk with more qualitative risk analysis related to physical risk.

Figure 15.6 represents sequences of events following along a scenario both in terms of physical risk (left) and transition risk (right). Four groups of IMPs (more are considered based on the warming level they lead to in 2100. Current Policies (CurPol) considers climate policies implemented in 2020 with only a gradual strengthening afterwards, leading to above 4°C warming (with respect to pre-industrial levels). Moderate Action (ModAct) explores the impact of implementing the NDCs (pledged mitigation targets) as formulated in 2020 and some further strengthening afterwards, leading to below 4°C, but above 3°C warming. In these two scenarios, there is no stabilization of temperature, meaning that further warming occurs after 2100 (and higher risk) even if stabilization could be eventually achieved. They are referred to as pathways with higher emissions. The warming levels reached along these two scenarios imply physical risk levels that are “Moderate” until 2050 and very high in 2050-2100 (with low levels of adaptation). Noting, that “Moderate” physical can mean for some countries (i.e. SIDS) significant and even hardly absorbable consequences (i.e. reaching hard adaptation limits). Transition risk is not relevant for these scenarios, since a transition is not pursued.

Illustrative Mitigation Pathways (IMP) include two groups of scenarios consistent with warming levels of *1.5°C* and < *2°C*, respectively. The two groups are representative for the IMPs defined in Chapter 3. In these scenarios, warming is stabilized before 2100. The warming levels along these paths imply “Moderate” physical risk until 2050 and “High” risk in 2050-2100 (with low levels of adaptation). Transition risk can arise along these trajectories from changes in expectations of economic actors about which of the scenarios is about to materialise. These changes imply, in turn, possible large variations in the financial valuation of securities and contracts, with losses on the portfolio of institutional investors and households. High policy credibility is key to avoid transition risk, by making expectations consistent early on with the scenario. Low credibility can delay the adjustment of expectations by several years, leading either to a late and sudden adjustment. However, if the policy never becomes credible, this changes the scenario since the initial target is not met.

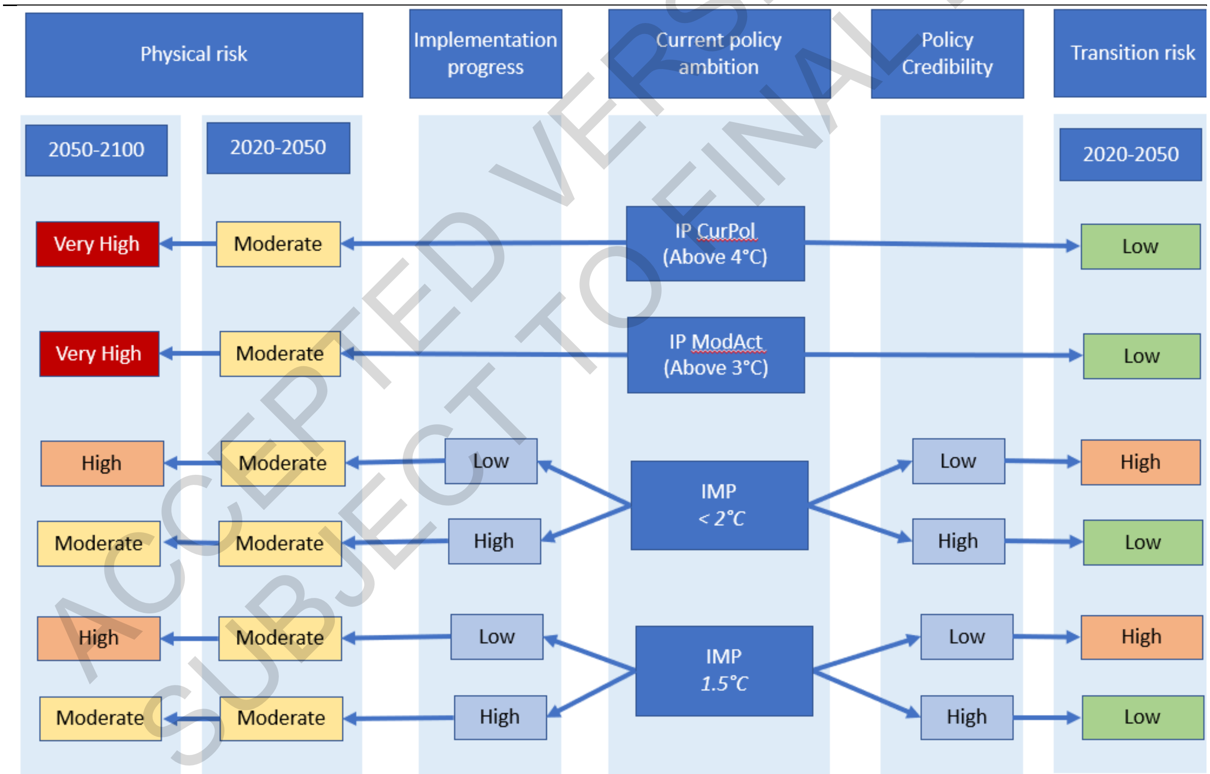


Figure 15.6 Schematic representation of climate scenarios in terms of both physical and transition risk. While the figure does not cover all possible events, it maps out how the combination of stated targets can lead to different paths in terms of risk, depending on implementation progress and policy credibility. IMP *1.5°C* and IMP < *2°C* are representative for IMP-GS (Sens. Neg; Ren), IMP-Neg, IMP-LD; IMP-Ren; IMP-SP. Note that the figure defines "High" progress as higher, but it is important that the physical risk varies by region and country. This means, that “Moderate” physical risk can be significant and even hardly absorbable for some countries.

15.6.2 Enabling environments

The Paris Agreement recognised for the first time the key role of aligning financial flows to climate goals. It further emphasises the importance of making financial flows to consistent with climate actions and SDGs (Zamarioli et al. 2021).This alignment has now to be operated in a specific environment where the scaling-up of climate policies is conditional upon their contribution to post-Covid recovery packages (see 15.2.2, 15.2.3 and Box 15.6). The enabling environments are to be established account for the structural parameters of the underinvestment on long-term assets. The persistent gap between the 'propensity to save' and 'propensity to invest' (Summers 2016) obstructs the scaling up of climate investments, and it results from a short-term bias of economic and financial decision making (Miles 1993; Bushee 2001; Black and Fraser 2002) that returns weighted on short-term risk dominate the investment horizon of financial actors. Overcoming this bias is the objective of an enabling environment apt to *launch of a self-reinforcing circle of trust* between project initiators, industry, institutional investors, the banking system, and governments.

The role of government is crucial for creating an enabling environment for climate (Clark 2018), and governments are critical in the launching and maintenance of this circle of trust by lowering the political, regulatory risks, macroeconomic and business risks (*high confidence*). The issue is not just to progressively enlarge the space of low-carbon investments but replacing one system (fossil fuels energy system) rapidly by another (low-carbon energy system). This is a wave of 'creative destruction' with the public support to developing new markets and new entrepreneurship and finance for green products and technologies in a context which requires strong complementarities between Schumpeterian (technological) and Keynesian (demand-related) policies (Dosi et al. 2017). However, it is challenging to overcome the constraint of public budget under the pressure of competing demands and of creditworthy constraints for countries that do not have an easy access to reserve currencies. It is needed to maximize, both at the national and international levels, the leverage ratio of public funds engaged in blended finance for climate change which is currently very low, especially in developing countries (Attridge and Engen 2019).

Transparency: Policy de-risking measures, such as robust policy design and better transparency, as well as financial de-risking measures, such as green bonds and guarantees, in both domestic and international level, enhance the attractiveness of clean energy investments (Steckel and Jakob 2018) (*high confidence*). Organizations such as the Task Force on Climate-related Financial Disclosures (TCFD) can help increase capital markets' climate financing, including private sector, by providing financial markets with information to price climate-related risks and opportunities (TCFD 2020). However, risk disclosures alone would likely be insufficient (Christophers 2017) *(high confidence)*. Transparency can help but on its own as long as market failures that inhibit the emergence of low-carbon investment initiatives with positive risk-weighted returns (Ameli et al. 2020).

Central banks and climate change. Central banks in all economies will likely have to play a critical role in supporting the financing of fiscal operations particularly in a post-COVID world *(high confidence)*. Instruments and institutional arrangements for better international monetary policy coordination will likely be necessary in the context of growing external debt stress and negative credit rating pressures facing both emerging and low-income countries. Central bankers have started examining the implications of disruptive risks of climate change, as part of their core mandate of managing the stability of the financial system (Chenet et al. 2021). Climate-related risk assessments and disclosure, including central banks' stress testing of climate change risks can be considered as a first step (Rudebusch 2019), although such risk assessments and disclosure may not be enough by themselves to spur increased institutional low-carbon climate finance (Ameli et al. 2020).

Green QE is now being examined as a tool for enabling climate investments (Dafermos et al. 2018) in which central banks could explicitly conduct a program of purchases of low-carbon assets (Aglietta et al. 2015). A green QE program 'would have the benefit of providing large amounts of additional liquidity to companies interested' in green projects (Campiglio et al. 2018) *(medium confidence)*. Green QE would have positive effects for stimulating a low-carbon transition, such as accelerating the development of green bond markets (Hilmi et al. 2021), encouraging investments and banking reserves, and reducing risks of stranded assets, while it might increase the income inequality and financial instability (Monasterolo and Raberto 2017)**.** While the short-term effectiveness would not be substantial, the central bank's purchase of green bonds could have a positive effect on green investment in the long run (Dafermos et al. 2018). However, the use of green QE needs to be cautious on potential issues, such as undermining central bank's independence, affecting central bank's portfolio by including green assets with poor financial risk standards, and potential regulatory capture and rent seeking behaviours (Krogstrup and Oman 2019).

Additional monetary policies and macroprudential financial regulation may facilitate the expected role of carbon pricing on boosting low-carbon investments (D'Orazio and Popoyan 2019) *(medium confidence)*. Commercial banks may not respond to the price signal and allocate credits to low-carbon investments due to the existence of market failure (Campiglio 2016). This could support the productivity of green capital goods and encourage green investments in the short-term, but might cause financial instability by raising non-performing loans ratio of dirty investments and creating green bubbles (Dunz et al. 2021). Financial supervisors needs to implement stricter guidelines to overcome the greenwashing challenges (Caldecott 2020).

Efficient Financial Markets and Financial Regulation. An influential efficient financial markets hypothesis (Fama 1970, 1991, 1997) proceeds from the assumption that in well-developed financial markets, available information at any point of time is already well captured in capital markets with many participants. Despite an increasing challenges to the theory (Sewell 2011), especially by repeated episodes of global financial crashes and crises, and other widely noted anomalies, a weaker form of the efficient markets hypothesis may still apply *(medium confidence)*. It is arguable that accumulating scientific evidence of climate impacts is being accompanied by rising levels of climate finance. Banks and institutional investors are also progressively rebalancing their investment portfolios away from fossil-fuels and towards low-carbon investments (IEA 2019b; Monasterolo and de Angelis 2020)**.** In the meantime, the world runs the risk of sharp adjustments, crises and irreversible 'tipping points' (Lontzek et al. 2015) sufficiently destabilizing climate outcomes. This leads to the policy prescription towards financial regulatory agencies requiring greater and swifter disclosure of information about rising climate risks faced by financial institutions in projects and portfolios and central bank attention to systemic climate risk problems as one possible route of policy action (Carney 2015; Dietz et al. 2016; Zenghelis and Stern 2016; Campiglio et al. 2018). However, disclosure requirements of risks and information in private settings remain mostly voluntary and difficult to implement (Battiston et al. 2017; Monasterolo et al. 2017).

Nevertheless, financial markets are innovating in search of solutions (see 15.6.6). Recognizing and dealing with stranded fossil-fuel assets is also a key area of growing concern that financial institutions are beginning to grapple with. Larger institutions with more patient capital (pensions, insurance) are also increasingly beginning to enter the financing of projects and green bond markets. The case for efficient financial markets in developing countries is worse (Abbasi and Riaz 2016; Hong et al. 2019) because of weaker financial institutions (Hamid et al. 2017), heightened credit rationing behaviour (Bond et al. 2015), and high-risk aversion as most markets are rated as junk, or below/barely investment grade (Hanusch et al. 2016). Other constraints such as limited long-term financial instruments and underdeveloped domestic capital markets, absence of significant domestic bond markets for investments other than sovereign borrowing, and inadequate term and tenor of financing, make the efficient markets thesis practically inapplicable for most developing countries.

Markets, finance and creative destruction. Branches of macro-innovation theory could be grouped into two principal classes (Mercure et al. 2016): 'equilibrium – optimisation' theories that treat innovators as rational perfectly informed agents and reaching equilibrium under market price signals; and the other 'non-equilibrium' theory where market choices are shaped by history and institutional forces and the role of public policy is to intervene in processes, given a historical context, to promote a better outcome or new economic trajectory. The latter suggests that new technologies might not find their way to the market without price or regulatory policies to reduce uncertainty on expected economic returns. A key issue is the perception of risk by investors and financial institutions. The financial system is part of complex policy packages involving multiple instruments (cutting subsidies to fossil fuels, supporting clean energy innovation and diffusion, levelling the institutional playing field and making risks transparent) (Polzin 2017) and the needed big systemic push (Kern and Rogge 2016) requires it takes on the role of 'institutional innovation intermediaries' (Polzin et al. 2016).

As far as climate finance is concerned, public R&D support had large cross-border knowledge spill-overs indicating that openness to trade was important, capacity expansion had positive effects on learning-by-doing on innovation over time, and that feed-in-tariffs (FiTs), in particular, had positive impacts on technology diffusion (Grafström and Lindman 2017) (see box 16.4 for further findings of public R&D on energy technologies). The FiTs program has been associated with rapid increase in early renewables capacity expansion across the world by reducing market risks in financing and stability in project revenues (Menanteau et al. 2003; Jacobsson et al. 2009). (see Chapter 9.9.5). Competitive auctions that the successful bidder with the lowest price or other criteria is selected for government's call for tender are increasing being utilised as an alternative to FITs due their strengths of flexibility, potential for real price discovery, ability to ensure greater certainty in price and quantity and capability to guarantee commitments and transparency (IRENA and CEM 2015).

Outside of RE, scattered but numerous examples are available on the role of innovative public policy to spur and create new markets and technologies (Arent et al. 2017): i) pro-active role of the state in energy transitions (the retirement of all coal-fired power plants in Ontario, Canada between 2007 and 2014 (Kern and Rogge 2016; Sovacool 2016), ii) Too early exit and design problems not considering the market acceptability and financing issues (e.g., energy-efficient retrofitting in housing in UK (Rosenow and Eyre 2016), low or negative returns in reality versus engineering estimates in weatherisation programs in US (Fowlie et al. 2018)), iii) Energy performance contracting for sharing the business risks and profits and improving energy efficiency (Energy service company (Bertoldi and Boza-Kiss 2017; Qin et al. 2017) and Utility Energy Service Contracts in the US (Clark 2018)).

Crowding out. Literature has discussed the risks of a low effectiveness of public interventions and of a crowding out effects of climate targeted public support to other innovation sectors (Buchner et al. 2013). However, much academic literature suggests no strong evidence of crowding out. (Deleidi et al. 2020). Examining the effect of public investment on private investment into renewables in 17 countries over 2004-2014, showed that the concept of crowding out or in does not apply well to sectoral studies and found that public investments positively support private investments in general.

Support of climate action via carbon pricing, taxes, and emission trading systems. Literature and evidence suggest that futures markets regarding climate are incomplete because they do not price in externalities (Scholtens 2017). As a result, low-carbon investments do not take place to socially and economically optimal levels, and the correct market signals would involve setting carbon prices high enough or equivalent trading in reduced carbon emissions by regulatory action to induce sufficient and faster shift towards low-carbon investments (Aghion et al. 2016) *(high confidence)*. Nonetheless, durable carbon pricing in economic and political systems must be implemented and approached combining related elements to both price and quantity (Grubb 2014).

The introduction of fiscal measures, such as carbon tax, or market-based pricing, such as emission trading scheme, to reflect carbon pricing have benefits and drawbacks that policymakers need to consider both country-specific conditions and policy characteristics. Carbon tax can be a simpler and easier way to implement carbon pricing, especially in developing countries, because countries can utilise the existing fiscal tools and do not need a concrete enabling conditions as market-based frameworks *(high confidence)*. The reallocation of revenues from carbon taxes can be used for low-carbon investments, supporting poorer sections of society and fostering technological change (High-Level Commission on Carbon Prices 2017). In combination with other policies, such as subsidies, public R&Ds on resource-saving technologies, properly designed carbon taxes can facilitate the shift towards low-carbon, resource-efficient investments (Bovari et al. 2018; Naqvi and Stockhammer 2018; Dunz et al. 2021). (see Chapter 9.9.3 for carbon taxes). The effectiveness of carbon pricing has been supported by various evidences. EU ETS has been cut the emissions by 42.8% in the main sectors covered (European Commission 2021a), and China had achieved emissions reductions and energy conservations through its pilot ETS between 2013 and 2015 (Hu et al. 2020; Zhang et al. 2019). Institutional learning, administrative prudence, appropriate carbon revenue management and stakeholder engagement are key ingredients for successful ETS regimes (Narassimhan et al. 2018).

The presence of carbon prices can promote low-carbon technologies and investments (Best and Burke 2018), and price signals, including carbon taxation, provide powerful and efficient incentives for households and firms to reduce CO_2 emissions (IMF 2019). The expansion of carbon prices is dependent on country-specific fiscal and social policies to hedge against regressive impacts on welfare, competitiveness, and employment (Michaelowa et al. 2018). Such impacts need to be offset using the proceeds of carbon taxes or auctioned emission allowances to reduce distortive taxation (Bovenberg and de Mooij 1994; Goulder 1995; de Mooij 2000; Chiroleu-Assouline and Fodha 2014) and fund compensating measures for the population sections that are most adversely impacted (Combet et al. 2010; Jaccard 2012; Klenert et al. 2018). This is more difficult for developing countries with a large share of energy-intensive activities, fossil fuels exporting countries and countries which have lower potential to mitigate impacts due to lower wages or existing taxes (Lefèvre et al. 2018).

Non-carbon price instruments, such as market-oriented regulation, public programs involving low carbon infrastructure, may be preferential in developing countries where market and regulatory failure and political economy constraints are more prevalent (Finon 2019). . While the carbon pricing was suggested by many economists and researchers (Nordhaus 2015; Pahle et al. 2018), overcoming the political and regulatory barriers would be necessary for the further implementation of an effective carbon pricing nationally and internationally. Without the strong political support, the effectiveness of carbon pricing would be limited to least-cost movements (Meckling et al. 2015).

Role of domestic financing sources. Efforts to address climate change can be scaled up through the mobilisation of domestic funds (Fonta et al. 2018). Publicly organised and supported low-carbon infrastructures through resurrected national development banks may be justified (Mazzucato and Penna 2016). It is important to efficiently allocate the public financing, and SIBs can take up key roles (i) to provide capital to assist with overcoming financial barriers, (ii) to signal and direct investments towards green projects, and (iii) to attract the private investors by taking up a de-risking role. Also, they can become a first mover by investing in new and innovative technologies or business models (Geddes et al. 2018). State owned enterprises (SOEs) can also have an overall positive effect on renewables investments, outweighing any effect of crowding out private competitors (Prag et al. 2018). Green investment banks (GIB) can assist in the green transition by developing valuable expertise in implementing effective public interventions to overcome investment barriers and mobilise private investment in infrastructure (OECD 2015c). De-risking measures may reduce investment risks, but lacking research and data availability hinders designing such measures (Dietz et al. 2016). Local governments efforts to de-risk by securitization might have negative effects by narrowing the scope for a green developmental state and encouraging privatisation of public services (Gabor 2019).

The potential role of coordinated multilateral initiatives. There is a growing awareness of the low leverage ratio of public to private capital in climate blended finance (Blended Finance Taskforce 2018b) and of a glass ceiling', caused by a mix of agencies' inertia and perceived loss of control over the use of funds, on the use of public guarantees by MDBs to increase it (Gropp et al. 2014; Schiff and Dithrich 2017; Lee et al. 2018) (*high confidence*). Many proposals have emerged for multilateral guarantee funds: Green Infrastructure Funds (de Gouvello and Zelenko 2010; Studart and Gallagher 2015), Multilateral Investment Guarantee Agency (Enhanced Green MIGA) (Déau and Touati 2018), guarantee funds to bridge the infrastructure investment gap (Arezki et al. 2016), and multi-sovereign guarantee mechanisms (Dasgupta et al. 2019). The obstacle of limited fiscal space for economic recovery and climate actions in low-income and some emerging economies can be overcome only in a multilateral setting. Several multilateral actions are being envisaged: G20's suspension of official bilateral debt payments, IMF's adoption of new SDRs allocation (IMF 2021b). However, any form of unconventional debt relief will generate development and climate benefits only if they credibly target bridging the countries' infrastructure gap with low-carbon climate-resilient options.

An interest of multilateral setting is a credibility-enhancing effect provided by reciprocal gains for both the donor and the host country. Guarantor countries can compensate the public cost of their commitments with the fiscal revenues of induced exports. As to the host countries, they would benefit from new capital inflows and the grant equivalents of reduced debt service which might potentially go far beyond 100 billion USD yr^{-1} (Hourcade et al. 2021a). A second interest would be to support a learning process about agreed-upon assessment and monitoring methods using clear metrics. Developing standardized and science-based assessment methods at low transaction costs is essential to strengthen the credibility of green investments and the emergence a pipeline of high-quality bankable projects which can be capitalized in the form of credible assets and supported with transparent and credible domestic spending. Multi-sovereign guarantees would provide a quality backing to developing countries and allow for expanding developing countries' access to capital markets at a lower cost and longer maturities, overcome the Basel III's liquidity impediment and the EU's Solvency II directive on liquidity (Blended Finance Taskforce 2018b), accelerate the recognition of climate assets by investors seeking safe investments havens (Hourcade et al. 2021b). It would also strengthen the efficacy of climate disclosure through high grades climate assets and minimize the risks of 'greening' of the portfolios by investing in 'carbon neutral' activities and not in low carbon infrastructures. Finally, it would free up grant capacities for SDGs and adaptation that mostly involve non-marketable activities by crowding in private investments for marketable mitigation activities.

***** START BOX 15.5 ******

Box 15.5 The role of enabling environments for decreasing-economic cost of renewable energy

A widely used indicator for the relative attractiveness of renewable energy but also development of price levels is the levelized cost of energy (LCOE). It is applied by a wide range of public and private stakeholders when tracking progress with regard to cost degression (Aldersey-Williams and Rubert 2019). LCOE calculation methodologies vary but in principle, consider project-level costs only (NEA 1989). Besides other weaknesses, the LCOE concept usually does not consider societal costs resulting from de-risking instruments and/or other public interventions/support and therefore caution has to be applied when using the LCOE as the indicator sole of the success of enabling environments. The yearly IRENA mapping on renewable energy auction results demonstrates the extremely broad ranges of LCOEs (equal to the agreed tariffs) for renewable energy which can be observed (IRENA 2019a). For example, in 2018, solar PV LCOEs for utility-scale projects came in between 0.04 USD/kWh and 0.35 USD/kWh with a global weighted average of 0.085 USD/kWh. However, comparative analysis taking into account societal costs are hardly available driven by challenges in the context of the quantification of public support.

The GET FiT concept argued that the mitigation of political and regulatory risk by sovereign and international guarantees is cost-efficient in developing countries illustrating the estimated impact of such risk-mitigation instruments on equity and debt financing costs and consequently required feed-in tariff levels (Deutsche Bank Climate Change Advisors 2011). The impact of financing costs on cost of renewable energy generation is well researched with significant differences across countries and technologies being observed with major drivers being the regulatory framework as well as the availability and type of public support instruments (Geddes et al. 2018; Steffen 2019). With a focus on developing countries and based on a case study in Thailand, (Huenteler et al. 2016) demonstrate the significant effect of regulatory environments but also local learning and skilled workforce on cost of renewables. The effect of those exceeds the one of global technology learning curves.

(Egli et al. 2018) identify macroeconomic conditions (general interest rate) and experience effects within the renewable energy finance industry as key drivers in developed countries with a stable regulatory environment contributing 5% (PV) and 24% (wind) to the observed reductions in LCOEs in the German market with a relatively stable regulatory environment. They conclude that 'extant studies may overestimate technological learning and that increases in the general interest rate may increase renewable energies' LCOEs, casting doubt on the efficacy of plans to phase out policy support' (Egli et al. 2018). A rising general interest rate level could heavily impact LCOEs – for Germany, a rise of interest rates to pre-financial crisis levels in five years could increase LCOEs of solar and wind by 11–25% respectively (Schmidt et al. 2019).

***** END BOX 15.5 ******

15.6.2.1 The public-private and mobilization narrative and current initiatives

Financing by development finance institutions and development banks aims to address market failures and barriers related to limited access to capital as well as provides direct and indirect subsidisation by accepting higher risk, longer loan tenors and/or lower pricing. Many development and climate projects in developing and emerging countries have traditionally been supported with concessional loans by DFIs/IFIs. With an increasing number of sectors becoming viable and increasing complaints of private sector players with regard to crowding-out (Bahal et al. 2018), a stronger separation and crowding-in of commercial financing at the project/asset level is targeted. MDBs and IFIs were crucial for opening and growth in the early years of the green bonds, which represent a substantial share of issuances (CBI 2019a). Drivers of an efficient private sector involvement are stronger incentives to have projects delivered on time and in budget as well as market competition (Hodge et al. 2018). It remains key that the private sector mobilization goes hand in hand with institutional capacity building as well as strong sectoral development in the host country as a strong, knowledgeable public partner with the ability to manage the private sector is a dominating success factor for public-private cooperation (WEF 2013; Yescombe 2017; Hodge et al. 2018).

Limited research is available on the efficiency of mobilization of the private sector at the various levels and/or the theory of change attached to the different approaches as applied in classical PPP. Also, transparency on current flows and private involvement at the various levels is limited with no differentiation being made in reporting (e.g., GCF co-financing reporting). Limited prioritization and agreement on prioritization on sectors and/or project categories being ready and/or preferred for direct private sector involvement which might become a challenge in the coming years (Sudmant et al. 2017a,b) *(high confidence)*.

Public guarantees have been increasingly proposed to expand climate finance, especially from the private sector, with scarce public finance, by reducing the risk premium of the low-carbon investment opportunities (de Gouvello and Zelenko 2010; Emin et al. 2014; Studart and Gallagher 2015; Schiff and Dithrich 2017; Lee et al. 2018; Steckel and Jakob 2018). They have the advantage of a broad coverage including the 'macro' country risks and to tackle the up-front risks, during the preparation, bidding and development phases of the project life cycle that deter projects initiators especially for capital intensive and immature options. Insurances are also powerful de-risking instruments (Déau and Touati 2018) but they entitle the issuer to review claims concerning events and cannot cope with up-front costs. Contractual arrangements like power purchase agreements are powerful instruments to reduce market risks through a guaranteed price but they weigh on public budgets. Risk-sharing that bring together public agencies, firms, local authorities, private corporates, professional cooperatives, and institutional financiers can reduce costs (UNEP 2011), and support the deployment of innovative business models (Déau and Touati 2018). Combined with emission taxes they can contribute to reducing credit rationing of immature and risky low-carbon technologies (Haas and Kempa 2020).

15.6.3 Considerations on availability and effectiveness of public sector funding

The gap analysis as well as other considerations presented in this chapter illustrate the critical role of increased volumes and efficient allocation of public finance to reach the long-term global goals, both nationally and internationally.

Higher public spending levels driven by the impacts of COVID-19 and related recovery packages. Higher levels of public funding represent a massive chance but also a substantial risk. A missing alignment of public funding and investment activity with the Paris Agreement (and sustainable development goals) would result in significant carbon lock-ins, stranded assets and thus increase transition risks and ultimately economic costs of the transition *(high confidence)*. Using IMF data for stimulus packages, (Andrijevic et al. 2020) estimated that COVID-19 related fiscal expenditure had surpassed 12 trillion USD by October 2020 (80% in OECD countries), a third of which being spent in liquidity support and healthcare. Total stimulus pledged to date are ten times higher than low-Paris-consistent carbon investment needs from 2020–2024 (Andrijevic et al. 2020; Vivid Economics 2020). Overall, stimulus packages launched include 3.5 trillion USD to sectors directly affecting future emissions, with overall fossil-fuel investment flows outweighing low-carbon technology investment (Vivid Economics 2020).

Lessons from the global financial crises show that although deep economic crises create a sharp short-term emission drop, and green stimulus is argued to be the ideal response to tackle both the economic and the climate crises at once, disparities between regional strategies hinder the low carbon transition *(high confidence)*. Indeed, inconsistent policies within countries can also counterbalance emission reductions from green stimulus, as well as a lack of transparency and green spending pledged not materialised (Jaeger et al. 2020). Also, aggressive monetary policy as a response to the global financial crisis, including quantitative easing that did not target low-carbon sectors, has been heavily criticised (Jaeger et al. 2020) . The COVID-19 crisis recovery, in contrast, benefits from developments which have taken place since, such as an emerging climate-risk awareness from the financial sector, reflected in the call from the Coalition of Finance Ministers for Climate Action (Coalition of Finance Ministers for Climate Action 2020), which reunites 50 countries' finance ministers, for a climate-resilient recovery.

The steep decrease in renewable electricity costs since 2010 also represents a relevant driver for a low carbon recovery (Jaeger et al. 2020). Many more sectors are starting to show similar opportunities for rapid growth with supportive public spending such as low-carbon transport and buildings (IEA 2020d). Expectations that the package will increase economic activity rely on the assumption that increased credit will have a positive effect on demand, the so-called demand-led policy (Mercure et al. 2019). Boosting investment should propel job creation, increasing household income and therefore demand across economic sectors *(high confidence)*. A similar plan has also been proposed by the US administration and the European Union through the Next Generation EU (European Council 2020).

Nevertheless, three uncertainties remain. First, only those countries and regions with highest credit-ratings (AAA or AA) with access to deep financial markets and excess savings will be able to mount such counter-cyclical climate investment paths, typically high-income developed economies *(high confidence)*. In more debt constrained developing countries have and lower access to global savings pool countries because of higher risk perceptions and lower credit ratings (BBB or less), exacerbated by COVID-19 and already leading to credit downgrades and defaults (Kose et al. 2020) and have long tended to be fiscally pro-cyclical (Mcmanus and Ozkan 2015). These include the general class of virtually all major emerging and especially low-income developing countries, to which such demand-stimulating counter-cyclical climate consistent borrowing path is likely To access such funds, these countries would need globally coordinated fiscal policy and explicit supporting cross-border instruments, such as sovereign guarantees, strengthening local capital markets and boosting the 100 billion USD annual climate finance commitment (Dasgupta et al. 2019).

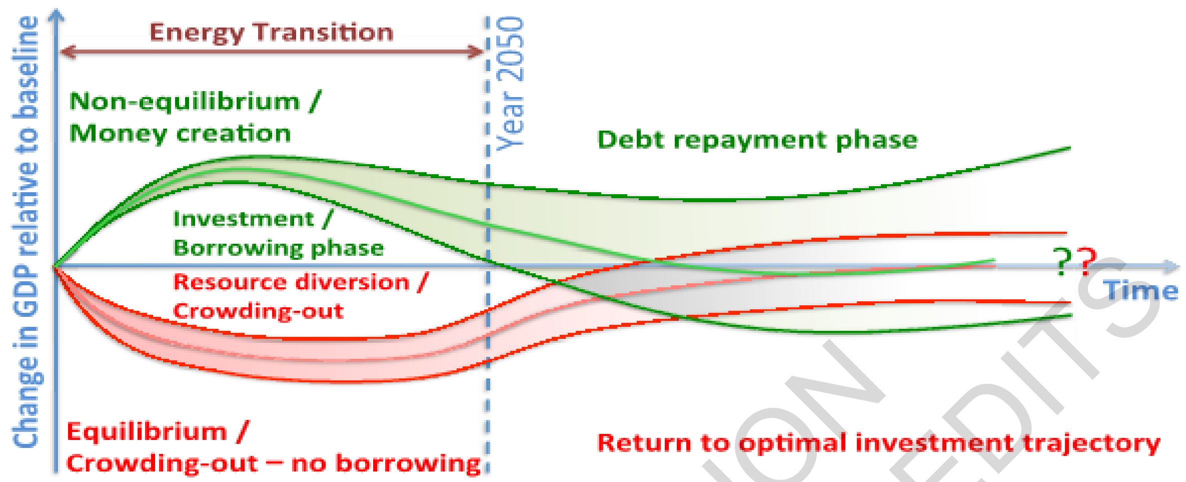
Second, a strong assumption is that voters will be politically supportive of extended and increased fiscal deficit spending on climate on top of COVID-19 related emergency spending and governments will overcome treasury biases towards fiscal conservatism (to preserve credit ratings). However, evidence strongly suggests that voters (and credit rating agencies) tend to be fiscally conservative (Peltzman 1992; Lowry et al. 1998; Alesina et al. 2011; Borge and Hopland 2020) especially where expenditures involve higher taxes in the future and do not identifiably flow back to their local bases (the 'public good' problem) *(high confidence)*. Such mistrust has been a reason for abortive return to fiscal austerity often in the past (most recently during global financial crisis) and may benefit for political support by consistently reframing the climate expenditures in terms of job creation benefits (Bougrine 2012), effectiveness of least-cost fiscal spending on climate for reviving private activity, and the avoidance of catastrophic losses (Huebscher et, al. 2020) from higher carbon emissions. A new understanding of debt sustainability including negative implications of deferred climate investments on future GDP has not yet been mainstreamed (see more on the debt sustainability discussion below (e.g. (Buhr et al. 2018; Fresnillo 2020)**)**. In addition, implications on the availability of international public finance flows are not yet clear since current additional funding prioritises urgent healthcare support rather than an increase of predictable mid/long-term financial support. Heavy investment needs for recovery packages in developed countries on the one hand and their international climate finance commitments might be perceived to compete for available "perceived as appropriate" budgets.

***** START BOX 15.6 ******

Box 15.6 Macroeconomics and finance of a Post-COVID-19 green stimulus economic recovery path

Financial history suggests that capital markets may be willing to accommodate extended public borrowing for transient spending spikes (Barro 1987) when macroeconomic conditions suggest excess savings relative to private investment opportunities (Summers 2015) and when public spending is seen as timely, effective and productive, with governments able to repay when conditions improve as economic crisis conditions abate *(high confidence)*. A surge in global climate mitigation spending in the post-pandemic recovery may be an important opportunity, which global capital markets are signalling (Global Investor Statement 2019). The standard 'neo-classical' macroeconomic model is often used in integrated energy-economy-climate assessments (Balint et al. 2016; Nordhaus 2018). This class of Computable General Equilibrium (CGE) models, however, have a limited treatment of the financial sector and assume that all resources and factors of production are fully employed, there is no idle capacity and no inter-temporal financial intermediation (Pollitt and Mercure 2018b). Investment cannot assume larger values than the sum of previously determined savings, as a fixed proportion of income. Such constraint, as stressed by (Mercure et al. 2019), implies that investment in low-carbon infrastructure, under the equilibrium assumptions, necessarily creates a (neo-Ricardian) crowding-out effect that contracts the remaining sectors. The graphic below shows the implications (in the red-shaded part of Figure 1).

Post-Keynesian demand-side macroeconomic models, with financial sectors and supply-side effects, in contrast, allow for the reality of non-equilibrium situations: persistent short to medium term underemployed economy-wide resources and excess savings over investment because of unexpected shocks, such as COVID-19. In these settings, economic stimulus packages allow a faster recovery with demand-led effects: "Economic multipliers are near zero when the economy operates near capacity. In contrast, during crises such as the GFC, economic multipliers can be high (Blanchard and Leigh 2013; Hepburn et al. 2020b). The expected results are opposite to the standard supply-led equilibrium models as a response to investment stimulus (the green-shaded part of Box 15.6, Figure 1), as intended by 'green-stimulus' packages such as proposed by the EU (Balint et al. 2016; Mercure et al. 2019).



Box 15.6, Figure 1 Two Worlds – Energy transition outcomes under alternative model assumptions (Keynesian vs General Equilibrium) Source: Mercure et al. (2019)

Even if demand-led models work better in depressions, the question nevertheless is whether the additional public borrowing for such 'green stimulus' can be undertaken by market borrowings given already high public debt levels and recovered in the future from taxes as the economy revives. The results of recent macroeconomic modelling work (Liu et al. 2021) represented by 10 major countries/regions suggests answers. It uses a non-standard macroeconomic framework, with Keynesian features such as financial and labour market rigidities and fiscal and monetary rules (McKibbin and Wilcoxen 2013). First, a global 'green stimulus' of about an average of 0.8% of GDP annually in additional fiscal spending between 2020-30 would be required to accelerate the emissions reduction path required for a 1.5°C transition. Second, such a stimulus would also accelerate the global recovery by boosting GDP growth rates by about 0.6% annually during the critical post-COVID period. Third, the optimal tax policy would be to backload the carbon taxes to later in the macroeconomic cycle, both because this would avoid dampening near-term growth while pre-announced carbon tax plans would incentivise long-term private energy transition investment decisions today and provide neutral borrowing. This macroeconomic modelling path thus replicates the 'green stimulus' impacts expected in theory (Box 15.6, Figure 1). There are also some other additional features of the modelled proposal: (a) fiscal stimulus—needed in the aftermath of the pandemic—can be an opportunity to boost green and resilient public infrastructure; (b) green research and development 'subsidies' are feasible to boost technological innovations; and (c) income transfers to lower income groups are necessary to offset negative impacts of rising carbon taxes.

Substantial effects of the COVID-19 pandemic, which is relatively unique on its public health impacts when combined with the consequences of deep economy-wide shocks (economic downturn, public finances, and debt), are expected to last for decades even in the absence of no significant future recurrence. A scenario where the pandemic recurs mildly every year for the foreseeable future further hinders GDP and investment recovery, where growth is unlikely to rebound to previous trajectories, even within OECD economies (McKibbin and Vines 2020) and with worse effects in developing regions. History is strongly supportive: studies on the longevity of pandemics' impacts indicate significant macroeconomic effects persisting for decades, with depressed real rates of return, increased precautionary savings (Jordà et al. 2020), unemployment (Rodríguez-Caballero and Vera-Valdés 2020) and social unrest (Barrett and Chen 2021). The direct effect on emissions is likely to be a small reduction from previous trajectories, but the longer-lasting impacts are more on the macroeconomic-finance side. Pandemic responses have increased sovereign debt across countries in all income bands (IMF 2021e). However, its sharp increase in most developing economies and regions has caused debt distress (Bulow et al. 2021), widening the gap in developing countries' access to capital (Hourcade et al. 2021b). While strong coordinated international recovery strategies with climate-compatible economic stimulus is justified (Pollitt et al. 2021; Barbier 2020; Barbier and Burgess 2020; Le Quéré et al. 2021; IMF 2020c), national recovery packages announced do not show substantial alignment with climate goals (Shan et al. 2021; Rochedo et al. 2021; D'Orazio 2021; Hourcade et al. 2021b). Contradictory post-COVID-19 investments in fossil fuel-based infrastructure may create new carbon lock-ins, which would either hinder climate targets or create stranded assets (Hepburn et al. 2020a; Le Quéré et al. 2021; Shan et al. 2021), whilst deepening global inequalities (Hourcade et al. 2021b).

***** END BOX 15.6 ******

Considerations on global debt levels and debt sustainability as well as implications for climate finance. The Paris Agreement marked the consensus of the international community that a temperature increase of well below 2 degrees needs to be achieved and the SR1.5 has demonstrated the economic viability of 1.5°C. However, in terms of increase of supply of, in particular, public finance, often the debate is still driven by the question on affordability, considerations around financial debt sustainability and budgetary constraints against the background of macroeconomic headwinds – even more in the (post-)COVID-19 world *(high confidence)*. The level of climate alignment of debt is hardly considered in debt related regulation and/or debt sustainability agreements like the Maastricht Treaty ceilings (3% of GDP government deficit and 60% of GDP (gross) government debt) not considering economic costs of deferred climate action as well as economic benefits of the transformation.

Robust studies on the economic costs and benefits in the short- to long-term of reaching the LTGG exist for only few countries and/or regions, primarily in the developed world (e.g. (BCG 2018; McKinsey 2020a) *(high confidence)*. With many studies underpinning the strong economic rationale for high investments in the short-term e.g.(McKinsey 2020a) [More studies to be added], regional differences are significant highlighting the need for extensive cooperation and solidarity initiatives.

For many developing countries, the focus of debt sustainability discussions is on the negative effect of climate change on the future GDP and the uncertainty with regard to short-term effects of climate change and their economic implications *(high confidence)*. With long-term economic impacts of climate change being in the focus of the modelling community, the volatility of GDP in the short term driven by shocks is more difficult to analyse and requires country-specific deep-dives. IPCC scenario data is often not sufficient to perform such analysis with additional assumptions being needed (Acevedo 2016) [Check for cross-referencing to WG1]. For debt sustainability analysis, these more short-term impacts are, however, a crucial driver with transparency being limited to the significance of climate-related revision of estimates. The latter might result in a continued overestimation of future GDP as happened in the past increasing the vulnerability of highly indebted countries (Guzman 2016; Mallucci 2020). While climate change considerations have already impacted country ratings and debt sustainability assessments (and financing costs), it is unclear whether current GDP forecasts are realistic. The review of the IMF debt sustainability framework leads to a stronger focus on vulnerability rather than only income thresholds when deciding upon eligibility for debt relief and/or concessional resources (Mitchell 2015), which could become a mitigation factor for the challenge described before.

Debt levels globally but particularly in developing and vulnerable countries have significantly increased over the past years with current and expected climate change impacts further burdening debt sustainability *(high confidence)*. For low and middle income countries, 2018 marked a new peak of debt levels amounting to 51% of GDP; between 2010 and 2018, external debt payments as a percentage of government budget grew by 83% in low- and middle-income countries, from an average of 6.71% in 2010 to an average of 12.56% in 2018 (Eurodad 2020). COVID-19 has further reduced the fiscal space of many developing governments and/or increased the likelihood of debt stress. With many vulnerable countries already being burdened with higher financing costs, this limited fiscal space further shrinks their ability to actively steer the required transformation (Buhr et al. 2018). Limited progress in increasing debt transparency remains another burden (see Section 15.6.7).

Considering the need for responses to both, short-term liquidity issues and long-term fiscal space, current G20/IMF/World Bank debt service suspension initiatives are focused the liquidity issue rather than underlying problems of more structural nature of many low-income (Fresnillo 2020). In order to ensure fiscal space for climate action in the coming decade a mix between debt relief, deferrals of liabilities, extended debt levels and sustainable lending practices including new solidarity structures need to be considered in addition to higher levels of bilateral and multilateral lending to reduce dependency on capital markets and to bridge the availability of sustainably structured loans for highly vulnerable and indebted countries. More standardised debt-for-climate swaps, a higher share of GDP linked bonds or structures ensuring (partial) debt cancellation in case countries are hit by physical climate change impacts/shocks appear possible. The "hurricane" clause introduced by Grenada, or wider natural disaster clauses provide issuers with an option to defer payments of interest and principal in the event of a qualifying natural disaster and can reduce short-term debt stress (UN AAAA Art. 102) (UN 2015a). A mainstreaming of such clauses has been pushed by various international institutions. The collective action clause might be a good example of a loan/debt term which became market standard. Definition of triggers is likely the most complex challenge in this context.

The use of debt-for-nature and debt-for-climate-swaps is still very limited and not mainstreamed but offers significant potential if used correctly *(high confidence)*.

An increasing number of debt-for-climate/nature swaps have been seen in recent years applied primarily in international climate cooperation and in bilateral contexts, however, not (yet) to an extent addressing severe and acute debt crises (Essers et al. 2021; Volz et al. 2021) offering significant potential if used correctly (Warland and Michaelowa 2015). Significant lead times, needs-based structuring, transparency with regard to the additionality of financed climate action, uncertainty with regard to own resource constraints and ODA accountability remain as barrier for a massive scale-up needed to make transactions relevant (Mitchell 2015; Fuller et al. 2018; Essers et al. 2021). At the same time, the limitation of the use of debt-based instruments as a response to climate-related disasters and counter-cyclical loans might be necessary (Griffith-Jones and Tyson 2010).

Ensuring efficient debt restructuring and debt relief in events of extreme shocks and imminent over-indebtedness and sovereign debt default are further crucial elements with a joint responsibility of debtors and creditors (UN 2015a) 2015). In this context, the Commonwealth Secretariat flagged that the diversification of the lender portfolio made debt restructuring more difficult with more and more heterogeneous stakeholders being involved (Mitchell 2015) and the UN AAAA raising concerns about non-cooperative creditors and disruption of timely completion of debt restructuring (UN 2015a) 2015). This is a side effect of a stronger use of capital markets, which need to be carefully considered in the context of sovereign bond issuances (see also 15.6.7).

Stranded assets. The debate around stranded assets focuses strongly on the loss of value to financial assets for investors (see Section 15.6.1, para. on the assessment of transition risk and carbon stranded assets), however, stranded asset and resources in the context of the transition towards a low emission economy "are expected to become a major economic burden for states and hence the tax payers" (EEAC 2016) *(high confidence)*. Assets include not only financial assets but also infrastructure, equipment, contracts, know-how, jobs as well as stranded resources (Bos and Gupta 2019)**.** Besides financial investors and fiscal budgets, consumers remain vulnerable to stranded investments. Against the background of the frequent simultaneousness of losses occurring for financial investors on the one hand

and negative employment effects as well as regional development and fiscal effects, negotiations about compensations and public support to compensate for negative effects of phasing out of polluting technologies often remain interlinked and compensation mechanisms and related redistribution effects untransparent.

Recent phase-out deals tend to aim for a (partial or full) compensation rather than no relief for losses. In contrast to the line of argument in the tobacco industry, the backward looking approach and a resulting obligation of compensation by investors in polluting assets can be observed rarely with the forward looking approach of compensations by future winners for current losers dominating – despite the high level of awareness about carbon externalities and resulting climate change impacts among polluters for many years (van der Ploeg and Rezai 2020). In particular, transactions in the energy sector show a high level of investor protection also against much needed climate action which is also well illustrated by share of claims settled in favour of foreign investors under the Energy Charter Treaty and investor-state dispute settlement (Bos and Gupta 2019)**.**

Late government action can delay action and consequently strengthen the magnitude of action needed at a later point in time with implications on employment and economic development in impacted regions requiring higher level of fiscal burden *(high confidence)*. This has also be considered in the context of global climate cooperation with prolonged support for polluting infrastructure resulting heavy lock-in effects and higher economic costs in the long-run (Bos and Gupta 2019)**.** Despite a significant share of fossil resources which need to become stranded in developing countries to reach the LTGG, REDD+ remains a singular example for international financial cooperation in the context of compensation for stranded resources. [Potentially add sentence on ADB buyout facility]

15.6.4 Climate-risk pooling and insurance approaches

Since 2000, the world has been experiencing significant increase in economic losses and damages from natural disasters and weather perils such as tropical cyclones, earthquake, flooding and drought. Total global estimate of damage is about 4,210 billion USD, 2000-2018 (Aon Benfield UCL Hazard Research Centre 2019). The largest portion of this is attributed to tropical cyclones (1,253 billion USD), followed by flooding (914 billion USD), earthquakes (757 billion USD) and drought (approximately 372 billion USD, or about 20 billion USD yr^{-1} losses) (Aon Benfield UCL Hazard Research Centre 2019). In the period 2017–2018, natural catastrophe losses total approximately 219 billion USD (Bevere 2019). According to the National Oceanic and Atmospheric Administration, 14 weather and climate disasters cost 91 billion USD in 2018 (NOAA NCEI 2019). The European Environment Agency reports that 'disasters caused by weather and climate-related extremes accounted for some 83% of the monetary losses over the period 1980–2017 for EU Member States (EU-28) and that weather and climate-related losses amounted to 426 billion EUR. For the EEA member countries (EEA-33), the 'total reported economic losses caused by weather and climate-related extremes' over the same period amounted to approximately 453 billion EUR (EEA 2019), (EEA 2019). Asia Pacific and Oceania has been particularly impacted by typhoon and flooding (China, India, the Philippines) resulting in economic losses of 58 billion USD, 2000–2017, and combination of flooding typhoon and drought totalling 89 billion USD in 2018 (inclusive of loss by private insurers and government sponsored programs (Aon Benfield UCL Hazard Research Centre 2019). Based on past historical analysis, a region such as the Caribbean, which has experienced climate-related losses equal to 1% of GDP each year since 1960 is expected to have significant increases in such losses in the future leading to possible upwards of 8% of projected GDP in 2080 (Commonwealth Secretariat 2016). Similarly, Latin America countries, such as Argentina, El Salvador and Guatemala, experienced severe losses in agriculture totalling about 6 billion USD due to drought in 2018 (Aon Benfield UCL Hazard Research Centre 2019). In the African region, where climate change is projected to get significantly warmer, continuing severe drought in parts of East Africa Tropical and Cyclone Idai, had devastating economic impacts. Mozambique, Zimbabwe and Malawi (WMO 2019). According to Munich Re, loss from about 100 significant events in 2018 for Africa are estimated at 1.4 billion USD (Munich Re 2019).

While there are questions about the sufficiency of insurance products to address the losses and damages of climate-related disasters, insurance can help to cover immediate needs directly, provide rapid response and transfer financial risk in times of extreme crisis (GIZ 2015; Lucas 2015; Schoenmaker and Zachmann 2015; Hermann et al. 2016; Wolfrom and Yokoi-Arai 2016; Kreft and Schäfer 2017; UNESCAP 2017; Matias et al. 2018; UNECA 2018; Broberg and Hovani-Bue 2019; EEA 2019; Martinez-diaz et al. 2019) *(high confidence)*. Commercial insurability is heavily driven by the predictability of losses and the resulting ability to calculate insurance premium levels properly. Climate change has become a major factor of increasing uncertainty. The previously strong reliance on historic data in calculation of premium levels may be but a starting point given the likely need for upward adjustment due to climate change and potential consequential economic damage. Different risk perceptions between policyholders and insurers will create contrary assessments on premium levels and consequently underinsurance. (McKinsey 2020b) also stresses the systemic effect of climate change on insurers' business models and resulting availability of appropriate insurance products.

The conventional approach to such protective or hedging position has been indemnity and other classical insurance micro, meso and macro level schemes (Hermann et al. 2016). These include micro insurance schemes such as index insurance and weather derivative approaches that cover individual's specific needs such as coverage for farm crops. Meso level insurance schemes, which primarily benefit intermediary institutions, such as NGOs, credit union, financial institutions and farmer credit entities, seek to reduce losses caused by credit default thereby 'enhancing investment potential', whereas macro-level insurance schemes 'allow both insured and uninsured individuals to be compensated for damages caused by extreme weather events' (Hermann et al. 2016). These macro-level insurance include catastrophe bonds and weather derivatives etc. that transfer risk to capital market (Hermann et al. 2016). Over the last decades, there have been a trend towards weather-index insurance and other parametric insurance products based on predefined pay-out risk pooling instrument. It has gained favour with governments in developing regions such as Africa, the Caribbean and the Pacific because it provides certainty and predictability about funding - financial preparedness - for emergency actions and initial reconstruction and reduces moral hazard. This 'financial resilience' is also increasingly appealing to the business sector, particularly MSMEs, in developing countries (MEFIN Network and GI RFPI Asia 2016; Woods 2016; Schaer and Kuruppu 2018).

To date, sovereign parametric climate risk pooling as a way of managing climate risk does not seem to have much traction in developed countries and does not appear to be attractive to actors in the G-20 countries. No G-20 members are yet party to any climate risk pooling initiative (Kreft and Schäfer 2017). However, international bilateral donors such as the USAID and the Foreign, Commonwealth & Development Office (FCDO, formerly DfID), and the multilateral development banks, are all, to different extent, supporters of the various climate risk pooling initiatives now operational in developing countries.

As noted also in IPCC AR5, risk sharing and risk transfer strategies provide 'pre-disaster financing arrangements that shift economic risk from one party to another' (IPCC 2012). Risk pooling among countries and regions is relatively advantageous when compared to conventional insurance because of the effective subsidizing of 'affected regions' using revenues from unaffected regions which involve pooling among a large subset of countries (Lucas 2015) *(high confidence)*. In general, the premiums are less costly than what an individual country or entity can achieve and disbursement is rapid and there are also fewer transaction costs(Lucas 2015; World Bank 2015). The World Bank argues that the experience with Pacific Catastrophe Risk Insurance Pilot (PCRIP) and Africa Risk Capacity risk pooling (ARC) show saving of 50% in obtaining insurance cover for pooled risk compared with purchasing comparable coverage individually (Lucas 2015; World Bank 2015; ARC 2016). However, it requires, as noted by UNESCAP, 'extensive coordination across participating countries, and entities' (Lucas 2015).

At the same time, this approach has substantial basis risk, (actual losses do not equal financial compensation) (Hermann et al. 2016) *(high confidence)*. With parametric insurance, pay-out are pre-defined and based on risk modelling rather than on the ground damage assessment so may be less than, equal to, or greater than the actual damage. It does not cover actual losses and damage and therefore, may be insufficient to meet the cost of rehabilitation and reconstruction. It may also be 'non-viable' or damaging to livelihood in the long run (UNFCCC 2008; Hellmuth et al. 2009; Hermann et al. 2016). Additionally, if the required threshold is not met, there may be no pay-out, though a country may have experienced substantial damages from a climatic event. (This occurred for the Solomon Islands in 2014 which discontinued its insurance with the Pacific Catastrophe Risk Insurance Pilot when neither its Santa Cruz earthquake nor the 2014 flash floods were eligible to receive a pay-out under the terms of the insurance (Lucas 2015).

Increasingly, climate risk insurance scheme is being blended into disaster risk management as part of a comprehensive risk management approach *(high confidence)*. The best-known example is the Caribbean Catastrophe Risk Insurance Facility (CCRIF SPC 2018), which involves cooperation among Caribbean states, Japan, Canada, UK and France and international organizations such as World Bank (UNESCAP 2017). But there are growing platforms of such an approach mainly under the umbrella of the G7's InsuResilience Initative (Deutsche Klimafinanzierung 2020), including, the Pacific Catastrophe Risk Assessment and Financing Initiative) for the Pacific Islands, the African Risk Capacity (ARC Agency and its financial affiliate), and the African Risk Capacity Limited (ARC Ltd/ the ARC Group) (ARC 2016) and in the Asian region, the South East Asian Disaster Risk Insurance Facility (SEADRIF) and the ASEAN Disaster Risk Financing and Insurance Program (ADRFI), (SEADRIF 2018; GIZ and World Bank 2019; Martinez-diaz et al. 2019; Vyas et al. 2019; World Bank 2019a). The group of 20 vulnerable countries (V-20) has also developed a Sustainable Insurance Facility (SIF), billed as technical assistance facility for climate-smart[5] insurance for MSMEs in 48 developing countries as well as potentially to de-risk renewable energy in these countries and regions (ACT Alliance 2020; V20 2020, 2021).

However, as noted above, climate risk pooling is not a panacea. There are very obvious and significant challenges. According to (Kreft and Schäfer 2017), limitations of insurance schemes, include coordination challenges, limited scope, de-stabilization due to exit of one or more members as premiums risk and inadequate attention to permanent (Schaeffer et al. 2014). There are also challenges with risk diversification, replication, and scalability *(high confidence)*. For example, CCRIF is extending both its membership and diversifying its geographic dimensions into Central America in seeking to lower covariate risk (similar shocks among cohorts such as droughts or floods). Under the SPC portfolio, CCRIF is able to segregate risk across the regions. Risk insurance does not obviate from the need to engage in capacity building to scale-up as well as having process for addressing systemic risk. Currently, risk pools have limited sectoral reach and may cover agriculture but not other important sectors such as fisheries and public utilities. Only recently (July 2019) has CCRIF initiated coverage of fisheries with the development of its he Caribbean Oceans and Aquaculture Sustainability Facility (COAST) instrument (CCRIF SPC 2019; ACT Alliance 2020). Historically, risk pool mechanisms, like

FOOTNOTE[5] According to the V20, 'the term "climate-smart" captures the need for two types of climate-related insurance products for MSMEs in vulnerable economies: (1) Climate risk insurance (2) Insurance products which enable low carbon investments, and thereby contribute to increased efficiencies through cost-savings from cheaper low-carbon technologies (2021).

CCRIF and ARC, only cover a small subset of perils, such as tropical cyclone, earthquake and excess rainfall but do not include other perils such as drought. Since 2016, ARC has increased its scope to cover drought and in 2019 launched ARC Replica which not only covers drought but offers premiums and coverage to NGOs and the World Food Programme through the START Network and a pastoral drought product for protecting small farmers and ensuring food security. In some regions and countries, there may also be limited access to reinsurance (Schaeffer et al. 2014; Lucas 2015). An important down-side of climate risk pooling is that it does not cover the actual cost of damage and losses. Though on the positive side, pay-out may exceed costs, but it may also be less than cost. Hence, the parametric approach is not a panacea and does not preclude having recourse to conventional indemnity insurance, which will cover full damage costs after a climate change event as it involves full on the ground assessment of factors such as the necessity and costs of repair versus say replacement value of damaged infrastructure. This may be important for governmental and publicly provided services such as schools, hospitals, roads, airports, communications equipment and water supply facilities. Given the growing popularity of parametric insurance and climate risk pooling, there are very ambitious attempts to expand this approach on several fronts (Scherer 2017). (Schoenmaker and Zachmann 2015) have proposed a global climate risk pool to help the most vulnerable countries. The pathway to this includes capacity building in underdeveloped financing sectors of developing countries. They argue that as climate extreme become more normalised, they will wipe out significant part of the infrastructure and productive capacity of developing countries. This will have knock-on impact on fiscal capacity due to lowered tax revenue and high rebuilding costs. 'Developing countries, (Schoenmaker and Zachmann 2015) argue, 'cannot insure against such event on a market basis, nor would it be sensible to divert scare fiscal resources away from infrastructure investment into accumulating a financial buffer for such a situation (Schoenmaker and Zachmann 2015). In that context, (Schoenmaker and Zachmann 2015) call for international risk pooling as 'the only sensible strategy' especially if it addresses the major gaps in climate risk insurance for poor and vulnerable communities by enhancing demand through 'smart support instrument' for premium support such as full or partial premium subsidies and investment in providing risk reduction (Schäfer et al. 2016; Le Quesne et al. 2017; MCII 2018; Vyas et al. 2019). This it is argued may help to smoothen out the limited uptake of regional institutions such as ARC, CCRIF SPC which are osnly in three regions of the world (with missing mechanism in South America). (Kreft and Schäfer 2017). Existing regional mechanisms, while they may perform very well, only cover a portion of climatic hazards and tend to have limited subscribers. For example, across the key four sovereign risk pools (ARC, CRIFSPC, PCRAFI and SEADRIF), though there are 68 countries only 1/3 or 32% have purchased coverage in 2019 and 46% 'did not deploy disaster risk financing instruments (ACT Alliance 2020).

Other gaps and challenges flagged by (Kreft and Schäfer 2017) include limited coverage of the full spectrum of contingency risks experienced by countries, inadequate role of risk management as a standard for all regional pools, though there are some emerging best practices in terms of data provision on weather-related risks, and incentivization of risk reduction *(high confidence)*. Here, they recognise the work of ARC's Africa Risk Capacity for not only providing the infrastructure to trigger disbursement but for also promoting national risk analysis. Another important gap in the landscape of climate risk pooling is lack of attention to financial institutions' lending portfolio that is vulnerable to weather shocks. In this regard subsidies as part of innovative financing schemes facilitated by the donor community can encourage the uptake of meso-level climate risk insurance solutions (Kreft and Schäfer 2017).

In the literature, there are two attempts at systematic evaluation or comprehensive assessment of regional climate risk pools. A comprehensive study by (Scherer 2017) and FCDO ten-year evaluation (2015-2024). Overall, none of these studies draw adverse conclusions about regional climate risk pooling initiatives/mechanisms. According to Scherer 'it appears that insurances work in principle and there is certainly successes' and 'initial experiences demonstrate regional climate risk insurances works'. The author cited the 28 pay-outs to 16 countries of 106 million USD arguing that it provides cash-starved countries with much needed cash (Scherer 2017, p. 4). The FCDO study examines the uptake of ARC and its impact on reducing vulnerability to disasters. It notes that there is scarce literature on disaster risk insurance mechanism in terms of impacts. In its current sample of 20 countries as of November 2017, 4 are projected to experience food security crisis (IPC Level 3) but are not signatories to the ARC which may signal that ARC is not attractive to all food insecure countries and that there is no overwhelming appetite for ARC among poorer countries. Additionally, (Panda and Surminski 2020), research on the importance of indicators and frameworks for monitoring the performance and impact of CDRI make no final assessment of any of the regional climate risk pool. However, they propose mechanisms to improve the transparency and accountability of the system. Both (Scherer 2017), (Forest 2018) and (Panda and Surminski 2020), seems to indicate that 'there is enthusiasm to support and scale up regional climate risk insurance' (Scherer 2017, p. 4) Examples of this support include, the Germany Ministry for Economic Cooperation and Development (BMZ) has provided 5.9 million USD for WFP to protect 1.2 million vulnerable African framers with climate risk insurance, through ARC Replica, and the G7, InsuResilience Vision 2025, which has committed to ensuring 400–500 million poor persons are covered against disaster shock by pre-arranged finance and insurance mechanism by 2025, some of this will be through ARC (WFP 2020). Of course, this does not mean that risk pools are without challenges or are not failing on specific sets of metrics. (Forest 2018) flags three failings areas: policy holder and hazard coverage, the cost of premium and risk transfer parameters and the use of pay-out, which in most cases are up to the government. Here, ARC is flagged among the three regional Risk pools, as the only one with contingency plan requirement that can support effective use of pay-outs. Other research exploring climate risk pool and its impacts, flag lack of transparency around pay-out, premium or risk transfer parameters. Ultimately, climate risk pools are not full insurance; they offer only limited coverage. Entities such as the UK Anti-Corruption Help desk is exploring how to mitigate potential corruption with regard to climate risk insurance.

15.6.5 Widen the focus of relevant actors: Role of communities, cities and sub-national levels

There is an urgency and demand to meet the financial needs of the climate change actions not only at the national level but also at the subnational level, to achieve low-carbon and climate-resilient cities and communities (Barnard 2015; Moro et al. 2018) *(high confidence)*. Scaling up subnational climate finance and investment is a necessary condition to achieve climate change mitigation and adaptation action (Ahmad et al. 2019).

The importance of exploring effective subnational climate finance. Stronger subnational climate action is indispensable to adapt cities to build more sustainable, climate-positive communities (Kuramochi et al. 2020). It has transformative potential as a key enabler of inclusive urban economic development through the building of resilient communities (Floater et al. 2017a; Colenbrander et al. 2018b; Ahmad et al. 2019) *(high confidence)*. Yet the significant potential of subnational climate finance mechanisms remains unfulfilled. Policy frameworks, governance, and choices at higher levels underpin subnational climate investments (Colenbrander et al. 2018b; Hadfield and Cook 2019). To scale climate investment, a systematical understanding of the preconditions to mobilizing high-potential financing instruments at the national and subnational levels is necessary.

Subnational climate finance needs and flows. Subnational climate finance covers financing mechanisms reaching or utilizing subnational actors to develop climate positive investment in urban areas. The fragility of interconnected national and subnational finances affects subnational finance flows, including the impact of the social-economic crisis (Canuto and Liu 2010; Ahrend et al. 2013). The effect of deficit in investment for global infrastructure towards the growing subnational-level debt also creates pressure on subnational finances and constrains future access to financing (Smoke 2019) *(high confidence)*.

The International Finance Corporation estimates a cumulative climate investment opportunity of 29.4 trillion USD across six urban sectors (waste, renewable energy, public transportation, water, electric vehicles, and green buildings) in emerging market cities, cities in the developing country with more than 500,000 population, to 2030 (IFC 2018). However, State of Cities Climate Finance report estimated that an average of USD 384 billion was invested in urban climate finance annually in 2017-2018 (Negreiros et al. 2021). The Institute for Environment and Development estimates that out of the 17.4 billion USD total investments in climate finance, less than 10% (1.5 billion USD) was approved for locally-focused climate change projects between 2003 and 2016 (Soanes et al. 2017).

Subnational climate public and private finance. Urban climate finance and investment are prominent among the subnational climate finance landscape (CCFLA 2015; Buchner et al. 2019). Finance mechanisms that can support climate investment for the urban sector include public-private partnerships (PPPs); international finance; national investment vehicles; pricing, regulation, standards; land value capture; debt finance; and fiscal decentralization (Granoff et al. 2016; Floater et al. 2017b; Gorelick 2018; White and Wahba 2019). Among these mechanisms, PPPs, debt finance, and land value capture have the potentials to mobilise private finance (Ahmad et al. 2019). Better standardization in processes is needed, including those bearing on contracts and regulatory arrangement, to reflect local specificities (Bayliss and Van Waeyenberge 2018) [Reference to Public private mobilization Section in 15.6.1.1].

PPPs are particularly important in cities with mature financial systems as the effectiveness of PPPs depends on appropriate investment architecture at scale and government capacity *(high confidence)*. Such cities can enable its infrastructure such as renewable energy production and distribution, water networks, and building developments to generate consumer revenue streams that incentivise private investors to purchase equity as a long-term investment (Floater et al. 2017b).

National-level investment vehicles can provide leadership for subnational climate financing and crowd in private finance by providing early-stage market support to technologies or evidence related to asset performance and costs-benefits *(high confidence)*. The use of carbon pricing is increasing at the subnational level along with regulation and standards on negative externalities, such as pollution, to steer investment towards climate financing (World BankGroup 2019).

Debt financing via subnational bonds and borrowing, including municipal bonds, is another potential tool for raising upfront capital, especially for rich cities *(high confidence)*. The share of sub-national, sub-sovereign, and sovereign bonds could grow over time, given efforts to expand the creditworthiness and ensure a sufficient supply of own-source revenue to reduce the default risk. As of now, subnational and sub-sovereign bonds are constrained by public finance limits and the fiscal capacities of governments. However, while green bonds have potential for growth at the subnational level and may result in a lower cost of capital in some cases, the market faces challenges related to scaling up and has been associated with limited measurable environmental impact to date (see Section 15.6.8 Innovative Financial Products for further discussion). Further, bonds with lower credit ratings drive higher issuance costs for climate risk cities, e.g., costs related to disclosure and reporting (Painter 2020).

Key challenges of subnational climate finance. Across all types of cities, five key challenges constrain the flow of subnational climate finance *(high confidence)*: (i) difficulties in mobilizing and scaling-up private financing (Granoff et al. 2016); (ii) deficient existing architecture in providing investment on the scale and with the characteristics needed (Anguelovski and Carmin 2011; Brugmann 2012); (iii) political-economic uncertainties, primarily related to innovation and lock-in barriers that increase investment risks (Unruh 2002; Cook and Chu 2018; White and Wahba 2019)); (iv) the deficit in investment for global infrastructure affects the growing subnational-level debt (Canuto and Liu 2010) and; (v) insufficient positive value capture (Foxon et al. 2015).

Different finance challenges between rich and poor cities. Access to capital markets has been one of major sources for subnational financing is generally limited to rich cities, and much of this occurs through loans *(high confidence)*. Different challenges accessing capital markets associated with wealthy and poorer cities are compounded into three main issues: (i) scarcity and access of financial resources (Bahl and Linn 2014; Colenbrander et al. 2018b; Cook and Chu 2018; Gorelick 2018), (ii) the level of implication from the existing distributional uncertainties to the current financing of infrastructural decarbonization across carbon markets (Silver 2015), and (iii) the policy and jurisdictional ambiguity in urban public finance institutions (Padigala and Kraleti 2014; Cook and Chu 2018). In poorer cities, these differing features continue to be inhibited by contextual characteristics of subnational finance, including gaps in domestic and foreign capital (Meltzer 2016), the mismatch between investment needs and available finance (Gorelick 2018), weak financial autonomy, insufficient financial maturity, investment-grade credit ratings in local debt markets (Bahl and Linn 2014), scarce diversified funding sources and stakeholders (Gorelick 2018; Zhan et al. 2018; Zhan and de Jong 2018) and weak enabling environments (Granoff et al. 2016).

The depth and character of the local capital market also affect cities differently in generating bonds *(high confidence)*. Challenges facing cities in developing countries include insufficient appropriate institutional arrangements, the issues of minimum size, and high transaction costs associated with green bonds (Banga 2019). Green projects and project pipelines are generally smaller in scale feasible for a bond market transaction (Saha and D'Almeida 2017; DFID 2020). De-risking in the different phases of long-term project financing can be promoted to improve appetite of capital market [Reference to development of local capital markets Section in 15.6.7].

Climate investment and finance for communities. There is insufficient evidence that which financing schemes contribute to climate change mitigation and adaptations at community level *(high confidence)*. There is growing interest in the linkages between microfinance and adaptation on the agriculture sector (Agrawala and Carraro 2010; Fenton et al. 2015; Chirambo 2016; CIF 2018; Dowla 2018), the finance for community-based adaptation actions (Fenton et al. 2014; Sharma et al. 2014), and the relations between remittances and adaptation (Le De et al. 2013). However, there is less discussion on community finance aside from the benefits of community finance and village funds in contributing to close investment gaps and community-based mitigation in the renewable energy and forest sectors (Ebers Broughel and Hampl 2018; Bauwens 2019; Watts et al. 2019) The full potential and barriers of the community finance model are still unknown and research needs to expand understanding of favourable policy environments for community finance (Bauwens 2019; Watts et al. 2019).

Implications for the transformation pathway.
Cities often have capacity constraints on planning and preparing capital investment plans. An integrated urban capital investment planning is an option to develop cross-sectoral solutions that reduce investment needs, boost coordination capacity, and increase climate-smart impacts (Negreiros et al. 2021) *(high confidence)*. In countries with weak and poorly functioning intergovernmental systems, alliances and networks may influence their organizational ability to translate adaptive capacity for transformation into actions (Leck and Roberts 2015; Colenbrander et al. 2018a). Deepening understanding of country-specific enabling environment for mobilizing urban climate finance among and within cities and communities, design of policy, institutional practices and intergovernmental systems are needed to reduce negative implications of transformation (Steele et al. 2015).

15.6.6 Innovative financial products

Innovative financial products with increased transparency on climate risk have attracted investor demand, and can facilitate investor identification of low carbon investments *(high confidence)*. Innovative products may not necessarily increase financial flows for climate solutions in the near term, however they can help build capacity on climate risk and opportunities within institutions and companies to pave the way for increased flows over time.

Investor demand is driving developments in innovative financial products *(high confidence)***.** Since AR5, innovative financial products such as sustainability and green labelled financial products have proliferated (see financial stock estimates in Section 0). These financial products are not necessarily 'new' in terms of financial design but are packaged or labelled in an innovative way to attract responsible and impact-oriented institutional investors.

The growth and diversity of the green bond market illustrates how innovative financial products can attract both public and private investors *(high confidence)*. Demand for green financial products initially stemmed from public sector pension funds. Pension funds and insurance companies in OECD countries have traditionally favoured bonds as an asset class with lower risk (OECD and Bloomberg 2015).

Since AR5, labelled green bonds have grown significantly, exceeding 290 billion USD issued in 2020 with a total of 1.1 trillion USD in outstanding bonds (CBI 2021a) (see also local capital markets Section 15.6.7). Corporates, financial institutions and government-backed entities (e.g. in real estate, retail, manufacturing, energy utilities) issued the largest volumes, with use of proceeds focused primarily on GHG mitigation in energy, buildings and transport projects (CBI 2021a). Given their focus on GHG mitigation, green bonds are also sometimes referred to as climate bonds, but the common market terminology is 'green'. Municipal green bond issuance has also been growing (see further discussion on municipal green bonds in Section 15.6.7 on local actors). Beyond green bonds, additional products such as green loans, green commercial paper, green initial public offerings (IPOs), green commodities, and sustainability-linked bonds and loans have also been introduced in the market (CBI 2019a) (see discussion on building yield curves in local capital markets Section 15.6.7).

Investor demand for green bonds is evidenced by over-subscription of deals. Recent studies indicate an over-subscription for green labelled bonds by an average of between three and five times, as compared to non-labelled bonds (Gore and Berrospi 2019; Nauman 2020). Results of a survey of global treasurers showed a higher demand for green bonds than non-labelled bonds for 70% of the respondents (CBI 2020a).

The financial crisis associated with COVID-19 has put increased pressure on debt issuers, and the extent to which the increase in indebtedness for sovereigns and corporates has been financed via climate-related labelled debt products is not known. Further, at this time there is no identified literature assessing the degree to which international versus domestic investors are financing sovereign green debt in developing countries (for further discussion on attracting different types of investors through the development of local capital markets Section 15.6.7) However, since the onset of the COVID-19 crisis, continued steady growth in issuance has been observed broadly across sustainable bonds (including green, social and sustainability bonds), with more significant growth in social bonds to support the COVID-19 recovery (Maltais and Nykvist 2020; CBI 2021a).

Index providers and exchanges can also play a supporting role in transparency for identification of benchmarks and innovative financial products for climate action. Low-carbon indices have proliferated in recent years, with varying approaches including reduced exposure to fossil, best-in-class performers within a sector, and fossil-free (UN PRI 2018) (see discussion on ESG index performance that follows in this section). Indices can provide transparency on low-carbon opportunities making it simpler for funds and investors to identify green investment options. Exchanges can also play a supporting role to the uptake of green financial products through transparent listings and requirements to improve credibility of green labelling. The number of green or sustainability bond listing segments tripled from five in 2016 to 15 in 2018 (SSE 2018). Green security listings can also be used to enhance local capital markets (see Section 15.6.7 for further discussion).

Significant potential exists for continued growth in innovative financial products, though some challenges remain *(high confidence)***.** Despite recent growth and diversification, green bonds face several challenges in scaling up. Issuance of green-labelled bonds constitutes approximately 1% of the global bond market issuance (ICMA 2020b; CBI 2021a) Potential exists to increase issuance amongst corporates, for instance, and across a broader regional scope (although subject to limitations of local capital markets). Yet there remain several challenges to growing the green bond market, including *inter alia* concerns about greenwashing and limitations in application to developing countries (Shishlov et al. 2018; Banga 2019).

There is no globally accepted definition of green bonds, and varied definitions of eligible green activities are evolving across regional bond markets. Beyond the most commonly used green label, other related labels such as blue, sustainable, transition, sustainable development goal (SDG), social and environmental, social and governance (ESG) have some overlapping applications (Schumacher 2020). The degree to which these labels represent climate relevant investments depend on underlying criteria and how they are applied (see also discussion in local capital markets Section 15.6.4).

There are several initiatives aimed at protecting the integrity of the green label. Guidance on use and management of proceeds established by the International Capital Markets Association's Green Bond Principles (GBP) is followed on a voluntary basis, which notes eligible use of proceeds as primarily climate mitigation and adaptation projects. The GBP also recommend independent external reviews at the time of issuance, with 89% of green bond issuers in 2020 with external reviews at the time of issuance (CBI 2021a). In addition to best practice based on voluntary principles, a further check on greenwashing, although insufficient on its own, is the fear of reputation risk on behalf of investors, issuers and intermediaries in the age of social media (Hoepner et al. 2017; Deschryver and de Mariz 2020). A report on post-issuance green bond impact reporting notes that despite concerns (Shishlov et al. 2018), greenwashing incidence is rare, with 77% of green bond issuers reporting on allocation and 59% reporting on impact, but with significant variance in quality and consistency of impact reporting (CBI 2021b).

Financial disclosure regulatory developments can help further align and specify definitions of green in the financial sector but are not a substitute for climate policy *(high confidence)*. Developing a common basis for understanding a green label could further reduce uncertainty or concerns of greenwashing. Regulatory developments in some regions seek to further guard against greenwashing with more specific definitions. The EU sustainable finance package, including the EU Taxonomy and EU Green Bond Standard draft regulations, is the broadest reaching, but not the only, regional initiative focused on disclosure of climate risk (see also Section 15.6.3). Taxonomies across regions are not always aligned on what can constitute a green project, for example with respect to transition activities (International Capital Market Association 2021) (see also discussion on local capital markets in Section 15.6.7). While standardisation can help reduce uncertainty in markets with imperfect knowledge, the green bond market is currently developing and is expected to continue to reflect regional differences in economic governance approaches (Nedopil et al. 2021). Regulations may also have trade-offs in terms of transaction costs for green financial product issuers. Classification approaches can also face challenges, depending on how they are designed, in their ability to capture new technologies and social impacts (see Section 15.4).

Green bonds have been primarily targeting climate mitigation projects, with far fewer projects identified as adaptation. Green bonds mainly finance projects in the energy, buildings and transportation sectors, which constituted 85% of the use of proceeds of green bonds in 2020 (CBI 2020b, 2021a). Agriculture and forestry projects, including adaptation projects, have been less suited to be financed in a bond structure, which could be in part due to the more dispersed and smaller nature of the projects and in part due to project 'bankability' or ability to contribute steady streams of financing to pay back the terms of a bond. However, adaptation projects may not be identified as such as resiliency becomes more mainstreamed into infrastructure planning (see Section 15.3.2)

While green bonds have the potential to further support financial flows to developing countries, local capital markets can be at varying stages of development (see discussion in Section 15.6.2 on enabling environments and in Section 15.6.7 on local capital markets for peer-learning examples and de-risking opportunities) (Banga 2019). While multilateral and bilateral development finance institutions have been active in the green bond market, global issuance in 2020 in the top 10 countries included only one developing country (CBI 2021a). Targeting international investors can be enhanced via de-risking activities (see further discussion in section 15.6.4).

Identifying green financial products can increase uptake and may result in a lower cost of capital in certain parts of the market *(high confidence)***.** Investors face a systematic under-pricing of climate risk in financial markets (Krogstrup and Oman 2019; Kumar et al. 2019). Transparent identification of financial products can make it easier for investors to include low carbon products in their portfolios. Investors with mandates that include or are focused on climate change are showing an interest in green-labelled financial products. Investors that identify themselves as green constitute approximately 53% of the investor base for green bonds in the first half of 2019 (CBI 2019b).

There is some evidence of a premium, or an acceptance of lower yields by the investor, for green bonds (*medium confidence*). A survey of recent literature finds some consensus of the existence of a green premium in 56% of the studies on the primary markets (with a wide variance of premium amount), and 70% of the studies on the secondary market (with an average premium of -1 to -9 basis points), particularly for government issued, investment grade and green bonds that follow defined governance and reporting practices (MacAskill et al. 2021). In the US municipal bond market, as credit quality for green labelled bonds has increased in the past few years, some studies show a positive premium for green bonds is arising (Baker et al. 2018; Karpf and Mandel 2018), or appearing only in the secondary market (Partridge and Medda 2020), while others find no evidence of a premium (Hyun et al. 2019; Larcker and Watts 2020). Several studies also show a recent emergence of a premium and oversubscription for some green labelled bonds denominated in EUR (CBI 2019b), in some cases for both USD or EUR (Ehlers and Packer 2017) green bonds, with a wide variation in the range of the observed difference in basis points focusing on the secondary market (Gianfrate and Peri 2019; Nanayakkara and Colombage 2019; Zerbib 2019), with financial institution and corporate green bonds exhibiting a marginal premium compared with their non-green comparisons (Hachenberg and Schiereck 2018; Kempa et al. 2021).

Spill over effects of green bonds may also impact equity markets and other financing conditions. Stock prices have been shown to positively respond to green bond issuance (Tang and Zhang 2020). One study linked enhanced credit quality induced by issuing green labelled bonds to a lower cost of capital for corporate issuers (Agliardi and Agliardi 2019). Issuers' reputation and use of third-party verification can also improve financing conditions for green bonds (Bachelet et al. 2019). Green bonds are strongly dependent on fixed income market movements and are impacted by significant price spill over from the corporate and treasury bond markets (Reboredo 2018). A simulation of future green sovereign bond issuances shows that this can promote green finance via firm's expectations and the credit market (Monasterolo and Raberto 2018).

Financial flows via these instruments have limited measurable environmental impact to date, however they can support capacity building on climate risk and opportunities within institutions to realise future impacts *(high confidence)***.** There is a lack of evidence to date that green and sustainable financial products have significant impacts in terms of climate change mitigation and adaptation (see also Box 15.7). Further, new products must be coupled with tightened climate policy and a reduction in investments associated with GHG-emitting activities to make a difference on the climate (see section 15.3.3.2 for further discussion on reduction of financial flows to emitting activities).

It is challenging to link specific emission reductions with specific instruments that mainly target climate activities such as green bonds. Data challenges point to an inability to link emission reductions, including Scope 3 GHG emissions, at the organization or firm level with green bond use-of-proceeds issuance (Ehlers et al. 2020; Tuhkanen and Vulturius 2020). However one study found evidence of a signalling effect of issuing green bonds resulting in emission reductions at the corporate level following issuance (Flammer 2020), and another study characterised the lifecycle emissions of renewable energy financed by green bonds, indicating potentially substantive avoided emissions but with variance up to a factor of 12 across bonds depending on underlying assumptions (Gibon et al. 2020). There is also a lack of impact reporting requirements and consistency in the green bond market. Impact reporting is not typically required for green bond listings on specific exchanges, nor are there any requirements for independent reviews of impact reporting, however this could change in future if investors apply pressure.

Green-labelled products may not necessarily result in increased financial flows to climate projects, although there can be benefits from capacity building with issuing institutions. Green bonds can be used to finance new climate projects or refinance existing climate projects, and thus do not necessarily result in finance for new climate projects constituting additional GHG reductions (a framing used in the Clean Development Mechanism). The labelling process itself may not necessarily lead to additional financing (Dupre et al. 2018; Nicol et al. 2018b). However, the labelling process has merit in contributing to building capacity within issuing institutions on climate change (Schneeweiss 2019), which could support identification of new green projects in the pipeline.

Climate risk disclosure initiatives, some of which are voluntary in nature, may have a limited direct climate impact. Transparency on climate risk may not change investor decisions nor result in divestment, especially in the emerging economies, as support and clear direction from regulatory and policy mechanisms are required to drive institutional investors at large (Ameli et al. 2021c). On the other hand, there is evidence of reduced fossil fuel investments following mandatory climate risk disclosure requirements, indicating a broader signalling effect of transparency (Mésonnier and Nguyen 2021).

***** START BOX 15.7. HERE *****

Box 15.7 Impact of ESG and sustainable finance products and strategies

While scaling up climate finance remains a challenge (see Section 15.3.2), there is consensus that investments that are managed taking into account broader sustainability criteria have increased consistently and ESG integration into sustainable investment is increasingly being mainstreamed by the financial sector over the last years (Maiti 2021). The United Nations Principles for Responsible Investment (PRI) grew to over 3000 signatories in 2020, representing over USD 100 trillion in assets under management (UN PRI 2020). And according to the 2018 biennial assessment by Global Sustainable Investment Alliance[6], sustainable investments in five major developed economies grew by 34% in the two year period following the 2016 assessment. The primary ESG approaches leveraged were exclusion criteria and ESG integration, which together amounted to over USD 37 trillion, accounting for two-thirds of the assessed sustainable investments, with novel strategies such as best-in class screening and sustainability themed investing showing significant growth, although together they accounted for around 6 percent of these investments (GSIA 2019). Shareholder activism or corporate engagement is the other key approach, which has been well established and continued to grow to nearly USD 10 trillion (GSIA 2019).

However, research indicates that ESG strategies by themselves, do not yield meaningful social or environmental outcomes (Kölbel et al. 2020). When it comes to the tangible impact of the financial sector on addressing climate change and sustainable development, there remains ambiguity. There is a growing need for more robust assessment of ESG scores, including establishing higher standardization

FOOTNOTE[6] GSIA is an international collaboration of membership-based sustainable investment organizations.

of scoring processes and a common understanding of the different ESG criteria and their tangible impact on addressing climate change. The issue was highlighted in an assessment of six of the leading ESG rating agencies' company ratings under the MIT Aggregate Confusion Project, which found the correlation among them to be 0.61, leading them to conclude that available ESG data was "noisy and unreliable" (Berg et al. 2020). This need is reaffirmed by (Drempetic et al. 2020), who claim that a thorough investigation of ESG scores remains a relatively neglected topic, with extraneous factors, such as firm size, influencing the score (Drempetic et al. 2020).

There continues to be a research gap in assessing the direct impact of ESG and sustainable investments on climate change indicators, with most existing studies assessing the co-relation between either the factors driving the sustainable finance trends and the impact on sustainable investments, or sustainable investments and the impact on corporate financial performance. Nevertheless, since the post SDG adoption period, there has been a notable uptake on research linking sustainable business practices and financial performance (Muhmad and Muhamad 2020a). This research shows that there is a growing business case for ESG investing, with evidence increasingly indicating a non-negative co-relation between ESG, SDG adoption and corporate financial performance (Friede et al. 2015; Muhmad and Muhamad 2020b), and ESG performance having a positive relation with stock returns (Consolandi et al. 2020). Research, focused on developed economies, also indicates towards a positive relation between ESG criteria and disclosure, and economic sustainability of a firm (Giese et al. 2019; Alsayegh et al. 2020) and allays investor fears by showing that sustainable finance initiatives, such as divestment, doesn't adversely impact investment portfolio performance (Henriques and Sadorsky 2018; Trinks et al. 2018). It should be reiterated, that this research assesses the co-relation between ESG criteria and corporate financial performance, with the researchers in some cases, such as (Friede et al. 2015), including disclaimers of the results being inconclusive and highlighting the need for a deeper assessment for linking ESG criteria with impact on financial performance.

On the other hand, there is growing evidence for a sustainable investment lens having a broader positive impact on creating an enabling environment and strengthening the case for such investments. For instance, CSR activities and investments on the environment dimension, specifically in the areas of emission and resource reduction, were found to be profitable and a predictor of future abnormal returns in the longer term, from additional cash flow and additional demand (Dorfleitner et al. 2018). These factors could be contributing to the increasing trend of sustainable and green investments, and can said to be further reiterated by the spate of investor led collaborative initiatives and recent announcements by leading finance institutes in the developed economies, which is well recorded in a range of recent grey literature, including new climate-aligned investment strategies and ambition towards net zero targets.

Yet there is also a risk of companies announcing projected sustainability or net zero targets and claiming the associated positive reputational impact, while having no clear action plan in place to achieve these. The lack of mandatory reporting frameworks, which results in an over-reliance on self-reported carbon data by companies for ESG assessments, can be a primary contributor (In and Schumacher 2021).

While there is a lack of research on the impact of sustainable finance products, divestment impact has been assessed in more detail. Although the research here also points towards the ambiguous direct impact of divestment on reducing GHG emissions or on the financial performance of fossil fuel companies, its indirect impact on framing the narrative around sustainable finance decisions (Bergman 2018), and the inherent potential of the divestment movement for building awareness and mobilizing broader public support for effective climate policies, have been better researched and could be considered to be the more relevant outcomes (Braungardt et al. 2019). Arguments against divestment point to its largely symbolic nature, but (Braungardt et al. 2019) elaborate on the broader positive impacts of divestment, which includes its ability to spur climate action as a moral imperative and stigmatise and reduce the power of the fossil fuel lobby, and the potential of the approach to mitigate systemic financial risks arising due to climate change and address the legal responsibilities of investors merging in this regard.

Challenges remain with regards to overlapping definitions of sustainable and ESG investment opportunities, which also vary depending on social norms and pathways. There is also a general need for more extensive ESG disclosure on a corporate level, against the background of emerging mandatory impact reporting for asset managers in some regions. A movement is building towards sustainable investment strategies and increased sustainable development awareness in the financial sector (Maiti 2021; Muhmad and Muhamad 2020b), which points to the ability of civil society movements, such as divestment campaigns, to have some influence on investor behaviour, although there are other influences such as climate risk disclosure initiatives and regulations.

***** END BOX 15.7. HERE *****

15.6.7 Development of local capital markets

International Situational Context. Developing countries make up two thirds of the world population, carry carbon intensive economies where 70% of investments need to be conducted to limit warming to 2°C. The focus for climate investments has been on China, USA, Europe, India and the G-20 (UNEP 2019) but studies highlight Paris and SDG attention should be devoted to Africa, LDCs and SIDS (Africa Union Commission 2015; GCA-AAI 2020; Feindouno et al. 2020; Warner 2020; AOSIS 2021). The "special needs, circumstances and vulnerability" of Africa, LDC and SIDS nations are recognised under UNFCCC and UN agreements (UN 2009, 2015a,b,c; UNFCCC 2010, 2015; Pauw et al. 2019). These nations currently contribute very little to global emissions. Developing countries with their growing economies, including the vast Africa continent roughly the size of China, Europe, USA, India combined (IEA 2014b, p. 20) with a 1 billion population expected to double by 2050, growing reliance on fossil fuels and 'cheap' biomass (charcoal use and deforestation) amid rising urbanization and industrialisation ambitions – collectively these nations hold large leap-frog potential for the energy transition as well as risks of infrastructure lock-in. Accelerated international cooperation is a critical enabler (IPCC 2018) in recognising this potential. This could mobilise global savings, scale up development of local capital markets for accelerated low carbon investment and adaptation in low and lower middle income countries as well as tackle illicit finance including tax avoidance leakages that deprive developing countries of valuable resources (US DoJ 2009; Hearson 2014; Hanlon 2017a; US DoJ 2019; UN IATFD 2021). Diversifying funding sources is important at a time hard-currency Eurobond issuances reach records (Panizza and Taddei 2020; Moody's Investors Service 2021). Otherwise, the structure of voluntary, nationally oriented, and financially fragmented arrangements under the Paris Agreement (see Chapter 17) could lead to 'regional rivalry' (SSP 3) pathways (IPCC 2018; Gazzotti et al. 2021). The benefits are many times greater than apparent costs in terms of expected decline in global GHG emissions and attaining SDGs. These could even generate large 'win-win' opportunities back in capital source countries which will benefit from a flow back in import demand (Hourcade et al. 2021a).

Lessons from literature on policy options in mobilising capital for Paris and SDGs in developing countries can be summarised as: a) development of national just transition strategies i) meet the 100 billion USD commitment on a grant-equivalent basis to support NDCs that integrate policies on COVID-19 recovery, climate action, sustainable development and equity b) increase the leverage of public funds on diverse sources of private capital through de-risking investments and public private partnerships involving location-based entities with AAA rated players and institutional investors c) co-ordination of project preparation and development of project pipelines by infrastructure co-ordinator agencies, one-stop structuring and financing shops, project risk facilities provided by cities development banks, green banks, world climate bank, global guarantee mechanism, and global infrastructure investment platform d) development of local currency bond markets backed-by cross-border guarantees, technical assistance, remediation assets especially by regional and national players whose mandates include nurturing local capital markets to support bond yield curve development and exchange listing options e) adopting advances in science-based assessment methods to foster accountability i) for project assessment, MRV and certification ii) for disclosures in climate, fossil fuels, SDG, debt transparency and debt sustainability iii) for progress on UN systems of national accounts particularly for public sector finance statistics.

Whole of society approach to mobilising diverse capital. There's no shortage of money globally: it is simply that it has yet to travel to where it's most needed. One challenge is unlocking unencumbered endowments to contribute to Paris and SDGs. *(high confidence).* The aggregate global wealth figures exceed 200 trillion USD (Davies et al. 2016; UBS 2017; Credit Suisse 2020; Heredia et al. 2020). Some developing countries have run pilots for investing in government bonds capitalising on fintech growth discussed in section 15.6.6 (The Economist 2017; Akwagyiram and Ohuocha 2021). Others are developing green products to encourage uptake by middle class retail investors (Eurosif 2018; HM Treasury and UK DMO 2021). Millennial-aged inheritors expected to receive intergenerational transfers mobilized by global citizen activism (see Chapter 2) invest in green retail and tech products (UBS 2017; Capgemini 2021; Morgan Stanley 2017). Historic inequity and diaspora-related private and public resources pledged and debated during the COVID-19 pandemic might have potential to contribute towards Paris and SDGs (Olusoga 2015; Glueck and Friedman 2020; Hall 2020; Piketty 2020; Timsit 2020; Goldman Sachs 2021; Guthrie 2021; Mieu 2021; Wagner 2021). Philanthropic institutions use grants, debt, equity, guarantees and issue investment grade bonds in using unencumbered endowments (Manilla 2018; Covington 2020; Moody's 2020) but only about 2% of their resources are dedicated to climate action (Williams 2015b; Kramer 2017; Morena 2018; Delanoë et al. 2021). The pandemic exemplified the unprecedented collaboration and mobilisation of multilateral and scientific communities supported by the COVAX risk sharing mechanism for COVID-19 vaccines with pooling of financial and scientific resources (OECD 2021d). This momentum in international cooperation can be harnessed to galvanise resources including for teaching of sciences in developing countries important in tackling society challenges, alleviating poverty (TWAS 2021) and inequity legacies compounded by climate impacts debated by many (Henochsberg 2016; Obregon 2018; The Economist 2021; Fernandez et al. 2021). Suggestions towards equitable models include "global adaptation funding approaches" (Chancel and Piketty 2015), a "world climate bank" to finance climate investments through long term bonds (Foley 2009; Broome 2012; Broome and Foley 2016), "cities development bank" (Alexander et al. 2019) , "public debt financing models" (Rendall 2021) to share the burden between generations which has precedence in history (Draper 2007; Fowler 2015).

Local financial institutions with local markets knowledge could benefit from technical assistance and partnership to scale up their potential. Institutional investors could be better mobilised *(high confidence).* The Global South has some 260 public development banks/PDBs representing 5 trillion USD in assets with a worldwide PDB capacity to provide more than 400 billion USD yr^{-1} of climate finance (IDFC and GCF 2020). Case studies discuss the potential for diaspora bond issuance being deployed for climate investments including securitisation of remittances as collateral for infrastructure bonds (Ketkar and Ratha 2010; Akkoyunlu and Stern 2012; Gelb et al. 2021). Such instruments could help harness diaspora remittances whose flows rose from under 100 to 530 billion USD during 1990-2018 (World Bank 2019b). PDBs could benefit from technical partnership with multilaterals and other local banks (Torres and Zeidan 2016). Their knowledge of local markets, can help build project pipelines (see Figure 15.7) to channel local, domestic and international capital (Griffith-Jones et al. 2020). Institutional domestic and international investors have growing assets estimated to exceed 100 trillion USD (*high confidence*) (Think Ahead Institute 2020; UN PRI 2020; Halland et al. 2021; Heredia et al. 2021; Inderst 2021) and could be better mobilized. Some 36 percent of total assets under management (AUM) by the 100 largest asset owners come from pensions and SWFs in the Asia Pacific region with the remainder split almost evenly across Europe, the Middle East, Africa and North

America. The largest pension fund in South Africa held about 130 billion USD AUM in 2019 and Africa institutional investors held USD 1.8 trillion in 2020 (GEPF 2019; PWC 2015; Bagus et al. 2020; Irving 2020). UK NGO (War on Want 2016) analysis of 101 fossil fuel and mineral resources companies listed on the London Stock Exchange (LSE) estimates these as holding a trillion USD assets inside Africa. The LAC region, holds just about USD 1 trillion AUM (Serebrisky et al. 2015; Cavallo and Powell 2019).

Investors with accumulated private capital are reported as looking for climate investments to ensure Just Transition, alignment with Paris and SDGs. However, progress remains pilot, slow and piecemeal (*high confidence*). Global investors have published statements on their possible contribution with recommendations to governments on de-risking to accelerate private sector investment to support Paris aligned NDCs in developing countries (IIGCC 2015, 2017, 2018, 2020; Global Investor Statement 2018; 2019). In March 2020, the UN Principles for Responsible Investment (PRI), had 3,038 members representing 103 trillion USD (UN PRI 2020); another coalition of investors published COVID-19 recovery plans (Investor Agenda 2020) and the Net Zero Asset Managers initiative was launched in December 2020 (NZAM 2020). However, it is still unclear how these pronouncements will be transformed to adequate financial flows and volumes of investment pipelines ((IEA 2021e), Chapter 3). (Rempel and Gupta 2020) posit that a proportion of institutional holding is in fossil fuels. Clean energy transition minerals raise ESG questions around inclusive development for indigenous populations and requires changes to supply chains exploiting child labour (Herrington 2021; IEA 2021a,f).

Options to mobilise institutional investors currently remain small pilots, relative to Paris and SDG ambitions *(high confidence*). In terms of sample examples: in the *women of colour-led arena*, a Chicago pension fund invested in a developing country using a *private equity fund*; (Langhorne 2021). Institutional Blackrock's blended finance vehicle with OECD MDB partners focuses on developing countries (Blackrock 2021). In regional AAA MDB partnerships, AfDB collaborates with Africa nations through a *regional infrastructure fund* (Africa50 2020); ADB collaborates with a Philippines state-owned pension fund and Dutch pension fund in using a *private equity fund* to catalyse private sector (ADB 2012). A UN entity with several pooled public-private investment platforms include a SDG blended finance vehicle (UN CDF 2020a,b, 2021a). Multilateral IFC blended finance fund, supported by a sovereign guarantee from Sweden's SIDA and separately a 1 billion USD green bond fund by IFC and Europe's Amundi asset manager buys green securities issued by developing country banks financing local currency climate investments (IFC 2018; IFC 2021 2021; Amundi and IFC 2019). The key parameter is the *investment multiplier,* the *ratio of private investment mobilised by a given amount of public fund*s which varies by product type. IFC's portfolio of blended finance investments point to a self-reported range of 3 to 15 times for project debt and even higher levels (10 to 30) for debt finance provided on concessional terms (IFC 2021a 2021). Although AAA-rated IFC blended finance fund was established in 2013, it took on seven of its eight institutional investors in 2017 with insurers AXA and Swiss Re investing 500 million USD each to bring the fund to 7 billion USD raised from eight global investors (Attridge and Gouett 2021). Critics of blended finance mechanisms point to lack of data transparency hampering independent assessment on i) value for public money and costs of blending versus other financial mechanisms ii) risks and benefits of de-risking private capital to collateralising climate vulnerable Global South populations iii) lack of partnership with local players iv) complex structures (Akyüz 2017; Mawdsley 2018; Convergence 2020; Daniela Gabor 2021; Attridge and Gouett 2021). Whilst blended finance transactions (BFTF 2018) are quite common in mature regulated markets with mandatory reporting requirements (Morse 2015; ICAEW 2021), the additional finance mobilised and their developmental impact remain unknown due to poor reporting that hammpers evidence-based policy making (Attridge and Gouett 2021). Projects that are aligned with blended finance principles in the UN Addis Agenda (UN 2015a) and take account of local contexts by involving local actors are much more likely to have sustainable impacts.

De-risking tools to lower capital costs and mobilise diverse investors. Paris aligned NDCs that integrate policies on COVID-19 pandemic recovery, climate action, sustainable development, just transition and equity can harness co-benefits including contribution to "*Invisible UN SDG 7 energy poverty sectors*" *(high confidence).* Developing countries require access to affordable finance for projects ranging from clean cooking solutions (Accenture 2018; World Bank et al. 2021); decentralised energy systems, intra-country power stations and regionally shared power pools with their associated energy distribution networks (IEA 2020d; IRENA 2020c). Close to 3 billion people in Africa and developing Asia have no access to clean cooking. For sub-Sahara Africa, the acute lack of electricity access lags behind all regions on SDG 7 indicators impacting mostly women and children (see Chapter 6, box 6.1; (IEA et al. 2021; IEA 2021e; Stritzke et al. 2021; Zhang 2021)). These dire statistics remind of compounding tensions: Historical inequities and the associated "first comer' exploiting Africa resources for development elsewhere, the local climate change, "latecomer" capacity development and technology transfer challenges, illicit mining finance and stranded assets (UNU-INRA 2019; Bos and Gupta 2019; War on Want 2016; Arezki 2021). The COVID-19 pandemic exacerbates this tension with more people pushed below the poverty line (Sumner et al. 2020) (see Box 15.6). Recent analysis points to the 60 largest banks providing 3.8 trillion USD to fossil fuel companies since 2016, including inside Africa (Rainforest Action Network et al. 2021). IMF estimated fossil fuel subsidies totalling 5.2 trillion USD or 6.5% of global GDP in 2017 (Coady et al. 2019) to be compared with the 2.4 trillion USD yr^{-1} energy investments over the next decade to limit global warming to 1.5°C (IPCC 2018). Analysts point to models in improvements to resources husbandry that include i) minerals strong governance SWFs for domestic development (Wills et al. 2016) and ii) compensation for Africa (Walsh et al. 2021) leaving fossil fuels underground (McGlade and Ekins 2015) in the *Just Transition* (section 15.2.4) and *Right to Develop* debates as assets continue to be mined (IEA 2019c). In many developing regions, some of the world's best renewable energy sources remain out of reach due to high costs which can be up to seven times that in developed countries (IEA 2021a). Shifting some risks through financial de-risking approaches could be instrumental (Schmidt 2014; Sweerts et al. 2019; Drumheller et al. 2020; Matthäus and Mehling 2020) .

Combining approaches: i) developed countries meeting UNFCCC 100 billion USD commitment on a grant-equivalent basis ii) stepped up technical assistance iii) infrastructure co-ordination iv) knowledge sharing by project preparation entities iv) harnessing project risk facilities such as guarantees could be instrumental for scaling climate finance for Paris-SDGs *(high confidence).* Figure 15.7 illustrates the interplay between infrastructure project financing phases, bond refinancing and opportunities for developing bond yield curve benchmarks in nurturing local capital markets and mobilising diverse investors. These project financing phases have varying risk-return profiles and different benchmarks to track performance are needed by investors for different types of securities that might be created (Ketterer 2014; Ketterer and Powell 2018).

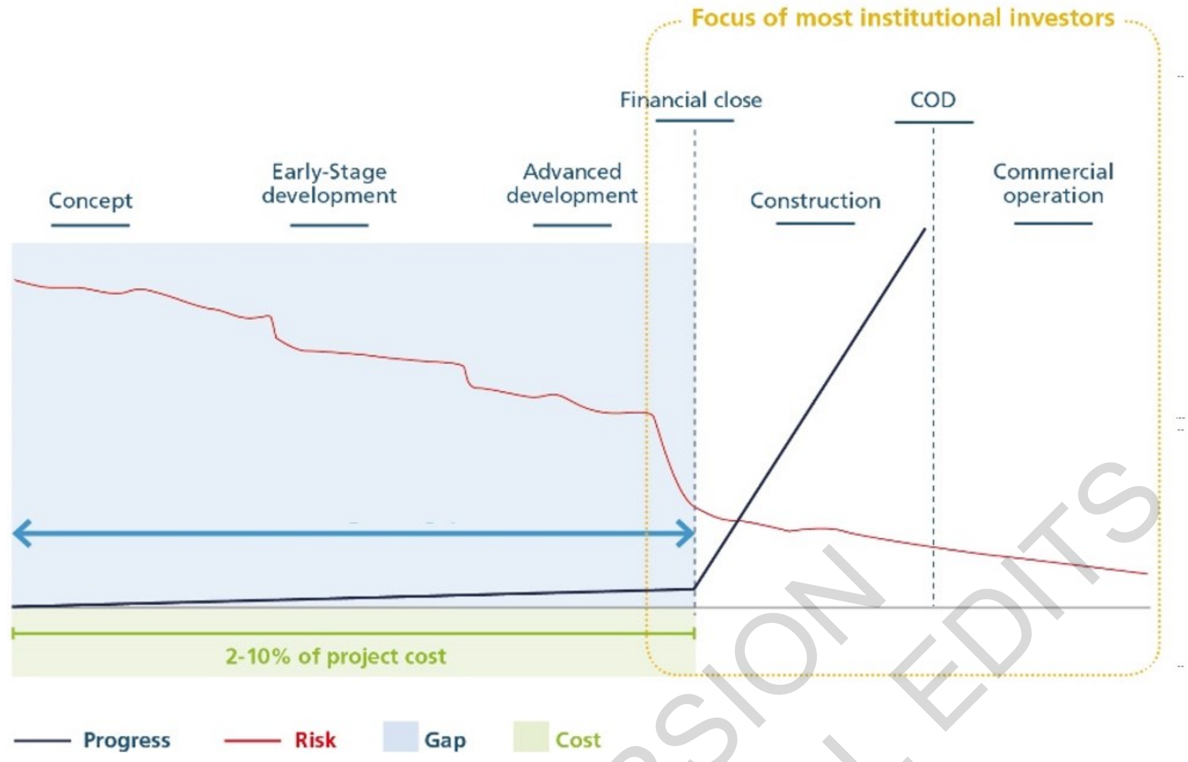


Figure 15.7 Bond refinancing mobilises institutional investors in mature project phase. De-risk early stage infrastructure projects. Source: Building on PIDG 2019

A (ODI 2018) survey of private and public project preparation facilities internationally, showed high failure rates in *early project preparation phases* with recommendations on "*one-stop-shops*" and knowledge sharing on effective approaches. During the very high-risk *concept phase* (Figure 15.7) – grants and technical assistance de-risk with design concepts, project proposals and feasibility studies completed to "kick-start" the right projects. The early stage developmental phase is characterised by short-term debt in the 2-5 year phase to complete construction enabled by concession finance. Bank loans are paid back by issuing bonds once the construction phase is completed. Such bond refinancing over say 15-25 years, in the *low risk mature project phase* can provide a lower cost of capital. Market-making to develop a pipeline of investment opportunities uses a complimentary mix of high-risk capital options in the form of grants, guarantees, equity, mezzanine financing that can help (Attridge and Gouett 2021) i) reduce up-front risks in the early phases ii) allow banks to recycle loans to new projects iii) galvanise multilateral technical assistance for building bond yield curve benchmarks and de-risking local currency bond issuance of long tenors such as green bonds/resilience bonds (Berensmann et al. 2015; CBI 2015; Mercer 2018; Dasgupta et al. 2019; PIDG 2019; Braga et al. 2021; CBI et al. 2021; Hourcade et al. 2021a,b) . Convergence 2019 points to investment from commercial banks with commercial debt of 11-15years maturity being covered by guarantees. To achieve scale, some have issued SPV green infrastructure project bonds combining tenors up to 15 years with credit ratings assigned to mobilise investors with community trusts for local participation (Mathews and Kidney 2012; Kaminker and Stewart 2012; Mbeng Mezui and Hundal 2013; Essers et al. 2016; Moody's Investors Service 2016; Ng and Tao 2016; Harber 2017). Bond refinancing could be facilitated through standardised national infrastructure style bonds, national infrastructure funds (Amonya 2009; Ketterer and Powell 2018) and country SPV infrastructure funds issuing bonds (Cavallo and Powell 2019) embedding MDBs.

Existing project risk facilities including guarantees could benefit from co-ordination, scaling and better reporting frameworks (high confidence**).** Individual and clubs of developed and developing countries currently provide public guarantees (ADB 2015; IIGCC 2015; Pereira Dos Santos 2018; GGGI 2019; PIDG 2019; AGF 2020; Garbacz et al. 2021). However MDB business model imposes limitations on use of guarantees and collaboration with other MDBs (Gropp et al. 2014; Schiff and Dithrich 2017; Lee et al. 2018; Pereira dos Santos and Kearney 2018b). Loans continue to dominate as the financial instrument of choice by MDBs and DFIs, with guarantees mobilising the most private finance for OECD reported data even if their use remains limited (IATFD 2020; OECD 2020c; Attridge and Gouett 2021). Ramping up the use of guarantees to mobilise private investment raises questions around understanding efficacy in the design as there is no one size that fits all and more research is required to better understand this aspect (Convergence 2019). Sample guarantee forms in literature: i) single country Sweden and USA DFI forms (SIDA 2016, DCA 2018) ii) multilateral institution offerings (Pereira Dos Santos 2018; IRENA 2020e) iii) multi-sovereign guarantees one-stop platforms such as those on the PIDG/Guarantco (PIDG 2019) and Africa Guarantee Fund owned by DFIs, including AfDB, AFD, NDF, and KfW (AGF 2020) iv) MIGA, established to provide political risk guarantees (enhanced green MIGA) (Déau and Touati 2018) v) multilateral partnerships with developing nations via infrastructure funds (see 15.6.7.2) and green infrastructure options (de Gouvello and Zelenko 2010; Studart and Gallagher 2015) vi) guarantees embedded in project risk facilities such as currency fund TCX established by 22 DFIs (TCX 2020) and vii) ASEAN and African multi-sovereign regional local currency bond guarantee funds and a co-guarantee platform (GGGI 2019; Garbacz et al. 2021). Fossil fuels currently benefit from de-risking tools from export credit agencies (Lawrence and Archer 2021) with questions around sustainable development (Wright 2011)); (Gupta et al. 2020) argue that these could be deployed for renewable energy. C40 Cities Facility; Blue Natural Capital Facility (IUCN 2021); Clean Cooking Fund (ESMAP 2021) and opportunities for guarantees in LDCs (Garbacz et al. 2021). World Bank's Renewables Risk Mitigation (GCF 2021), World Bank's Global Infrastructure Facility. UNEP Seed Capital are sample project facilities across diverse project types (GGGI 2019). Multilaterals offer credit enhancement to manage both actual and perceived risks: in the India corporate sector, renewable energy SPV project bonds have been guaranteed jointly by ADB and an infrastructure company raising the credit rating from sub-investment grade to investment grade to lower borrowing costs (ADB 2018; Agarwal and Singh 2018; Carrasco 2018).

Investment vehicles into green infrastructure come in various forms *(high confidence)* and can include indirect corporate investment such as bonds; semi-direct investment funds via pooled vehicles such infrastructure funds and private equity funds and project investment (direct) in green projects through equity and debt including loan, project bonds and green bonds. Pension funds in Australia and Canada direct investment in infrastructure is about 5% of total AUM (Inderst and Della Croce 2013) whilst less than 1% for OECD pension funds go to green infrastructure (Kaminker et al. 2013). Some regional developing country institutional investors use a variety of investment vehicles that span SPVs, private equity, domestic and regional local currency bond markets with statutory level mandates to address historic inequities (GEPF 2019). Cross-border collaboration in regional power markets such as Europe's Nordpool; for developing countries could be led by technical partnership from infrastructure funds and multilaterals (Oseni and Pollitt 2016; Juvonen et al. 2019; Chen et al. 2020; Nordpool 2021)**.** Barriers to investments include non-standardised investment vehicles of scale and lack of national infrastructure road maps to give investor confidence in government commitment. Some have set up infrastructure co-ordinating entities embedding local science and engineering R&D (IPA 2021; National Infrastructure Commission (NIC) 2021). (Arezki et al. 2016) argue that co-ordination within existing platforms could create a global infrastructure investment platform for de-risking through guarantees and securitization; (Matthäus and Mehling 2020) point to a global guarantee mechanism. Such multilateral approaches create credibility enhancing effects in developing capital markets. (Hourcade et al. 2021a) suggest that the overall economic efficiency could be higher with guarantees calibrated per ton on an agreed *"social, economic, and environmental value of mitigation actions [and] their co-benefits*" (Article 108, Paris

Agreement) which would operate as a notional carbon price (High-Level Commission on Carbon Prices 2017). The grant equivalent of guarantees and induced equity inflows could be far beyond the US 100 billion promise. Such cooperative solutions in adopting development of local capital markets would end the drawbacks of the current plethora of low-scale fragmented project-by-project and 'special-purpose' pilots and programs.

Harnessing existing bond markets and securities exchanges in nascent markets. The G20 has an action plan to support strengthening local currency bond markets and development of local capital markets is also part of the option for financing UN SDGs in developing countries (UN 2015a) 2015; UN 2019, 2020; IATFD 2016; UN IATFD 2021). Primers are available on bond market development to support policy choices (World Bank and IMF 2001; Silva et al. 2020; World Bank 2020; Adrian et al 2021; IMF and World Bank 2021). Developing government bond yield curves with different maturities can be an important policy objective *(high confidence)***.** This can support pricing discovery, liquidity (Wooldridge 2001) and can be achieved through step by step tranches from shorter to longer maturities to boost confidence and encourage municipals and other quasi-sovereigns. Money market instruments (such as, green commercial paper) anchor the short end of the yield curve with bonds of varying maturity issued by sovereign/quasi-sovereign entities (national treasuries, SOEs, municipalities) to mobilise investors (Goodfriend 2011; LSEG 2018; Tolliver et al. 2019). A variety of bonds are being used for developing countries including green (Ketterer et al. 2019), blue-water(Roth et al. 2019), transition, SDG/social, biodiversity bonds (Aglionby 2019), green/resilience bonds (AAC 2021); gender bonds (Andrade and Prado 2020)(; diaspora (LSEG 2017) and infrastructure project bonds (CBK 2021). Local policy-makers would gain from technical and financial assistance in building green yield curves, for example with support from multilaterals (EIB 2012; IATFD 2016; Shi 2017; EIB 2018). Green bonds are one of the most readily accessible to help fund Paris goals (Tolliver et al. 2019; Tuhkanen and Vulturius 2020). Section 15.3.2 refers to the growth in labelled bond markets (CBI 2021b), low borrowing costs and yield curve building in Europe (Bahceli 2020; Serenelli 2021; Stubbington 2021; HM Treasury and UK DMO 2021). For developing countries, labelled bonds have mostly been in hard currency (e.g. (Smith 2021)) despite local currency markets making up more than 80 percent total debt stock (IMF and World Bank 2016; Silva et al. 2020; Adrian et al 2021; Inderst 2021). The labelled bonds issuance by multilaterals do not currently mobilise the trillion levels needed. Research studies show that participating in green bond markets in part depends on a country having credible NDCs (Tolliver et al. 2020a,b) and highlights diverse approaches working together to support local bond market development (Amacker and Donovan 2021; ICMA 2021; IMF and World Bank 2021)

Technical assistance options would benefit from co-ordination. Labelled bond costs remain high. Developing countries are using fiscal incentives, grants, and guarantees to support nascent bond markets with most taxonomies under development *(high confidence*). Technical assistance requirements to improve the investment climate and bond market development will vary across national capacities. These would benefit from the 100 billion USD UNFCCC grant equivalent basis to develop i) regulatory and policy frameworks ii) UN national statistical systems (Singh et al. 2016; MacFeely and Barnat 2017; Paris21 2018; Bleeker and Abdulkadri 2020);iii) credible NDC and SDG investment plans iv) project assessment certification and taxonomies v) bond market guidelines vi) public finance management (US DoJ 2019, 2009). Other technical assistance channels include diaspora entities, universities and learned societies (ICEAW 2012; Mahmud and Huq 2018; UNFCCC 2021). LDCs are least likely to have active capital markets. Clubs of LDCs are partnering with AAA MDBs in aggregation approaches (AfDB 2020; GCF 2020b). Some UN entities provide technical assistance on municipal aggregation of projects (UN CDF 2020) with Africa, LDC, SIDS nations and cities accessing green technical facilities and listings for labelled bonds (C40 Cities Climate Leadership Group 2016; Gorelick 2018; Jackson 2019; FSD Africa and CBI 2020; Gorelick and Walmsley 2020; MoE Fiji 2020 2020; IFC 2021). Elevated climate risks imperil developing country ability to repay debts (Schmidt 2014; Buhr et al. 2018; Volz et al. 2020; Dibley et al. 2021). To lower overall costs and achieve more - entities have accessed technical assistance, listed local currency labelled bonds, used credit enhancing bond guarantees, regulatory treatments and philanthropy schemes (Europe 2020 Project Bond Initiative 2012; SBN 2018; Agliardi and Agliardi 2019; Banga 2019). In the regions, China issued guidelines for stock exchanges and regulatory support for green bonds (Cao and Ma 2021), India issued regulations for local issuance of green bonds (CBI 2019a) while in the LAC region; both plain vanilla and labelled bonds use the same authority (Ketterer et al. 2019). Africa, LDC and SIDS nations are reviewing ways to harness local exchanges (SSE 2018; GCF 2019; ASEA et al 2021; UN CDF 2021b). For taxonomies, the differences reflect the multitude of local Just Transition pathways, some with purely environmental focus and others incorporating livelihood improvements (ICMA 2021). The sustainable bond market has been expanding as transition bonds become listed in anticipation of future developments (Roos 2021).

Progress towards transparency using scientific-based methods to build trust and accountability. After 60years of development finance, critics underline limits coming from i) lack of aid and debt transparency (Moyo 2009; Mkandawire 2010; PWYF 2020) ii) mining-fossil fuels sector and illicit finance (Plank 1993; Sachs and Warner 2001; Hanlon 2017b)) iii) lack of developed country commitment to pledges (Nhamo and Nhamo 2016) iv) unregulated players as financial intermediaries in blended finance (Pereira 2017; Donaldson and Hawkes 2018; Tan 2019) v) weak accountability reflected in soft SDG data measurement and vi) burden of responsibility in mobilising resources for Paris and SDG to countries with historically soft institutional capacity (Hickel 2015; Donald and Way 2016; Scheyvens et al. 2016; Liverman 2018). Literature around trust in blended finance pinpoints four progress areas in accountability. First, debt transparency through public debt registries, centralised UN legacy debt restructuring and science-centred UN national statistical systems (Donaldson and Hawkes 2018; Jubilee Debt Campaign 2019; Stiglitz and Rashid 2020). Second, international reporting bell-weathers could be called upon to produce harmonized mandatory reporting frameworks that capitalize on TCFD to capture climate, debt sustainability (see 15.6.7.3), SDG and fossil fuel (GISD 2020); third, standardization of assessment by third parties of the quantity and values of carbon saved by green projects (Hourcade et al. 2012) and of their contribution to quantified performance biodiversity targets (FfB 2021) to facilitate their bundling, securitization and repackaging in standardized liquid products and bonds (Arezki et al. 2016; Blended Finance Taskforce 2018a).

15.6.8 Facilitating the development of new business models and financing approaches

New and innovative business models and financing approaches have emerged to help overcome barriers related to transactions costs by aggregating and/or transferring financing needs and establishing supply of finance for stakeholder groups lacking financial inclusion *(high confidence)*.

15.6.8.1 Service-based business models in the energy and transport sectors

Energy-as-a-service (EaaS) is a business model whereby customers pay for an energy service without having to make any upfront capital investment (PWC 2014; Hamwi and Lizarralde 2017; Cleary and Palmer 2019). EaaS performance-based contracts can also be a form of "creative financing" for capital improvement that makes it possible to fund energy upgrades from cost reductions and deployment of decentralised renewable energy (KPMG 2015; Moles-Grueso et al. 2021). Innovation in EaaS has started at the household level, where smart meters using real-time data are used to predict peak demand levels and optimise electricity dispatch (Chasin et al. 2020)(Government of UK 2016) (Smart Energy International 2018).

Aggregators. An aggregator is a grouping of agents in a power system to act as a single entity when engaging in power system markets (MIT 2016). Aggregators can use operation optimisation platforms to provide real-time operating reserve capacity and a range of balancing services to integrate higher shares of variable renewable energy (VRE) (Zancanella et al. 2016)(Ma et al. 2017; Enbala 2018; Research and Markets 2017; IRENA 2019b). This makes a business case for deferred investments in grid infrastructure *(medium confidence)*. Aggregating and managing demand-response of heat systems (micro CHP and heat pumps) has shown reduction in peak demand (TNO 2016).

Peer-to-peer (P2P) electricity trading. Producers and consumers can directly trade electricity with other consumers in an online marketplace to avoid the relatively high tariffs and the relatively low buy-back rates of traditional utilities (IRENA 2020f; Liu et al. 2019). P2P models trading with distributed energy resources reduce transmission losses and congestion (Mengelkamp et al. 2018; SEDA 2020; Lumenaza 2020; Sonnen 2020; UNFCCC 2020).

Community-ownership models. Community-ownership models refer to the collective ownership and management of energy-related assets with lower levels of investment, usually distributed renewable energy resources but also recently in heating systems and energy services (e.g. storage and charging) (Gall 2018; IRENA 2018; Kelly and Hanna 2019; Singh et al. 2019; Bisello et al. 2021; Maclurcan and Hinton 2021). Community-ownership projects may need significant upfront investments, and the ability of communities to raise the required financing might prove insufficient, which can be supported by microcredits in the initial stages of the projects (Aitken 2013; Federici 2014; REN21 2016; Rescoop 2020).

Payment method: Pay-as-you-go (PayGo). PayGo business models emerged to address the energy access challenge and provide chiefly solar energy at affordable prices, using mobile telecommunication to facilitate payment through instalments (IRENA 2019c) (Yadav et al. 2019). However, PayGo has the technology and product risk, requires a financially viable and large customer base, and the system supplier must provide a significant portion of the finance and requires substantial equity and working capital (C40 Cities Climate Leadership Group 2018).

Transport sector business models. Analog to EaaS, Mobility-as-a-Service (MaaS) offers a business model whereby customers pay for a mobility service without making any upfront capital investment (e.g., buying a car). MaaS tends to deliver significant urban benefits (e.g., cleaner air) and brings in efficiency gains in the use of resources *(high confidence)*. However, the switch to MaaS hardly improves the carbon footprint and further tempted on-demand mobility is likely to nurture carbon emissions (Suatmadi et al. 2019). Therefore, to support climate change mitigation, MaaS must be integrated with the deployment of smart charging of electric (autonomous) vehicles coupled to renewable energy sources (IRENA 2019d)(Jones and Leibowicz 2019).

Financial technology applications to climate change. Financial technology abbreviated as 'fintech' applies to data-driven technological solutions that aims to improve financial services (Schueffel 2018; Dorfleitner et al. 2017; Lee and Shin 2018). Fintech can enhance climate investment in innovative financial products and build trust through data, but also presents some challenges including related to potentially significant emissions from increased energy use with distributed transactions (Lei et al. 2021). Blockchain is a key fintech that secures individual transactions in a distributed system, which can have many applications with high impact potential but is also associated with uncertainty (OECD 2019c; World Energy Council 2019). Fintech applications with climate change mitigation potential have been growing recently, including tracking payment or asset history for credit scoring in AFOLU activities (Nassiry 2018; Davidovic et al. 2019), blockchain supported grid transactions (Livingston et al. 2018), carbon accounting throughout value chains (World Bank 2018b), or transparency and verification mechanisms for green financial instrument investors (Kyriakou et al. 2017; Stockholm Green Digital Finance 2017). Generally, blockchain and digital currency applications are not well covered by governance systems (Tapscott and Kirkland 2016; Nassiry 2018), which could lead to problems with security (Davidovic et al. 2019), and some licensing and prudential supervision frameworks are in flux.

15.6.8.2 Nature-based solutions including REDD+

Nature-based solutions are 'actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits (Cohen-Shacham et al. 2016)'. Nature-based solutions consist of a wide range of measures including ecosystem-based mitigation and adaptation.

The studies on the investment and finance for the nature-based solutions is still limited. However, framework and schemes to incentivise the implementation of nature-based solutions, such as reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries (REDD+), which contributes to the climate change mitigation has been actively discussed under the UNFCCC, with lessons from finance for REDD+ being available.

If effectively implemented, nature-based solutions can be cost-effective measures and able to provide multiple benefits, such as enhanced climate resilience, enhanced climate change mitigation, biodiversity habitat, water filtration, soil health, and amenity values (Griscom et al. 2017; Keesstra et al. 2018; OECD 2019d; Griscom et al. 2020; Dasgupta 2021) *(high confidence)*.

The nature-based solutions have large potential to address climate change and other sustainable development issues *(high confidence)*. Nature-based solutions are undercapitalised and the limited investment and finance, especially limited private capital is widely recognised as one of the main barriers to the implementation and monitoring of the nature-based solutions (Seddon et al. 2020; Toxopeus and Polzin 2021; UNEP et al. 2021) Finance and investment models that generates its own revenues or consistently saves costs are necessary to reduce dependency on grants (Schäfer et al. 2019; Wamsler et al. 2020).

REDD+. REDD+, can significantly contribute to climate change mitigation and also produce other co-benefits like climate change adaptation, biodiversity conservation, and poverty reduction, if well-implemented (Milbank et al. 2018; Morita and Matsumoto 2018) *(high confidence)*. We use the term REDD+ broadly, not limited to REDD+ implemented under the UNFCCC decisions, including Warsaw Framework for REDD+ (see Chapter 14), but include voluntary REDD+ projects, such as projects which utilise voluntary carbon markets. Finance is a core element that incentivise and implement REDD+ activities. Various financial sources are financing REDD+ activities, including bilateral and multilateral, public and private, and international and domestic sources, with linking with several finance approaches/mechanisms including results-based finance and voluntary carbon markets (FAO 2018). However, there is lack of sufficient finance for REDD+ (Lujan and Silva-Chávez 2018; Maguire et al. 2021). REDD+ under the UNFCCC are implemented in three phases, readiness, implementation, and results-based payment phases. The Ecosystem Marketplace identified that at least USD 5.4 billion in REDD+ in three phases funding committed through multiple development finance institutions so far (Maguire et al. 2021), and public funds are main sources that are supporting three phases, and most of the REDD+ finance were spent to the readiness phase (Atmadja et al. 2018; Lujan and Silva-Chávez 2018; Watson and Schalatek 2021). There is significant gap between the existing finance and finance needs of REDD+ in each phase (Lujan and Silva-Chávez 2018). Furthermore, private sector contribution to REDD+ is currently limited mostly to the project-scale payments for carbon offsets/units through voluntary carbon market (McFarland 2015; Lujan and Silva-Chávez 2018).

Current main challenges of REDD+ finance include the uncertainty of compliance carbon markets (which allow regulated entities to obtain and surrender emissions allowances or offsets to meet regulatory emissions reduction targets) (Maguire et al. 2021), as well as limited engagement of private sector in REDD+ finance *(high confidence)*. With regard to the compliance carbon markets, at the international level, integrating climate cooperation through carbon markets into Article 6 of the Paris Agreement and including REDD+ has potential to enable emission reduction in more cost-effective way, while the links between carbon markets and REDD+ under the Article 6 is under discussion at the

UNFCCC (Environmental Defense Fund 2019; Maguire et al. 2021) (see Chapter 14). At the national and subnational levels, although compliance carbon markets such as in New Zealand, Australia and Colombia allow forest carbon units, how REDD+ will be dealt in the national and subnational government- led compliance carbon markets are uncertain (Streck 2020; Maguire et al. 2021). As for limited engagement of private sector in REDD+ finance, there are various reasons why mobilising more private finance in REDD+ is difficult (Dixon and Challies 2015; Laing et al. 2016; Golub et al. 2018; Ehara et al. 2019; Streck 2020). The challenges include the needs of a clear understanding of carbon rights and transparent regulation on who can benefit from national REDD+ (Streck 2020); a clear regulatory framework and market certainty (Dixon and Challies 2015; Laing et al. 2016; Golub et al. 2018; Ehara et al. 2019); strong forest governance (Streck 2020), and implementation of REDD+ activities in different levels, national and subnational levels. Other challenges are associated with the nature of forest-based mitigation activities, the costs and complexity for monitoring, reporting and verification of REDD+ activities, because of the need to consider the risks of permanence, carbon leakage, and precisely determine and monitor the forest carbon sinks (van der Gaast et al. 2018; Yanai et al. 2020). Although REDD+ has many challenges to mobilise more private finance, there is discussion on exploring other finance opportunities for forest sector, such as building new blended finance models combining different funding sources like public and private finance (Streck 2016; Rode et al. 2019), and developing enhanced bonds for forest-based mitigation activities (World Bank 2017).

Private finance opportunities for nature-based solutions. The development of nature-based solutions face barriers that relate to the value proposition, value delivery and value capture of nature-based solutions business models and sustainable sources of public/private finance to tap into (Toxopeus and Polzin 2017; Mok et al. 2021) *(high confidence)*. However, the demand of establishing new finance and business models to attract both public and private finance to nature-based solutions is increasing in a wide range of topics such as urban areas, forestry and agriculture sectors, and blue natural capital including mangroves and coral reefs (Toxopeus and Polzin 2017; EIB 2019; Cziesielski et al. 2021; Mok et al. 2021; Thiele et al. 2021; UNEP et al. 2021) Furthermore, the recognition of the needs of financial institutions to identify the physical, transition and reputational risks resulting from not only the climate change but also loss of biodiversity is gradually increasing (De Nederlandsche Bank and PBL Netherlands Environmental Assessment Agency 2020; Dasgupta 2021; TNFD 2021). Development of finance and business models for nature-based solutions need to be explored, for example through utilizing a wide range of financial instruments (e.g. equity, loans, bonds, and insurance), and creating standard metrics, baselines and common characteristics for nature-based solutions to promote the creation of a new asset class (Thiele et al. 2021; UNEP et al. 2021).

15.6.8.3 Exploring gender-responsive climate finance

Global and national recognition of the lack of finance for women has led to increasing emphasis on financial inclusion for women (*high confidence*). Currently, it is estimated that 980 million women are excluded from formal financial system (Miles and Wiedmaier-Pfister 2018); and there is a 9% gender gap in financial access across developing countries (Demirguc-Kunt et al. 2018). This gender gap is the percent of men and women with bank accounts as measured and reported in the Global Financial Inclusion (Global Findex) database. Policies and framework to expand and enhance financial inclusion also extend to the area of climate finance (*high confidence*). Since AR5, there remains many questions and not enough evidence on the gender, distribution and allocative effectiveness of climate finance in the context of gender equality and women's empowerment (Williams 2015a; Chan et al. 2018; Wong et al. 2019). Nonetheless, the existing global policy framework (entry points, policy priorities etc.) of climate funds is gradually improving in order to support women's financial inclusion in both the public and the private dimensions of climate finance/investment (Schalatek 2015; Chan et al. 2018; Schalatek 2020). At the level of public multilateral climate funds, there have been significant improvements in integrating gender equality and women's empowerment issues in the governance structures, policies, project approval and implementation processes of existing multilateral climate funds such as the UNFCCC's funds managed by the Global Environment Facility, the Green Climate Fund and the World

Bank's CIFs (Schalatek 2015; Williams 2015a; GGCA 2016; GCF 2017) (*high confidence*). But according to a recent evaluation report, the integration of gender into operational policies and programme is fragmented and there is lack of an 'adequate, systematic and comprehensive gender equality approach for the allocation and distribution of funds for projects and programmes on the ground' (GEF Independent Evaluation Office 2017; Schalatek 2018). The review found that 'almost half of the analysed sample of 70 climate projects were judged to be largely gender-blind, and only 5% considered to have successfully mainstreamed gender, including in two Least Developed Countries Fund adaptation projects' (GEF Independent Evaluation Office 2017; Schalatek 2018). While the GCF requires funding proposals to consider gender impact as part of their investment framework[7], the fund does not have its own funding stream targeted to women's project on the ground, nor is there as yet an evaluation as to how entities are actually implementing gender action plan in the projects. In the case of the CIFs, as noted by (Schalatek 2018), 'gender is not included in the operational principles of the Pilot Program on Climate Resilience (PPCR), which funds programmatic adaptation portfolios in a few developing countries, although most pilot countries have included some gender dimensions'. And, 'gender is not integrated into the operations of the Clean Technology Fund (CTF), which finances large-scale mitigation in large economies and accounts for 70% of the CIFs pledged funding portfolio of 8.2 billion USD' (Schalatek 2018). However, both the Forest Investment Program (FIP) and the Scaling-Up Renewable Energy in Low-Income Countries Program (SREP) have integrated gender equality as either a co-benefit or core criteria of these programmes (Schalatek 2018).

Overall, efforts to promote gender responsive/sensitive climate finance, at national and local levels, both in the public and private dimensions and more specifically in mitigation-oriented sectors such as clean and renewable energy remains deficient (*high confidence*). Recent developments in the capital markets in the areas of social bond are focused around gender bonds -- debt instruments targeted to activities and behaviours that are relevant to gender equality and women's empowerment. These bonds are aligned with Sustainability-linked Bonds as well as Social Bonds Principles of the International Capital Market Association. Issuances of gender-labelled bonds are increasing in the Asia Pacific region (the most comprehensive initiative is the Impact Investment Exchange's (IIX) multi-country USD150 million Women's Livelihood Bond[8]) and in Latin America, Columbia, Mexico and Panama each have gender bond issuances). Additionally, a few developing countries, such as Pakistan (May 2021) and Morocco (March 2021) have issued gender bond guidelines for financial market participants.

Linkage to sectoral climate change issues and gender and climate finance. Subsets of actions designed to enhance women's more formal integration into climate policies, programmes and actions by the global private sector include: investment in clean energy, redirecting funds to support women and vulnerable region as a component of social and green bonds as well as insurance for climate risk management. In the latter context, insurance providers are arguing that 'given the fact that women are disproportionately affected by climate change, there could be new finance innovations to address this gap.' AXA and IFC estimate that the global women's insurance market has the opportunity to grow to three times its current size, to 1.7 trillion USD by 2030 (AXA Group et al. 2015; GIZ et al. 2017). However, across the board and in particular with regard to public funds, despite improvements in the substantive gender sensitization and operational gender responsiveness of multilateral and bilateral climate finance funds operations, current flows of public and climate finance do not seem to be going

FOOTNOTE[7] Notably, the GCF provides guidance to Accredited Entities submitting funding proposals on the inclusion of an initial gender and social assessment during the project planning, preparation and development stage and a gender and social inclusion action plan at the project preparation stage.

FOOTNOTE[8] The WLB series has been on the market since 2017 when WLB1 was launched. WLB2 issuance of $12 million arrived January 2020. WLB 3was launched December 2020 **to** support 180,000 underserved women and women entrepreneurs in the Asia Pacific to respond, to recover from, and to build resilience in the aftermath of the COVID-19 pandemic. See (IIX 2020) and (Rockfeller Foundation and Shujog 2016).

to women and the local communities in significant amounts (Chan et al. 2018; Schalatek 2020). At the same time, evaluations of the effectiveness of climate finance show that equitable flow of climate finance can play an important role in levelling the playing field and in enabling women and men to successful respond to climate change and to enable the success and sustainability of local response in ensuring effective and sustainable climate strategies that can contribute to the global goals of the Paris Agreement (Minniti and Naudé 2010; Bird et al. 2013; Barrett 2014; Eastin 2018). This is particularly, so in the case of female-owned MSMEs, who, the literature increasingly show, are key to promoting resilience at micro and macro scale in many developing countries (Omolo et al. 2017; Atela et al. 2018; Crick, F. et al. 2018).

Frequently Asked Questions

FAQ 15.1 What's the role of climate finance and the finance sector for a transformation towards a sustainable future?

The Paris Agreement has widened the scope of all financial flows from climate finance only to the full alignment of finance flows with the long-term goals of the Paris Agreement. While climate finance relates historically to the financial support of developed countries to developing countries, the Paris Agreement and its Article 2.1(c) has developed on a new narrative on that goes much beyond traditional flows and relates to all sectors and actors. Finance flows are consistent when the effects are either neutral with or without positive climate co-benefits to climate objectives; or explicitly targeted on climate benefits in adaptation and/or mitigation result areas. Climate-related financial risk is still massively underestimated by financial institutions, financial decision-makers more generally and also among public sector stakeholders limiting the sector's potential of being an enabler of the transition. The private sector has started to recognise climate-related risks and consequently redirect investment flows. Dynamics vary across sectors and regions with the financial sector being an enabler of transitions in only some selected (sub-)sectors and regions. Consistent, credible, timely and forward-looking political leadership remains central to strengthen the financial sector as enabler.

FAQ 15.2 What's the current status of global climate finance and the alignment of global financial flows with the Paris Agreement?

There is no agreed definition of climate finance. The term 'climate finance' is applied to the financial resources devoted to addressing climate change by all public and private actors from global to local scales, including international financial flows to developing countries to assist them in addressing climate change. Total climate finance includes all financial flows whose expected effect aims to reduce net greenhouse gas (GHG) emissions and/or to enhance resilience to the impacts of current and projected climate change. This includes private and public funds, domestic and international flows and expenditures. Tracking of climate finance flows faces limitations, in particular for national climate finance flows.

Progress on the alignment of financial flows with low GHG emissions pathways remains slow. Annual global climate finance flows are on an upward trend since the fifth Assessment Report, according to CPI reaching more than 630 billion USD in 2019/2020, however, growth has likely slowed down and flows remain significantly below needs. This is driven by barriers within and outside the financial sector. More than 90% of financing is allocated to mitigation activities despite the strong economic rationale of adaptation action. Adjusting for higher estimates on current flows for energy efficiency based on IEA data, the dominance of mitigation becomes even stronger. Persistently high levels of both public and private fossil-fuel related financing as well as other misaligned flows continue to be of major concern despite promising recent commitments. Significant progress has been made in the commercial finance sector with regard to the awareness of climate risks resulting from inadequate financial flows and climate action. However, a more consequent investment and policy decision making that enables a rapid redirection of financial flows is needed. Regulatory support as a catalyser is an essential convey of such redirections. Dynamics across sectors and regions vary with some being better positioned to close financing gaps and to benefit from an enabling role of finance in the short-term.

FAQ 15.3 What defines a financing gap, and where are the critically identified gaps?

A financing gap is defined as the difference between current flows and average needs to meet the long term goals of the Paris Agreement. Gaps are driven by various barriers inside (short-termism, information gaps, home bias, limited visibility of future pipelines) and outside (e.g. missing pricing of externalities, missing regulatory frameworks) of the financial sector. Current mitigation financing flows come in significantly below average needs across all regions and sectors despite the availability of sufficient capital on a global basis. Globally, yearly climate finance flows have to increase by factor between 3 to 6 to meet average annual needs until 2030.

Gaps are in particular concerning for many developing countries with COVID-19 exacerbating the macroeconomic outlook and fiscal space for governments. Also, limited institutional capacity represents a key barrier for many developing countries burdening risk perceptions and access to appropriately priced financing as well as limiting their ability to actively manage the transformation. Existing fundamental inequities in access to finance as well as its terms and conditions, and countries exposure to physical impacts of climate change overall result in a worsening outlook for a global just transition.

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Chapter 16: Innovation, technology development and transfer

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Date of Draft: 28/11/2021

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Executive summary

Innovation in climate mitigation technologies has seen enormous activity and significant progress in recent years. Innovation has also led to, and exacerbated, trade-offs in relation to sustainable development. (*high confidence*). Innovation, can leverage action to mitigate climate change by reinforcing other interventions. In conjunction with other enabling conditions innovation can support system transitions to limit warming and help shift development pathways. The currently widespread implementation of solar photovoltaic (solar PV) and LEDs, for instance, could not have happened without technological innovation *(high confidence)*. Technological innovation can also bring about new and improved ways of delivering services that are essential to human well-being. At the same time as delivering benefits, innovation can result in trade-offs that undermine both progress on mitigation and progress towards other sustainable development goals. Trade-offs include negative externalities – for instance greater environmental pollution and social inequalities – rebound effects leading to lower net emission reductions or even increases in emissions, and increased dependency on foreign knowledge and providers *(high confidence)*. Effective governance and policy has the potential to avoid and minimise such misalignments (*medium evidence, high agreement*). {16.1, 16.2, 16.3, 16.4, 16.5.1, 16.6}

A systemic view of innovation to direct and organize the processes has grown over the last decade. This systemic view of innovation takes into account the role of actors, institutions, and their interactions and can inform how innovation systems that vary across technologies, sectors and countries, can be strengthened (*high confidence).* Where a systemic view of innovation has been taken, it has enabled the development and implementation of indicators that are better able to provide insights in innovation processes. This, in turn, has enabled the analysis and strengthening of innovation systems. Traditional quantitative innovation indicators mainly include R&D investments and patents. Systemic indicators of innovation, however, go well beyond these approaches. They include structural innovation system elements including actors and networks, as well as indicators for how innovation systems function, such as access to finance, employment in relevant sectors, and lobbying activities. For example, in Latin America, monitoring systemic innovation indicators for the effectiveness of agroecological mitigation approaches has provided insights on the appropriateness and social alignment of new technologies and practices. Climate-energy-economy models, including integrated assessment models, generally employ a stylised and necessarily incomplete view of innovation, and have yet to incorporate a systemic representation of innovation systems {16.2, 16.2.4, 16.3, 16.3.4, 16.5, Table 16.7, Box 16.1, Box 16.5}.

A systemic perspective on technological change can provide insights to policymakers supporting their selection of effective innovation policy instruments *(high confidence)*. A combination of scaled-up innovation investments with demand-pull interventions can achieve faster technology unit cost reductions and more rapid scale-up than either approach in isolation *(high confidence).* These innovation policy instruments would nonetheless have to be tailored to local development priorities, to the specific context of different countries, and to the technology being supported. The timing of interventions and any trade-offs with sustainable development also need to be addressed. Public R&D funding and support as well as innovation procurement have shown to be valuable for fostering innovation in small to medium cleantech firms. Innovation outcomes of policy instruments not necessarily aimed at innovation, such as feed-in tariffs, auctions, emissions trading schemes, taxes and renewable portfolio standards, vary from negligible to positive for climate change mitigation. Some specific designs of environmental taxation can also result in negative distributional outcomes. Most of the available literature and evidence on innovation systems come from industrialised countries and larger developing countries. However, there is a growing body of evidence from developing countries and small island developing states (SIDS) {16.4, 16.4.4.3, 16.4.4.4, 16.5, 16.7}.

Experience and analyses show that technological change is inhibited if technological innovation system functions are not adequately fulfilled, this inhibition occurs more often in developing countries. *(high confidence)*. Examples of such functions are knowledge development, resource mobilisation, and activities that shape the needs, requirements and expectations of actors within the innovation system (guidance of the search). Capabilities play a key role in these functions, the build-up of which can be enhanced by domestic measures, but also by international cooperation *(high confidence)*. For instance, innovation cooperation on wind energy has contributed to the accelerated global spread of this technology. As another example, the policy guidance by the Indian government, which also promoted development of data, testing capabilities and knowledge within the private sector, has been a key determinant of the success of an energy-efficiency programme for air conditioners and refrigerators in India. {16.3, 16.5, 16.6, Cross-Chapter Box 12 in this chapter, Box 16.3}

Consistent with innovation system approaches, the sharing of knowledge and experiences between developed and developing countries can contribute to addressing global climate and sustainable development goals. The effectiveness of such international cooperation arrangements, however, depends on the way they are developed and implemented (*high confidence*). The effectiveness and sustainable development benefits of technology sharing under market conditions appears to be determined primarily by the complexity of technologies, local capabilities and the policy regime. This suggests that the development of planning and innovation capabilities remains necessary, especially in least-developed countries and SIDSs. International diffusion of low-emission technologies is also facilitated by knowledge spillovers from regions engaged in clean R&D (*medium confidence*).

The evidence on the role of intellectual property rights (IPR) in innovation is mixed. Some literature suggests that it is a barrier while and other sources suggests that it is an enabler to the diffusion of climate-related technologies *(medium confidence).* There is agreement that countries with well-developed institutional capacity may benefit from a strengthened IPR regime, but that countries with limited capabilities might face greater barriers to innovation as a consequence. This enhances the continued need for capacity building. Ideas to improve the alignment of the global IPR regime and addressing climate change include specific arrangements for least-developed countries, case-by-case decision-making and patent-pooling institutions. {16.2.3.3, 16.5, Box 16.10}

Although some initiatives have mobilised investments in developing countries, gaps in innovation cooperation remain, including in the Paris Agreement instruments. These gaps could be filled by enhancing financial support for international technology cooperation, by strengthening cooperative approaches, and by helping build suitable capacity in developing countries across all technological innovation system functions (*high confidence*). The implementation of current arrangements of international cooperation for technology development and transfer, as well as capacity building, are insufficient to meet climate objectives and contribute to sustainable development. For example, despite building a large market for mitigation technologies in developing countries, the lack of a systemic perspective in the implementation of the Clean Development Mechanism, operational since the mid-2000s, has only led to some technology transfer, especially to larger developing countries, but limited capacity building and minimal technology development (*medium confidence)*. In the current climate regime, a more systemic approach to innovation cooperation could be introduced by linking technology institutions, such as the Technology Mechanism, and financial actors, such as the financial mechanism. {16.5.3}

Countries are exposed to sustainable development challenges in parallel with the challenges that relate to climate change. Addressing both sets of challenges simultaneously presents multiple and recurrent obstacles that systemic approaches to technological change could help resolve, provided they are well managed *(high confidence)*. Obstacles include both entrenched power relations dominated by vested interests that control and benefit from existing technologies, and governance structures that continue to reproduce unsustainable patterns of production and consumption (*medium confidence*). Studies also highlight the potential of cultural factors to strongly influence the pace and direction of technological change. Sustainable solutions require adoption and mainstreaming of locally novel technologies that can meet local needs, and simultaneously address the Sustainable Development Goals (SDGs). Acknowledging the systemic nature of technological innovation, which involve many levels of actors, stages of innovation and scales, can lead to new opportunities to shift development pathways towards sustainability. {16.4, 16.5, 16.6}

An area where sustainable development, climate change mitigation and technological change interact is digitalisation. Digital technologies can promote large increases in energy efficiency through coordination and an economic shift to services, but they can also greatly increase energy demand because of the energy used in digital devices. System-level rebound effects may also occur. (*high confidence*) Digital devices, including servers, increase pressure on the environment due to the demand for rare metals and end-of-life disposal. The absence of adequate governance in many countries can lead to harsh working conditions and unregulated disposal of electronic waste. Digitalization also affects firms' competitiveness, the demand for skills, and the distribution of, and access to, resources. The existing digital divide, especially in developing countries, and the lack of appropriate governance of the digital revolution can hamper the role that digitalization could play in supporting the achievement of stringent mitigation targets. At present, the understanding of both the direct and indirect impacts of digitalization on energy use, carbon emissions and potential mitigation, is limited (*medium confidence*). {Cross-Chapter Box 11 in this chapter, 16.2}

Strategies for climate change mitigation can be most effective in accelerating transformative change when actions taken to strengthen one set of enabling conditions also reinforce and strengthen the effectiveness of other enabling conditions *(medium confidence)*. Applying transition or system dynamics to decisions can help policymakers take advantage of such high-leverage intervention points, address the specific characteristics of technological stages, and respond to societal dynamics. Inspiration can be drawn from the global unit cost reductions of solar PV, which were accelerated by a combination of factors interacting in a mutually reinforcing way across a limited group of countries (*high confidence*). {Box 16.2, Cross-Chapter Box 10 in chapter 14}

Better and more comprehensive data on innovation indicators can provide timely insights for policymakers and policy design locally, nationally and internationally, especially for developing countries, where such insights are missing more often. Data needed include on those that can show the strength of technological, sectoral and national innovation systems. It is also necessary to validate current results and generate insights from theoretical frameworks and empirical studies for developing countries contexts. Innovation studies on adaptation and mitigation other than energy and ex-post assessments of the effectiveness of various innovation-related policies and interventions, including R&D, would also provide benefits. Furthermore, methodological developments to improve the ability of Integrated Assessment Models (IAMs) to capture energy innovation system dynamics, and the relevant institutions and policies (including design and implementation), would allow for more realistic assessment. {16.2, 16.3, 16.7}

16.1 Introduction

Technological change and innovation are considered key drivers of economic growth and social progress (Brandão Santana et al. 2015; Heeks and Stanforth 2015). The economic benefit derived from increased production and consumption of goods as well as services create higher demands for improved technologies (Gossart 2015). Since the Industrial Revolution, however, and notwithstanding the benefits, this production and consumption trend and the technological changes associated to it have also come at the cost of long-term damage to the life support systems of our planet (Alarcón and Vos 2015; Steffen et al. 2015). The significance of the such impacts depends on the technology, but also on the intrinsic characteristics of the country or region analysed (Brandão Santana et al. 2015).

Other chapters in this volume have discussed technological change in various ways, including as a framing issue (chapter 1), in the context of specific sectors (chapters 6-11), for specific purposes (chapter 12) and as a matter of policy, international cooperation and finance (chapters 13-15). Chapter 2 discusses past trends in technological change and chapters 3 and 4 discuss it in the context of future modelling. In general, implicitly or explicitly, technological change is assigned an important role in climate change mitigation and achieving sustainable development (Thacker et al. 2019), also in past IPCC reports (IPCC 2014, 2018a). Chapter 16 describes how a well-established innovation system at a national level, guided by well-designed policies, can contribute to achieve mitigation and adaptation targets along with broader sustainable development goals avoiding, in the process, undesired consequences of technological changes.

The environmental impacts of social and economic activities, including emissions of GHG, are greatly influenced by the rate and direction of technological changes (Jaffe et al. 2000). Technological changes usually designed and used to increase productivity and reduce the use of natural resources can lead to increasing production and consumption of goods and services through different rebound effects that diminish the potential benefits of reducing the pressure on the environment (Grübler 1998; Kemp and Soete 1990; Gossart 2015; Sorrell 2007; Barker et al. 2009).

Those environmental impacts depend not only on which technologies are used, but also on how they are used (Grübler et al. 1999a). Technological change is not exogenous to social and economic systems; technologies are not conceived, selected, and applied autonomously (Grubler et al. 2018). Underlying driving forces of the problem, such as more resource intensive lifestyles and larger populations (Hertwich and Peters 2009; UNEP 2014), remain largely unchallenged. Comprehensive knowledge of the direct and indirect effects of technological changes on physical and social systems could improve decision-making, also in those cases where technological change mitigates environmental impacts.

A sustainable global future for people and nature requires rapid and transformative societal change by integrating technical, governance (including participation), financial and societal aspects of the solutions to be implemented (Pörtner et al. 2021; Sachs et al. 2019). A growing body of interdisciplinary research from around the world can inform implementation of adaptive solutions that address the benefits and drawbacks of linkages in social-ecological complexity, including externalities and rebound effects from innovation and technological transformation (Pörtner et al. 2021; Balvanera et al. 2017).

Technological change and transitional knowledge can reinforce each other. The value of traditional wisdom and its technological practices provide examples of sustainable and adaptive systems that could potentially adapt to and mitigate climate change (Singh et al. 2020; Kuoljok 2019). Peasants and traditional farmers have been able to respond well to climate changes through their wisdom and traditional practices (Nicholls and Alteri 2013). The integration of the traditional wisdom with new technologies can offer new and effective solutions (Galloway McLean 2010).

Achieving climate change mitigation and other sustainable development goals thus also requires rapid diffusion of knowledge and technological innovations. However, these are hampered by various barriers, some of which are illustrated in Table 16.1 (Markard et al. 2020).

Table 16.1 Overview of Challenges to Accelerated Diffusion of Technological Innovations. Based on (Markard et al. 2020)

Challenges	Description	Examples
Innovations in whole systems	Since entire systems are changing, also changes in system architecture are needed, which may not keep pace.	Decentralization of electricity supply and integration of variable sources.
Interaction between multiple systems and subsystems	Simultaneous, accelerating changes multiple systems or sectors, vying for the same resources and showing other interactions.	Electrification of transport, heating and industry all using the same renewable electricity source.
Industry decline and incumbent resistance	Decline of existing industries and businesses can lead to incumbents slowing down change, and resistance from e.g. unions or workers.	Traditional car industry leading to facture closures, demise of coal mining and coal-fired power generation leading to local job loss.
Consumers and social practices	Consumers need to change practices and demand patterns.	Less car ownership in a sharing economy, trip planning for public and non-motorised transport, fuelling practices in electric driving.
Coordination in governance and policy	Increasing complexity of governance requires coordination between multiple levels of government and a multitude of actors relevant to the transition, e.g. communities, financial institutions, private sector.	Multi-level governance between European Commission and member states in Energy Union package.

The literature on how, in a systemic way, the barriers to sustainability transition can be overcome in various circumstances has been growing rapidly over the past decades. A central element is that national systems of innovation can help achieving both climate change and sustainable development goals, by integrating new ideas, devices, resources, new and traditional knowledge and technological changes for more effective and adaptive solutions (Lundvall 1992). At the organizational level, innovation is seen as a process that can bring value by means of creating more effective products, services, processes, technologies, policies and business models that are applicable to commercial, business, financial and even societal or political organizations (Brooks 1980; Arthur 2009).

The literature refers to the terms "technology push," "market pull," "regulatory push-pull," and "firm specific factors" as drivers for innovation, mostly to inform policymakers (Zubeltzu-Jaka et al. 2018). There has also been growing interest in social drivers, motivated by the recognition of social issues, such as unemployment and public health, linked to the deployment of innovative low-carbon technologies (Altantsetseg et al. 2020). Policy and social factors and the diverse trajectories of innovation are influenced by regional and national conditions (Tariq et al. 2017), and such local needs and purposes need to be considered in crafting international policies aimed at fostering the global transition towards increased sustainability (Caravella and Crespi 2020). From this standpoint, a multidimensional, multi-actor systemic innovation approach would be needed to enhance global innovation diffusion (de Jesus and Mendonça 2018), especially if this is to lead to overall sustainability improvements rather than resulting in new sustainability challenges.

Policies to mitigate climate change do not always take into account the effects of mitigation technologies on other environmental and social challenges (Arvesen et al. 2011). Policies also often disregard the strong linkages between technological innovation and social innovation; the latter understood as the use of soft technologies that brings about transformation through establishing new institutions, new practices, and new models to create a positive societal impact characterized by collaboration that crosses traditional roles and boundaries, between citizens, civil society, the state, and the private sector (Reynolds et al. 2017). Market forces do not provide sufficient incentives for investment in development or diffusion of technologies, leaving a role for public policy to create the conditions to assure a systemic innovation approach (Popp 2010; Popp and Newell 2012). Moreover, public action is more than just addressing market failure, it is an unalienable element of an innovation system (Mazzucato 2013).

Coupling technological innovation with sustainable development and the SDGs would need to address overall social, environmental, and economic consequences, given that public policy is intertwined with innovation, technological changes and other factors in a complex manner. Chapter 16 is organized in the following manner to provide an overview of innovation and technology development and transfer for climate change and sustainable development.

Section 16.2 discusses drivers of innovation process, including macro factors that can redirect technological change towards low-carbon options. Representations of these drivers in mathematical and statistical models allow for explaining the past and constructing projections of future technological change. They also integrate the analysis of drivers and consequences of technological change within economic-energy-economy (or integrated assessment) models (see Chapter 3). The section also describes the different phases of innovation and metrics, such as the widely used but also criticized technology readiness levels (TRLs).

Section 16.3 discusses innovation as a systemic process based on recent literature. While the innovation process is often stylized as a linear process, innovation is now predominantly seen as a systemic process in that it is a result of actions by, and interactions among, a large set of actors, whose activities are shaped by, and shape, the context in which they operate and the user group with which they are engaging.

Section 16.4 presents innovation and technology policy, including technology push (e.g., publicly funded R&D) and demand-pull (e.g., governmental procurement programmes) instruments that addresses potential market failures related to innovation and technology diffusion. The section also assesses the cost-effectiveness and other policy assessment criteria introduced in Chapter 13 of innovation policies.

In section 16.5, the chapter assesses the role of international cooperation in technology development and transfer, in particular the mechanisms established under the UNFCCC, but also other international initiatives for technology cooperation. The discussion on international cooperation includes information exchange, research, development and demonstration cooperation, access to financial instruments, intellectual property rights, as well as promotion of domestic capacities and capacity building.

Section 16.6 describes the role of technology in sustainable development, including unintended effects of technological changes, and synthesizes the chapter. Finally, section 16.7 discusses gaps in knowledge emerging from this chapter.

16.2 Elements, drivers and modelling of technology innovation

Models of the innovation process, its drivers and incentives provide a tool for technology assessment, constructing projections of technological change and identifying which macro conditions facilitate development of low-carbon technologies. The distinction between stages of innovation process allows to assess technology readiness (Section 16.2.1). Qualitative and quantitative analysis of main elements underpinning innovation - R&D, learning-by-doing, spillovers allow for explanation of past and project future technological change (Section 16.2.2). In addition, general purpose technologies can play a role in climate change mitigation.

In the context of mitigation pathways, the feasibility of any emission reduction targets depends on the ability to promote innovation in low- and zero-carbon technologies, as opposed to any other technology. For this reason, the section reviews the literature of the levers influencing the *direction* of technological change in favour of low- and zero-carbon technologies (Section 16.2.3). Moreover, representation of drivers in mathematical and statistical models from section 16.2.2 allows integrating its analysis with economic and climate effects within IAMs, hence permitting more precise modelling of decarbonisation pathways (Section 16.2.4).

In addition to technological innovation, other innovation approaches are relevant in the context of climate mitigation and more broadly sustainable development (Section 16.6). Frugal innovations, i.e. "good enough" innovations that fulfil the needs of non-affluent consumers mostly in developing countries (Hossain 2018), are characterized by low costs, concentration on core functionalities, and optimised performance level (Weyrauch and Herstatt 2016) and are hence often associated with (ecological and social) sustainability (Albert 2019). Grassroots innovations are products, services and processes developed to address specific local challenges and opportunities, and which can generate novel, bottom-up solutions responding to local situations, interests and values. (Dana et al. 2021; Pellicer-Sifres et al. 2018).

16.2.1 Stages of the innovation process

The innovation cycle is commonly thought of as having three distinct innovation phases on the path between basic research and commercial application: Research and Development (R&D), demonstration, and deployment and diffusion (IPCC 2007). Each of these phases differs with respect to the kind of activity carried out, the type of actors involved and their role, financing needs and the associated risks and uncertainties. All phases involve a process of trial and error, and failure is common; the share of innovation that successfully reaches the deployment phase is small. The path occurring between basic research to commercialization is not linear (see also Section 16.3); it often requires a long time and is characterized by significant bottlenecks and roadblocks. Furthermore, technologies may regress backwards in the innovation cycle, rather than move forward (Skea et al. 2019). Successfully passing from each stage to the next one in the innovation cycle requires overcoming "valleys of deaths" (Auerswald and Branscomb 2003; UNFCCC 2017), most notably the demonstration phase (Frank et al. 1996; Weyant 2011; Nemet et al. 2018). Over time, new and improved technologies are discovered; this often makes the dominant technology obsolete, but this is not discussed here further.

Table 16.2 summarizes the different innovation stages and main funding actors, and maps phases into the technology readiness levels (TRLs) discussed in Section 16.2.1.4.

Table 16.2 Stages of the innovation process (16.2.1) mapped onto Technology Readiness Levels (16.2.1.4)

Stage	Main funding actors	Phases	Related TRL
Research and development	Governments Firms	Basic research	1 – Initial idea (basic principles defined)
		Applied research and technology development	2 – Application formulated (technology concept and application of solution formulated)
			3 – Concept needs validation (solutions need to be prototyped and applied
			4 – Early prototype (prototype proven in test conditions)
			5 – Full prototype at scale (components proven in conditions to be deployed)
Demonstration	Governments Firms Venture Capital Angel investors	Experimental pilot project or full scale testing	6 – Full prototype at scale (prototype proven at scale in conditions to be deployed)
			7 – Pre-commercial demonstration (solutions working in expected conditions)
			8 – First-of-a-kind commercial (commercial demonstration, full scale deployment in final form)
Deployment and diffusion	Firms Private equity Commercial banks Mutual funds	Commercialization and scale up *(business)*	9 – Commercial operation in early environment (solution is commercial available, needs evolutionary improvement to stay competitive) 10 – Integration needed at scale (solution is commercial and competitive but needs further integration efforts) 11 – Proof of stability reached (Predictable growth)
	International organizations and financial institutions NGOs	Transfer	

Adapted from: Auerswald and Branscomb (2003), Technology Executive Committee (2017), IEA (IEA 2020a)

16.2.1.1 Research and Development

This phase of the innovation process focuses on generating knowledge or solving particular problems by creating a combination of artefacts that is intended to perform a particular function, or to achieve a specific goal. R&D activities comprise basic research, applied research and technology development. Basic research is experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundations of phenomena and observable facts, without any particular application or use in view. Applied research is original investigation undertaken in order to acquire new knowledge, primarily directed towards a specific, practical aim or objective (OECD 2015a). Importantly, R&D activities can be incremental, i.e. focused on addressing a specific need by marginally improving an already existing technology, or radical, representing a paradigm shift, promoted by new opportunities arising with the accumulation of new knowledge (Mendonça et al. 2018). Technology development, often leading to prototyping, consists of generating a working model of the technology that is usable in the real world, proving the usability and customer desirability of the technology and giving an idea of its design, features and functioning (OECD 2015a). These early stages of technological innovation are referred to as "formative phase", during which the conditions are shaped for a technology to emerge and become established in the market (Wilson and Grubler 2013) and the constitutive elements of the innovation system emerging around a particular technology are set up (see Section 16.3)(Bento et al. 2018; Bento and Wilson 2016).

The outcomes of R&D are uncertain: the amount of knowledge that will result from any given research project or investment is unknown ex ante (Rosenberg 1998). This risk to funders (Goldstein and Kearney 2020) translates into underinvestment in R&D due to low appropriability (Sagar and Majumdar 2014; Weyant 2011). In the case of climate mitigation technologies, low innovation incentives for the private sector also result from a negative environmental externality (Jaffe et al. 2005). Furthermore, in absence of stringent climate policies and targets, incumbent fossil-based energy technologies are characterized by lower financing risk, are heavily subsidized (Kotchen 2021; Davis 2014) and depreciate slowly (see Section 16.2.3) (Nanda et al. 2016; Semieniuk et al. 2021; Arrow 1962a). In this context public research funding therefore plays a key role in supporting high-risk R&D both in developed and developing economies: it can provide patient and steady funding not tied to short-term investment returns (see Section 16.4) (Anadon et al. 2014; Mazzucato 2015a; Howell 2017; Zhang et al. 2019; Anadón et al. 2017; Chan and Diaz Anadon 2016; Kammen and Nemet 2007). Public policies also play a role increasing private incentives in energy research and development funding (Nemet 2013). R&D statistics are an important indicator of innovation and are collected following the rules of the Frascati Manual (OECD 2015b) (Section 16.3.3, Box 16.3, Table 16.7).

16.2.1.2 Demonstration

Demonstration is carried out through pilot projects or large-scale testing in the real world. Successfully demonstrating a technology shows its utility and that it is able to achieve its intended purpose and, consequently, that the risk of failure is reduced (i.e. that it has market potential) (Hellsmark et al. 2016). Demonstration project are an important step to promote the deployment of low-carbon energy and industrial technologies in the context of the transition. government funding often plays a large role in energy technology demonstration projects because scaling up hardware energy technologies is expensive and risky (Brown and Hendry 2009; Hellsmark et al. 2016). Governments' engagement in low-carbon technology demonstration also signals support for business willing to take the investment risk (Mazzucato 2016). Venture capital, traditionally not tailored for energy investment, can play an increasingly important role also thanks to the incentives (e.g. through de-risking) provided by public funding and policies (Gaddy et al. 2017; IEA 2017a).

16.2.1.3 Deployment and diffusion

Deployment entails producing a technology at large scale and scaling up its adoption use across individual firms or households in a given market, and across different markets (Jaffe 2015). In the context of climate change mitigation and adaptation technologies, the purposeful diffusion to developing countries, is referred to as "technology transfer". Most recently, the term " innovation cooperation" has been proposed to indicate that technologies needs to be co-developed and adapted to local contexts (Pandey et al. 2021). Innovation cooperation is an important component of stringent mitigation strategies as well as international agreements (see Section 16.5).

Diffusion is often sluggish due to lock-in of dominant technologies (Liebowitz and Margolis 1995; Unruh 2000; Ivanova et al. 2018), as well as the time needed to diffuse information about the technologies, heterogeneity among adopters, the incentive to wait until costs fall even further, the presence of behavioural and institutional barriers and the uncertainty surrounding mitigation policies and long-term commitments to climate targets (Corey 2014; Haelg et al. 2018; Gillingham and Sweeney 2012; Jaffe 2015). In addition, novel technology has been hindered by the actions of powerful incumbents who accrue economic and political advantages over time, as in the case of renewable energy generation (Unruh 2002; Supran and Oreskes 2017; Hoppmann et al. 2019).

Technologies have been shown to penetrate the market with a gradual non-linear process in a characteristic logistic (S-shaped) curve (Rogers 2003; Grübler 1996). The time needed to reach widespread adoption varies greatly across technologies relevant for adaptation and mitigation (Gross et al. 2018); in the case of energy technologies, the time needed for technologies to get from a 10 to 90% market share of saturation ranges between 5 to over 70 (Wilson 2012). Investment in commercialization of low-emission technology is largely provided by private financiers; however, governments play a key role in ensuring incentives through supportive policies, including R&D expenditures providing signals to private investors (Haelg et al. 2018), pricing carbon dioxide emissions, public procurement, technology standards, information diffusion and the regulation for end-life cycle treatment of products (Cross and Murray 2018) (see Section 16.4).

16.2.1.4 Technology Readiness Levels

Technology Readiness Levels (TRLs) are a categorization that enables consistent, uniform discussions of technical maturity across different types of technology. They were developed by NASA in the 1970s (Mankins 2009, 1995) and originally used to describe the readiness of components forming part of a technological system. Over time, more classifications of TRLs have been introduced, notably the one used by the EU. Most recently, the IEA extended previous classifications to include the later stages of the innovation process (IEA 2020b) and applied it to compare the market readiness of clean energy technologies and their components (OECD 2015a; IEA 2020b). TRLs are currently widely used by engineers, business people, research funders and investors, often to assess the readiness of whole technologies rather than single components. To determine a TRL for a given technology, a Technology Readiness Assessment (TRA) is carried out to examine programme concepts, technology requirements, and demonstrated technology capabilities. In the most recent version of the IEA (IEA 2020b), TRLs range from 1 to 11, with 11 indicating the most mature (see Table 16.2).

The purpose of TRLs is to support decision making. They are applied to avoid the premature application of technologies, which would lead to increased costs and project schedule extension (US Department of Energy 2011). They are used for risk management, and can also be used to make decisions regarding technology funding and to support the management of the R&D process within a given organization or country (De Rose et al. 2017).

In practice, the usefulness of TRLs is limited by several factors. These include limited applicability in complex technologies or systems, the fact that they do not define obsolescence, nor account for manufacturability, commercialization or the readiness of organizations to implement innovations (European Association of Research Technology Organisations 2014) and do not consider any type of technology-system mismatch or the relevance of the products' operation environment to the system under consideration (Mankins 2009). Many of these limitations can be eased by using TRLs in combination with other indicators such as System Readiness Levels and other economic indicators on, for example, investments and returns (IEA 2020b).

16.2.2 Sources of technological change

The speed of technological change could be explained with the key drivers of innovations process: R&D effort, learning-by-doing and spillover effects. In addition, new innovations are sometimes enabled by the development of general purpose technologies, such as digitalization.

16.2.2.1 Learning-by-doing and research and development

Learning by doing and R&D effort are two factors commonly used by the literature to explain past and project future speed of technological change (Klaassen et al. 2005; Mayer et al. 2012; Bettencourt et al. 2013). Learning-by-doing is the interaction of workers with new machines or processes that allows them to use them more efficiently (Arrow 1962b). R&D effort is dedicated to looking for new solutions (e.g. blueprints) that could increase the efficiency of existing production methods or result in entirely new methods, products or services (see section 16.2.1.1).

Learning-by-doing and research and development are interdependent. Young (1993) postulates that learning-by-doing cannot continue forever without R&D because it is bounded by an upper physical productivity limit of an existing technology. Research and development can shift this limit because it allows replacing the existing technology with a new one. On other hand, incentives to invest in R&D depend on future cost of manufacturing, which in turn depend on the scale of learning-by-doing. The empirical evidence for virtuous circle between costs reduction, market growth and R&D were found in the case of PV market ((Watanabe et al. 2000); see also Box 16.4), but could also lead to path dependency and lock-in (Erickson et al. 2015). Section 16.4.4 and Chapter 13 Section 13.7.3.1. discuss how simultaneous use of technology push and pull policies could amplify effects of research and learning.

The benefits of R&D and learning-by-doing are larger at the economy level than at the firms level (Romer 1990; Arrow 1962b). As a result, the market, left to its own, tends to generate less investment than socially optimal. For instance, if the cost of a technology is too high before a large amount of learning-by-doing has occurred, there is a risk that it will not be adopted by the market even if it is economically advantageous for the society. Indeed, initially new technologies are often expensive and cannot compete with the incumbent technologies (Cowan 1990). Large numbers of adopters could lower this cost via learning-by-doing to a level sufficient to beat the incumbent technology (Gruebler et al. 2012). However, firms could hesitate to be the first adopter and bear the high cost (Isoard and Soria 2001). If this disadvantage overwhelms the advantages of being a first mover[1] and if adopters are not able to coordinate, it will lead to situation of a lock-in (Gruebler et al. 2012).

The failure of markets to deliver the size of R&D investment and learning-by-doing that would be socially optimal is one of the justifications of government intervention. Policies to address these market failures can be categorized as technology push and demand pull policies. The role of these policies is explained in Table 16.3. Section 16.4 discusses individual policy instruments in greater detail.

Table 16.3 Categories of policies and interventions accelerating technological changes, the factors promoting them and slowing them down, illustrated with examples

	What it refers to:	What promotes technological change	What slows down technological change	Examples
Technology Push	Support the creation of new knowledge to make it easier to invest in innovation	R&D, funding and performance of early demonstrations (Brown and Hendry 2009; Hellsmark et al. 2016)	Inadequate supply of trained scientists and engineers (Popp and Newell 2012); gap with demand pull (Grübler et al. 1999b).	Japan's Project Sunshine, the US Project Independence in the 1970s. Breakthrough Energy Coalition and Mission Innovation, respectively private- and public-sector international collaborations to respectively focus energy innovation and double energy R&D, both initiated concurrently with the Paris Agreement in 2015 (Sanchez and Sivaram 2017).

FOOTNOTE[1] see e.g. (Spence 1981) and (Bhattacharya 1984) for discussion of first-mover advantages

Demand Pull	Instruments creating market opportunities.	Enlarging potential markets, increasing adoption of new fuels and mitigation technology. Digital innovations Social innovation and awareness	Willingness of consumers to accept new technology. Policy and political volatility can deter investment.	Subsidies for wind power California, the German feed-in tariff for PV, quotas for electric vehicles in China (Wang et al. 2017a) and Norway (Pereirinha et al. 2018) Biofuels (Brazil); Social innovation with Wind Energy (Denmark, Germany)

The size of learning-by-doing effect is quantified in literature using learning rates i.e. estimates of negative correlation between costs and size of deployment of technologies. The results from this literature include estimates for energy technologies (McDonald and Schrattenholzer 2001), electricity generation technologies (Rubin et al. 2015; Samadi 2018), for storage (Schmidt 2017), for end-of-pipe control (Kang et al. 2020) and for energy demand and energy supply technologies (Weiss et al. 2010). Meta-analyses find learning rates vary across technologies, within technologies and over time (Wei et al. 2017; Nemet 2009a; Rubin et al. 2015). Moreover, different components of one technology have different learning rates (Elshurafa et al. 2018). Central tendencies are around 20% cost reduction for each doubling of deployment (McDonald and Schrattenholzer 2001).

Studies of correlation between cumulative deployment of technologies and costs are not sufficiently precise to disentangle the causal effect of increase in deployment from the causal effects of research and development and other factors (Nemet 2006). Numerous subsequent studies attempted to, amongst others, separate the effect of learning-by-doing and research and development (Klaassen et al. 2005; Mayer et al. 2012; Bettencourt et al. 2013), economies of scale (Arce 2014), and knowledge spillovers (Nemet 2012). Once those other factors are accounted for, some empirical studies find that the role of learning-by-doing in driving down the costs becomes minor (Kavlak et al. 2018; Nemet 2006). In addition the relation could reflect reverse causality: increase in deployment could be an effect (and not a cause) of a drop in price (Witajewski-Baltvilks et al. 2015; Nordhaus 2014). Nevertheless, in some applications, learning curves can be a useful proxy and heuristic (Nagy et al. 2013).

The negative relation between costs and experience is a reason to invest in a narrow set of technologies; the uncertainty regarding the parameters of this relation is the reason to invest in wider ranges of technologies (Way et al. 2019; Fleming and Sorenson 2001). Concentrating investment in narrow sets of technologies (specialization) enables fast accumulation of experience for these technologies and large cost reductions. However, when the potency of technology is uncertain, one does not know which technology is truly optimal in the long-run. The narrower the set the higher the risk that the optimal technology will not be supported, and hence will not benefit from learning-by-doing. Widening the set of supported technologies would reduce this risk (Way et al. 2019). Uncertainty is present because noise in historical data hides the true value of learning rates as well as because of unanticipated future shocks to technology costs (Lafond et al. 2018). Ignoring uncertainty in integrated assessment models implies that these model results are biased towards supporting narrow set of technologies neglecting the benefits of decreasing risk trough diversification (Sawulski and Witajewski-Baltvilks 2020).

16.2.2.2 Knowledge spillovers

Knowledge spillovers drive continuous technological change (Rivera-Batiz and Romer 1991; Romer 1990) and are for that reason relevant to climate technologies as well as incumbent, carbon-intensive technologies. Knowledge embedded in innovations by one innovator give an opportunity for others to create new innovations and increase the knowledge stock even further. The constant growth of knowledge stock through spillovers translates into constant growth of productivity and cost reduction.

By allowing for experimenting with existing knowledge and combining different technologies, knowledge spillovers can result in the emergence of novel technological solutions, which has been referred to as recombinant innovation (Weitzman 1998; Olsson and Frey 2002; Tsur and Zemel 2007; Arthur 2009; Fleming and Sorenson 2001). Recombinant innovations speed up technological change by combining different technological solutions, and make things happen that would be impossible with only incremental innovations (Safarzyńska and van den Bergh 2010; van den Bergh 2008; Frenken et al. 2012). It has been shown that 77% of all patents granted between 1790 and 2010 in the US are coded by a combination of at least two technology codes (Youn et al. 2015). Spillovers related to energy and low-carbon technologies has been documented by a number of empirical studies (*high confidence*) (Popp 2002; Aghion et al. 2013; Witajewski-Baltvilks et al. 2017; Verdolini and Galeotti 2011; Conti et al. 2018). The presence of spillovers can have both positive and negative impacts on climate change mitigation *(high confidence)*.

The spillover effect associated with innovation in carbon-intensive technologies may lead to lock-in of fossil-fuel technologies. Continuous technological change of carbon-intensive industry raises the bar for clean technologies: a larger drop in clean technologies' cost is necessary to become competitive (Acemoglu et al. 2012; Aghion et al. 2013). The implication is that delaying climate policy increases the cost of that policy (Aghion 2019).

On the other hand, the spillover effect associated with innovation in low-emission technologies increase the potency of climate policy (Aghion 2019). For instance, a policy that encourages clean innovation leads to accumulation of knowledge in clean industry which, through spillover effect encourages further innovation in clean industries. Once the stock of knowledge is sufficiently large, the value of clean industries will be so high, that technology firms will invest there even without policy incentives. Once this point is reached, the policy intervention can be discontinued (Acemoglu et al. 2012).

In addition, the presence of spillovers implies that a unilateral effort to reduce emissions in one region could reduce emissions in other regions (*medium confidence*) (Gerlagh and Kuik 2014; Golombek and Hoel 2004). For instance, in the presence of spillovers, a carbon tax that incentivises clean technological change increases the competitiveness of clean technologies not only locally, but also abroad. The size of this effect depends on the size of spillovers. If they are sufficiently strong, the reduction of emissions abroad due to clean technological change could be larger than the increase of emissions due to carbon leakage (Gerlagh and Kuik 2014). Different types of carbon leakage are discussed in Chapter 13, Section 13.7.1 and other consequences of spillovers for the design of policy are discussed in Chapter 13, Section 13.7.3.

16.2.2.3 General purpose technologies and digitalization

General purpose technologies (GPTs) provide solutions that could be applied across sectors and industries (Goldfarb 2011) by creating technological platforms for a growing number of interrelated innovations. Examples of GPTs relevant to climate change mitigation are hydrogen and fuel cell technology, which may find applications in transport, industry and distributed generation (Hanley et al. 2018), and nanotechnology which played a significant role in advancement of all the different types of renewable energy options (Hussein 2015). Assessing the environmental, social and economic implications of such technologies, including increased emissions through energy use, is challenging (see Chapter 5, Section 5.3.4.1 and Cross-Chapter Box 11 below).

Several GPTs relevant for climate mitigation and adaptation emerged as a result digitalization, namely the adoption or increase in use of information and communication technologies (ICTs) by citizens, organizations, industries or countries and the associated restructuring of several domains of social life and of the economy around digital technologies and infrastructures (IEA 2017b; Brennen and Kreiss 2016). The digital revolution is underpinned by innovation in key technologies, e.g. ubiquitous connected consumer devices such as mobile phones (Grubler et al. 2018), rapid expansions of global internet infrastructure and access (World Bank 2014), and steep cost reductions and performance improvements in computing devices, sensors, and digital communication technologies (Verma et al. 2020). The increasing the pace at which the physical and digital worlds are converging increase the relevance of disruptive digitalization in the context of climate mitigation and sustainability challenges (European Commission 2020) (see Cross-chapter Box 11 in this chapter and Chapter 4, Section 4.4.1).

Digital technologies require energy, but increase efficiency, potentially offering technology-specific GHG emission savings; they also have larger system wide impacts (Kaack et al. 2021). In industrial sectors, robotization, smart manufacturing (SM), internet of things (IoT), artificial intelligence (AI), and additive manufacturing (AM or 3D printing), have the potential to reduce material demand and promote energy management (Chapter 11, Section 11.3.4.2). Smart mobility is changing transport demand and efficiency (Chapter 10, Section 10.2.3). Smart devices in buildings, the deployment of smart grids and the provision of renewable energy increase the role of demand-side management (Serrenho and Bertoldi 2019) (Chapter 9, Sections 9.4 and 9.5), and support the shift away from asset redundancy (Chapter 6, Section 6.4.3). Digital solutions are equally important on the supply side, for example by accelerating innovation with simulations and deep learning (Rolnick et al. 2021) or realizing flexible and decentralized opportunities through energy-as-a-service concepts and particularly with Pay-As-You-Go (Chapter 15, Box 15.8, Table 1).

Yet, increased digitalization could give increase energy demand, thus wiping away potential efficiency benefits, unless appropriately governed (IPCC 2018a). Moreover, digital technologies could negatively impact labour demand and increase inequality (Cross-Chapter Box 11 in this chapter).

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Cross-Chapter Box 11: Digitalization: efficiency potentials and governance considerations

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Digital technologies impact positively and negatively GHG emissions through their own carbon footprint, via technology application for mitigation, and via induced larger social change. Digital technologies also raise broader sustainability concerns due to their use of rare materials and associated waste, and their potential negative impact on inequalities and labour demand.

Direct impacts emerge because digital technologies consume large amounts of energy, but also have the potential to steeply increase energy efficiency in all end-use sectors through material input savings and increased coordination (*medium evidence, medium agreement*) (Horner et al. 2016; Jones 2018) (Huang et al. 2016; IEA 2017b)**.** Global energy demand from digital appliances reached 7.14 EJ in 2018 (Chapter 9, Box 9.5), implying higher related carbon emissions. However, a small smart phone offers services previously requiring many different devices (Grubler et al. 2018). Demand for data services is increasing rapidly; quantitative estimates of the growth of associated energy demand range from slow and marginal to rapid and sizeable, depending the efficiency trends of digital technologies (see Chapter 5.3.4.1)(Avgerinou et al. 2017; Stoll et al. 2019; Vranken 2017; Masanet et al. 2020). Renewable energy serves as low-carbon energy provider for the operation of data centre, which in turn can provide waste heat for other purposes. Digital technologies can markedly increase the energy efficiency of mobility and residential and public buildings, especially in the context of systems integration (IEA 2020a). Reduction in energy demand and associated GHG emissions from buildings and industry while maintaining service levels equal is estimated at 5 to 10%, with larger savings possible. Approaches include building energy management systems (BEMS), home energy management system (HEMS), demand response and smart charging (Cross-Chapter Box 11, Table 1. Data centres can also play a role in energy system management, e.g., by increasing renewable energy generation through predictive control (Dabbagh et al. 2019), and by helping drive the market for battery storage and fuel cells (Riekstin et al. 2014). Temporal and spatial scheduling of electricity demand can provide about 10 GW in demand response in the European electricity system in 2030 (Koronen et al. 2020; Wahlroos et al. 2017, 2018; Laine et al. 2020).

However, system-wide effects may endanger energy and GHG emission savings (*high evidence, high agreement*). Economic growth resulting from higher energy and labour productivities can increase energy demand (Lange et al. 2020) and associated GHG emissions. Importantly, digitalization can also benefit carbon-intensive technologies (Victor 2018). Impacts on GHG emissions are varied in smart and shared mobility systems, as ride hailing increases GHG emissions due to deadheading, whereas shared pooled mobility and shared cycling reduce GHG emissions, as occupancy levels and/or weight per person km transported improve (Chapter 5, Section 5.3). Energy and GHG emissions impacts from the ubiquitous deployment of smart sensors and service optimization applications in smart cities through are insufficiently assessed in the literature (Milojevic-Dupont and Creutzig 2021). Systemic effects have wider boundaries of analysis, including broader environmental impacts (e.g. demand for rare materials, disposal of digital devices). These need to be integrated holistically within policy design (Kunkel and Matthess 2020), but they are difficult to quantify and investigate (Bieser and Hilty 2018). Policies and adequate infrastructures and choice architectures can help manage and contain the negative repercussions of systemic effects (Section 5.4, 5.6, 9.9).

Cross-chapter Box 11, Table 1. Selected sector approaches for reducing GHG emissions that are supported by new digital technologies. Contributions of digitalization include a) supporting role (+), b) necessary role in mix of tools (++), c) necessary unique contribution (+++), but digitalization may also increase emissions (−). See also chapters 5, 8, 9, and 11.

Sector	Approach	Quantitative evidence	Contribution of digitalization	Systems perspective and broader societal impacts	References
Residential energy use	Nudges (feedback, information, etc.)	2-4% reduction in global household energy use possible	+ in combination with monetary incentives, non-digital information	New appliances increase consumption	(Buckley 2020; Zangheri et al. 2019; Khanna et al. 2021; Nawaz et al. 2020)
Smart mobility	Shared mobility and digital feedback (ecodriving)	Reduction for shared cycling and shared pooled mobility; increase for ride hailing/ ride sourcing; reduction for ecodriving	− or ++ Apps together with big data and machine learning algorithm key precondition for new shared mobility	Ride hailing increases GHG emissions, especially due to deadheading	(OECD and ITF 2020; Zeng et al. 2017)
Smart cities	Using digital devices and big data to make urban transport and building	Precise data about roadway use can reduce material intensity and associated GHG	++ Big data analysis necessary for optimization	Efficiency gains are often compensated by more driving and other rebound effects; privacy	(Milojevic-Dupont and Creutzig 2021) (Chapter 10, Box 10.1)

	use more efficient	emissions by 90%,		concerns linked with digital devices in homes	
Agriculture	Precision agriculture through sensors and satellites providing information on soil moisture, temperature, crop growth and livestock feed levels,	Very high potential for variable-rate nitrogen application, moderate potential for variable-rate irrigation	+ ICTs provide information and technologies which enables farmers to increase yields, optimize crop management, reduce fertilizers and pesticides, feed and water; increases efficiency of labour-intensive tasks	The digital divide is growing fast, especially between modern and subsistence farming; Privacy and data may erode trust in technologies	(Townsend et al. 2019; Deichmann et al. 2016; Soto Embodas et al. 2019; Chlingaryan et al. 2018)
Industry	Industrial Internet of Things (IIoT)	Process, activity & functional optimization increases energy and carbon efficiency	++ increased efficiency ++ 1.3 Gt CO_2-eq estimated abatement potential in manufacturing + promote sustainable business models	Optimization in value chains can reduce wasted resources	(GeSI 2012; Parida et al. 2019; Rolnick et al. 2021; Wang et al. 2016)
Load management and battery storage optimization	Big data analysis for optimizing demand management and using flexible load of appliances with batteries	Reduces capacity intended for peak demand, shifts demand to align with intermittent renewable energy availability	+ Accelerated experimentation in material science with artificial intelligence ++ / +++ Forecast and control algorithms for storage and dispatch management	Facilitate integration of renewable energy sources Improve utilization of generation assets System-wide rebound effects possible	(Akorede et al. 2010; Hirsch et al. 2018; de Sisternes et al. 2016; Sivaram 2018a; Gür 2018; Aghaei and Alizadeh 2013; Vázquez-Canteli and Nagy 2019; Voyant et al. 2017) (Chapter 6, Section 6.4)

Broader societal impacts of digitalization can also influence climate mitigation because of induced demand for consumption goods, impacts on firms' competitiveness, changes the demand for skills and labour, worsening of inequality – including reduced access to services due to the digital divide – and governance aspects (*low evidence, medium agreement*) (Chapter 4, Section 4.4, Chapter 5, Sections 5.3, 5.6). Digital technologies expand production possibilities in sectors other than ICTs through robotics, smart manufacturing, and 3D printing, and have major implications on consumption patterns (Matthess and Kunkel 2020). Initial evidence suggests that robots displace routine jobs and certain skills, change the demand for high-skilled and low-skilled workers, and suppress wages (Acemoglu and Restrepo 2019). Digitalization can thus reduce consumers' liquidity and consumption (Mian et al. 2020) and contribute to global inequality, including across the gender dimension, raising fairness concerns (Kerras et al. 2020; Vassilakopoulou and Hustad 2021). Digital technologies can lead to additional concentration in economic power (e.g. Rikap 2020) and lower competition; open source digital technologies can however counter this tendency (e.g. Rotz et al. 2019). Digital technologies play a role in mobilizing citizens for climate and sustainability actions (Westerhoff et al. 2018; Segerberg 2017).

Whether the digital revolution will be an enabler or a barrier for decarbonization will ultimately depend on the governance of both digital decarbonization pathways and digitalization more in general (*medium evidence, high agreement*). The understanding of the disruptive potential of the wide range of digital technologies is limited due to their ground-breaking nature, which makes it hard to extrapolate from previous history/experience. Municipal and national entities can make use of digital technologies to manage and govern energy use and GHG emissions in their jurisdiction (Bibri 2019a,b) and break down solution strategies to specific infrastructures, building, and places, relying on remote sensing and mapping data, and contextual (machine-) learning about their use (Milojevic-Dupont and Creutzig 2021). Mobility apps can provide mobility-as-a-service access to cities ensuring due preference to active and healthy modes (see 9.9 for the example of the Finnish city of Lahti). Trusted data governance can promote the implementation of local climate solutions, supported by available big data on infrastructures and environmental quality (Hansen and Porter 2017; Hughes et al. 2020). Governance decisions, such as taxing data, prohibiting surveillance technologies, or releasing data that enable accountability can change digitalization pathways, and thus underlying GHG emission (Hughes et al. 2020).

Closing the digital gap in developing countries and rural communities enables an opportunity for leapfrogging (*medium evidence, medium agreement*). Communication technologies (such as mobile phones) enable participation of rural communities, especially in developing countries, and promote technological leapfrogging, e.g. decentralized renewable energies and smart farming (Ugur and Mitra 2017; Foster and Azmeh 2020; Arfanuzzaman 2021). Digital technologies have sector-specific potentials and barriers, and may benefit certain regions/areas/socioeconomic groups more than others. For example, integrated mobility services benefit cities more than rural and peripheral areas (OECD 2017).

Appropriate mechanisms also need to be designed to govern digitalization as megatrend (*medium evidence, high agreement*). Digitalization is expected to be a fast process, but this transformation takes place against entrenched individual behaviours, existing infrastructure, the legacy of time frames, vested interest and slow institutional processes and requires trust from consumers, producers and institutions. A core question relates to who controls and manages data created by everyday operations (calls, shopping, weather data, service use, etc.). Regulations that limit or ban the expropriation and exploitation of behavioural data, sourced via smart phones, represent crucial aspects in digitalization pathways, alongside the possibility to create climate movements and political pressure from the civil society. Governance mechanisms need to be developed to ensure that digital technologies such as artificial intelligence take over ethical choices (Craglia et al. 2018; Rahwan et al. 2019). Appropriate governance is necessary for digitalization effectively work in tandem with established mitigation technologies and choice architectures. Consideration of system-wide effects and overall management is essential to avoid run-away effects. Overall governance of digitalization remains a challenge, and will have large-scale repercussions on energy demand and GHG emissions.

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16.2.2.4 Explaining past and projecting future technology cost changes

Researchers and policymakers alike are interested in using observed empirical patterns of learning to project future reductions in costs of technologies. Studies cutting across a wide range of industrial sectors (not just energy) have tried to relate cost reductions to different functional forms, including cost reductions as a function of time (Moore's law) and cost reductions as a function of production or deployment (Wright's law, also known as Henderson's law), finding that those two forms perform better than alternatives combining different factors, with costs as a function of production (Wright's law) performing marginally better (Nagy et al. 2013). A comparison of expert elicitation and model-based forecasts of the future cost of technologies for the energy transition indicates that model-based forecast medians were closer to the average realized values in 2019 (Meng et al. 2021).

Recent studies attempt to separate the influence of learning-by-doing (which is a basis of Wright's law) versus other factors in explaining cost reductions specifically in energy technologies. Some studies explain cost reductions with two factors: cumulative deployment (as proxy for experience) and R&D investment (see the "two factor" learning curve (Klaassen et al. 2005). However, reliable information on public energy R&D investments for developing countries is not systematically collected. Available data for OECD countries cannot be precisely assigned to specific industrial sectors or sub-technologies (Verdolini et al. 2018). Some learning-curve studies take into account that historical variation in technology costs could be explained by variation in key materials and fuel costs (for example steel costs for wind turbines (Qiu and Anadon 2012) silicon costs (Kavlak et al. 2018; Nemet 2006) coal and coal plant construction costs (McNerney et al. 2011). Economies of scale played a significant role in the PV cost reductions since the early 2000s (Yu et al. 2011) (See also Box 16.4), which can also be the case in organic PV technologies (Gambhir et al. 2016; Kavlak et al. 2018).

16.2.3 Directing technological change

Technological change is characterized not only by its speed, but also its direction. The early works that considered the role of technology in economic and productivity growth (Solow 1957; Nelson and Phelps 1966) assumed that technology can move forward along only one dimension - every improvement led to an increase in efficiency and increased demand for all factors of production. This view however ignores the potency of technological change to alter the otherwise fixed relation between economic growth and the use of resources.

Technological change that saves fossil fuels could decouple economic growth and CO_2 emissions (Acemoglu et al. 2014; Hémous 2016; Greaker et al. 2018; Acemoglu et al. 2012). Saving of fossils could be obtained with increasing efficiency of producing alternatives to fossils (Acemoglu et al. 2012, 2014). This is the case of oil consumption by combustion engine cars which could be substituted with electric cars (Aghion et al. 2013). If there is no close substitute to dirty resource, then its intensity in production could still be reduced by increasing efficiency of the dirty resource relative to efficiency of other inputs (Hassler et al. 2012; André and Smulders 2014; Witajewski-Baltvilks et al. 2017). For instance, energy efficiency improvement leads to drop in relative demand for energy (Hassler et al. 2012; Witajewski-Baltvilks et al. 2017).

16.2.3.1 Determinants of technological change direction: prices, market size and government

Firms change their choice of technology upon change in prices: when one input (e.g. energy) becomes relatively expensive, firms pick technologies which allow them to economize on that input, according to price-induced technological change theory (Reder and Hicks 1965; Samuelson 1965; Sue Wing 2006). For example, an increase in oil price will lead to a choice of fuel-saving technologies. Such response of technological change was evident during the oil-price shocks in the 1970s (Hassler et al. 2012). Technological change that is induced by an increase in price of a resource can never lead to an increase in use of that resource. In other words, rebound effects associated induced technological change can never offset the saving effect of that technological change (Antosiewicz and Witajewski-Baltvilks 2021).

The impact of energy prices on the size of low-carbon technological change is supported by large number of empirical studies (Popp 2019; Grubb and Wieners 2020). Studies document that higher energy prices are associated with higher number of low-carbon energy or energy efficiency patents (Noailly and Smeets 2015; Ley et al. 2016; Lin and Chen 2019; Newell et al. 1999; Popp 2002; Witajewski-Baltvilks et al. 2017; Verdolini and Galeotti 2011). Sue Wing (2008) finds that innovation induced by energy prices had a minor impact on the decline in U.S. energy intensity in the last decades of 20th century and that autonomous technological change played a more important role. Several studies explore the impact of a carbon tax on green innovation (see Section 16.4). However, disentangling the effect of policy tools is complex because presence of some policies could distort the functioning of other policies (Böhringer and Rosendahl 2010; Fischer et al. 2017) and because the impact of policies could be lagged in time (Antosiewicz and Witajewski-Baltvilks 2021).

The direction of technological change depends also on the market size for dirty technologies relative to the size of other markets (Acemoglu et al. 2014). Due to this dependence, climate and trade policy choices in a single region can alter the direction of technological change at the global level (see Section 16.2.3.3).

The value of the market for clean technologies is determined not only by a current but also by firm's expectations of future stream of profits (Alkemade and Suurs 2012; Greaker et al. 2018; Aghion 2019). One implication is that bolstering the credibility and durability of policies related to low-carbon technology is crucial to accelerating technological change and inducing the private sector investment required (Helm et al. 2003), especially in rapidly growing economies of Asia and Africa who are on the brink of making major decisions about the type of infrastructure they build as they grow, develop, and industrialize (Nemet et al. 2017).

If governments commit to climate policies, firms expect that the future size of markets for clean technologies will be large and they are eager to redirect research effort towards development of these technologies today. Furthermore the commitment would also incentivise acquiring skills that could further reduce the costs of those technologies (Aghion 2019). However, historical evidence shows that policies related to energy and climate over the long term have tended to change (Nemet et al. 2013; Taylor 2012; Koch et al. 2016). Still, where enhancing policy durability has proven infeasible, multiple uncorrelated potentially overlapping policies can provide sufficient incentives (Nemet 2010).

16.2.3.2 Determinants of direction of technological change: financial markets

The challenges of investing in innovation in energy when compared to other important areas, such as IT and medicine are also reflected in the trends in venture capital funding. Research found that early-stage investments in clean-tech companies were more likely to fail and returned less capital than comparable investments in software and medical technology (Gaddy et al. 2017), which led to a retreat from investors from hardware technologies required for renewable energy generation and storage to software based technologies and demand-side solutions (Bumpus and Comello 2017).

The preference for particular types of investments in renewable energy technologies depends on investors attitude to risk (Mazzucato and Semieniuk 2018). Some investors invest in only one technology, others may spread their investments, or invest predominantly in high-risk technologies. The distribution of different types of investors will affect whether finance goes to support deployment of new high-risk technologies, or diffusion of more mature, less-risky technologies characterized by incremental innovations. The role of finance in directing investment is further discussed in Chapter 15, Section 15.6.2.

16.2.3.3 Internationalization of green technological change

A unilateral effort to reduce emission (via a combination of climate, industrial and trade policies) in a coalition of regions that are technology leaders will reduce cost of clean technologies, which will induce emission reduction in the countries outside the coalition (Di Maria and Smulders 2005; Di Maria and van der Werf 2008; van den Bijgaart 2017; Golombek and Hoel 2004; Hémous 2016). The literature suggests various mechanisms leading to this result. Di Maria and van der Werf (2008) argues that the effort to reduce emission in one region reduces global demand for dirty good. This will redirect global innovation towards clean technologies, leading to drop in cost of clean production in every region.

The model in Hemous (2016) predict that the coalition could induce acceleration of clean technological change with a mix of carbon tax, clean R&D subsidies and trade policies in that region leading to reduction of cost of clean production inside the coalition. Export of goods produced with clean technologies to a region outside the coalition reduces demand for dirty good in that region. In the model by van den Bijgaart (2017) local advancements of clean technologies by a coalition with strong R&D potential are imitated outside the coalition. Furthermore, advancements of clean technologies will incentivise future clean R&D outside the coalition due to intertemporal knowledge spillovers. In Golombek and Hoel (2004) increase in environmental concern in one region increases abatement R&D in that region. Part of this knowledge spills over to other regions, increasing their incentive to increase abatement too, providing the latter regions did not invest in abatement before.

However, this chain breaks if the regions that are behind technological frontier (i.e., technological followers) are not able to absorb the solutions developed by regions at the frontier. New technologies might fail due to deficiencies of political, commercial, industrial, and financial institutions, which we list in table 16.4. For instance, countries might not benefit fully from international knowledge spillover due to insufficient domestic R&D investment, since local knowledge is needed to determine the appropriateness of technologies for the local market, adapting them, installing and using effectively (Gruebler et al. 2012). From the policy perspective this implies that simple transfer of technologies could be insufficient to guarantee adoption of new technologies (Gruebler et al. 2012).

Table 16.4 Examples of institutional deficiencies preventing deployment of new technologies in countries behind technological frontier.

Institutions	Examples of deficiencies	Literature reference
Industrial	Inability to benefit fully from international knowledge spillover due to insufficient domestic R&D investment	(Mancusi 2008; Unel 2008; Gruebler et al. 2012)
Commercial	Insufficient experience with the organization and management of large-scale enterprise	(Abramovitz 1986; Aghion et al. 2005)
Political	Vested interests and customary relations among firms and between employers and employees	(Olson 1982; Abramovitz 1986).
Financial	Financial markets incapable of mobilizing capital for individual firms at large scale	(Abramovitz 1986; Aghion et al. 2005)

Research relying on patent citations has indicated that Foreign Direct Investment (FDI) is a mechanism for firms to both contribute to the recipient country's innovation output as well as benefitting from the recipient country both in industrialized countries (Branstetter 2006) and in developing countries (Newman et al. 2015). However, insights specific for energy or climate change mitigation areas are not available, nor is there much information about how other innovation metrics may react to FDI.

Finally, technologies could be not efficient in developing countries even if they are efficient in countries at the technological frontier. For instance, technologies that are highly capital intensive and labour saving will be efficient only in countries where costs of capital are low and costs of labour are high. Similarly, technologies which require large number of skilled labour will be more competitive in a country where skilled labour is abundant (and hence cheap) than where it is scarce (Basu and Weil 1998; Caselli and Coleman 2006).

16.2.3.4 Market failures in directing technological change

Market forces alone cannot deliver Pareto optimal (i.e. socially efficient) due to at least two types of externalities: GHG emissions that cause climate damage and knowledge spillovers that benefit firms other than the inventor. Nordhaus (2011) argues that these two problems would have to be tackled separately: once the favourable intellectual property right regimes (i.e. the laws or rules or regulation on protection and enforcement) are in place, a price on carbon that corrects the emission externality is sufficient to induce optimal level of green technological change. Acemoglu et al. (2012) demonstrates that subsidizing clean technologies (and not dirty ones) is also necessary to break the lock-in of dirty technological change. Recommendations for technical changes often are based on climate considerations only and neglect secondary externalities and environmental costs of technology choices (such as loss of biodiversity due to inappropriate scale-up of bioenergy use). The scale of adverse side effects and co-benefits varies considerably between low-carbon technologies in the energy sector (Luderer et al. 2019).

16.2.4 Representation of the innovation process in modelled decarbonization pathways

A variety of models are used to generate climate mitigation pathways, compatible with 2°C and well below 2°C targets. These include Integrated Assessment Models (IAMs), energy system models, computable general equilibrium models and agent based models. They range from global (Chapter 3) to national models and include both top-down and bottom-up approaches (Chapter 4). Innovation in energy technologies, which comprises the development and diffusion of low-, zero- and negative-carbon energy options, but also investments to increase energy efficiency, is a key driver of emissions reductions in model-based scenarios.

16.2.4.1 Technology cost development

Assumptions on energy technology cost developments are one of the factors that determine the speed and magnitude of the deployment in climate-energy-economy models. The modelling is informed by the empirical literature estimating rates of cost reductions for energy technologies. A first strand of literature relies on the extrapolation of historical data, assuming that costs decrease either as a power law of cumulative production, exponentially with time (Nagy et al. 2013) or as a function of technical performance metrics (Koh and Magee 2008). Another approach relies on expert estimates of how future costs will evolve, including expert elicitations (Verdolini et al. 2018).

In these models, technology costs may evolve exogenously or endogenously (Krey et al. 2019; Mercure et al. 2016). In the first case, technology costs are assumed to vary over time at some predefined rate, generally extrapolated from past observed patterns or based on expert estimates. This formulation of cost dynamics generally underestimates future costs (Meng et al. 2021) as, among other things, it does not capture any policy-induced carbon-saving technological change or any spillover arising from the accumulation of national and international knowledge (Section 16.2.2 and 16.2.3) or positive macroeconomics effects of a transition (Karkatsoulis et al. 2016). The influence of cost and diffusion assumptions may be evaluated through sensitivity analysis. In the second case, costs are a function of a choice variable within the model. For instance, technology costs decrease as a function of either cumulative installed capacity (learning-by-doing) (Seebregts et al. 1998; Kypreos and Bahn 2003) or R&D investments or spillovers from other sectors and countries.

One factor in this 'learning-by-researching' is applied to a wide range of energy technologies but also to model improvements in the efficiency of energy use (Goulder and Schneider 1999; Popp 2004). More complex formulations include two-factor learning processes (see Section 16.2.2.1) (Criqui et al. 2015;

Emmerling et al. 2016; Paroussos et al. 2020), multi-factor learning curves (Kahouli 2011; Yu et al. 2011), or other drivers of cost reductions such as economies of scale and markets (Elia et al. 2021). The application of two-factor learning curves to model energy technology costs is often constrained by the lack of information on public and/or private energy R&D investments in many fast-developing and developing countries (Verdolini et al. 2018). The approach used to model energy technology costs reductions varies across technologies, even within the same model, depending on the availability of data and/or the level of maturity. Less mature technologies generally depend highly on learning-by-research, whereas learning-by-doing dominates in more mature technologies (Jamasb 2007).

In addition to learning, knowledge spillover effects are also integrated in climate-energy-economy models to reflect the fact that innovation in a given country depends also on knowledge generated elsewhere (Fragkiadakis et al. 2020; Emmerling et al. 2016). Models with a more detailed representation of sectors (Paroussos et al. 2020) can use spillover matrices to include bilateral spillovers and compute learning rates that depend on the human capital stock and the regional and/or sectoral absorption rates (Fragkiadakis et al. 2020). Accounting for knowledge spillovers in the EU for PV, wind turbines, EVs, biofuels, industry materials, batteries and advanced heating and cooking appliances can lead to the following results in a decarbonization scenario over the period 2020–2050 as compared to the reference scenario: an increase of 1.0–1.4% in GDP, 2.1–2.3% in investment, and 0.2–0.4% in employment by clean energy technologies (Paroussos et al. 2017). When comparing two possible EU transition strategies - being a first-mover with strong unilateral emission reduction strategy until 2030 versus postponing action for the period after 2030 - endogenous technical progress in the green technologies sector can alleviates most of the negative effects of pioneering low-carbon transformation associated with loss of competitiveness and carbon leakage (Karkatsoulis et al. 2016).

16.2.4.2 Technology deployment and diffusion

To simulate possible paths of energy technology diffusion for different decarbonisation targets, models rely on assumptions about the cost of a given technology cost relative to the costs of other technologies and its ability to supply the energy demand under the relevant energy system and physical constraints. These assumptions include, for example, considerations regarding renewable intermittency, inertia on technology lifetime (for instance, under less stringent temperature scenarios early retirement of fossil plants does not take place), distribution, capacity and market growth constraints, as well as the presence of policies. These factors change the relative price of technologies. Furthermore, technological diffusion in one country is also influenced by technology advancements in other regions (Kriegler et al. 2015).

Technology diffusion may also be strongly influenced, either positively or negatively, by a number of non-cost, non-technological barriers or enablers regarding behaviours, society and institutions (Knobloch and Mercure 2016)These include network or infrastructure externalities, the co-evolution of technology clusters over time ("path dependence"), the risk-aversion of users, personal preferences and perceptions and lack of adequate institutional framework which may negatively influence the speed of (low-carbon) technological innovation and diffusion, heterogeneous agents with different preferences or expectations, multi-objectives and/or competitiveness advantages and uncertainty around the presence and the level of environmental policies and institutional and administrative barriers (Iyer et al. 2015; Baker et al. 2015; Marangoni and Tavoni 2014; van Sluisveld et al. 2020; Napp et al. 2017; Biresselioglu et al. 2020). These types of barriers to technology diffusion are currently not explicitly detailed in most of the climate-energy-economy models. Rather, they are accounted for in models through scenario narratives, such as the ones in the Shared Socioeconomic Pathways (Riahi et al. 2017), in which assumptions about technology adoption are spanned over a plausible range of values. Complementary methods are increasingly used to explore their importance in future scenarios (Turnheim et al. 2015; Gambhir et al. 2019; Trutnevyte et al. 2019; Doukas et al. 2018; Geels et al. 2016). It takes a very complex modelling framework to include all aspects affecting technology cost reductions and technology diffusion, such as heterogeneous agents (Lamperti et al. 2020), regional labour costs (Skelton et al. 2020), materials cost and trade and perfect foresight multi-objective optimization (Aleluia Reis et al. 2021). So far, no model can account for all these interactions simultaneously.

Another key aspect of decarbonization regards issues of acceptability and social inclusion in decision-making. Participatory processes involving stakeholders can be implemented using several methods to incorporate qualitative elements in model-based scenarios on future change (Doukas and Nikas 2020; van Vliet et al. 2010; Nikas et al. 2017, 2018; van der Voorn et al. 2020).

16.2.4.3 Implications for the modelling of technical change in decarbonization pathways

Although the debate is still ongoing, preliminary conclusions indicate that integrated assessment models tend to underestimate innovation on energy supply but overestimate the contributions by energy efficiency (IPCC 2018b). Scenarios emerging from cost-optimal climate-energy-economy models are too pessimistic, especially in the case of rapidly changing technologies such as wind and batteries in the past decade Conversely, they tend be too optimistic regarding the timing of action, or the availability of a given technology and its speed of diffusion (Shiraki and Sugiyama 2020). Furthermore, some technological and economic transformations may emerge as technically feasible from IAMs, but are not realistic if taking into account political economy, international politics, human behaviours, and cultural factors (Bosetti 2021).

There is a range of projected energy technology supply costs included in the AR6 Scenario Database (Box 16.1). Variations of costs over time and across scenarios are within ranges comparable to those observed in recent years. Conversely, model results show that limiting warming to 2°C or 1.5°C will require faster diffusion of installed capacity of low-carbon energy options and a rapid phase out of fossil-based options. This points to the importance of focusing on overcoming real-life barriers to technology deployment.

START BOX 16.1 HERE

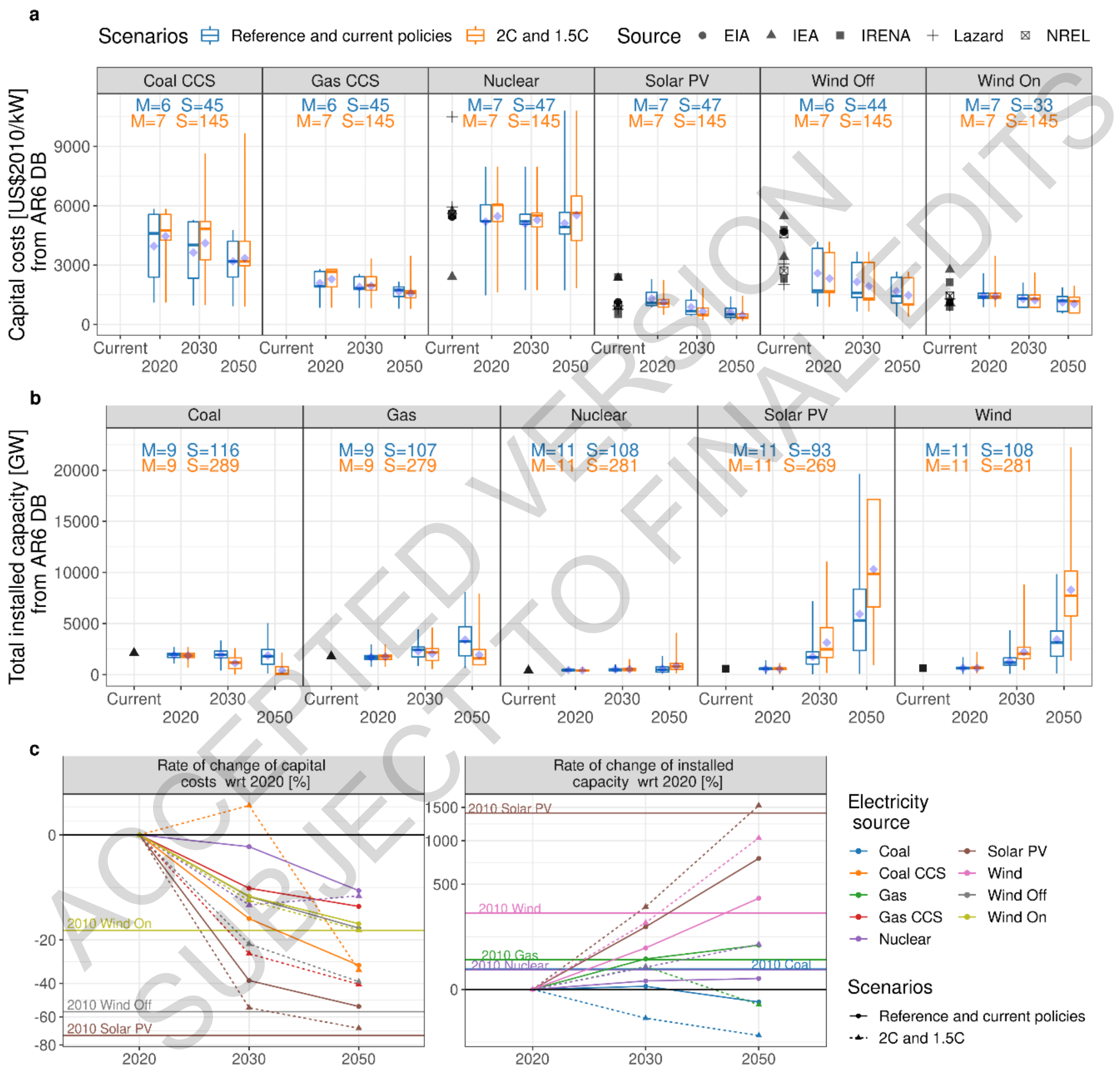
Box 16.1 Comparing observed energy technology costs and deployment rates with projections from AR6 low-carbon pathways

Currently observed costs and deployment for electricity supply technologies from a variety of sources are compared with projections from two different sets of scenarios contained in the AR6 Scenario database: 1) reference and current policies including NDCs and 2) 2°C and well-below 2°C (AR6 model database). Global aggregate costs are shown for the following technologies: Coal with CCS, Gas with CCS, Nuclear, Solar PV, Onshore and Offshore Wind.

The decrease in forecasted capital costs is not large compared to current capital costs for most technologies, and does not differ much between the two scenarios (Box 16.1, Figure 1a). For Wind offshore some of the models are more optimistic than the current reality (Timilsina 2020). Several sources of current solar PV costs report values that are at the low end of the AR6 model scenario database. By 2050, the median technology cost forecasts decrease by between 5% for nuclear and 45-52% for solar (Box 16.1, Figure 1c).

Median values of renewables installed capacity increase with respect to 2020 capacity in "*current policies"* scenarios (Box 16.1, Figure 1b), where energy and climate policies are implemented in line with the current NDCs. More ore stringent targets (2°C) are achieved through a higher deployment of renewable technologies: by 2050 solar (wind) capacity is estimated to increase by a factor of 15 (10) (Box 16.1, Figure 1c). This is accompanied by an almost complete phase out of coal (-87%). The percentage of median changes in installed capacity in the current policies scenarios is within comparable ranges of that observed in the last decade. In the case of the 2°C and well-below 2°C scenarios, capacity installed is higher for renewable technologies and nuclear, and lower for fossil-based technologies (Box 16.1, Figure 1c).

The higher deployment in 2°C scenarios cannot be explained solely as a result of technology cost dynamics. In IAMs, technology deployment is also governed by system constraints that characterize both scenarios, e.g. the flexibility of the energy system, the availability of storage technologies. From a modelling point of view, implementing more stringent climate policies to meet the 2°C targets forces models to find solutions, even if costly, to meet those intermittency and flexibility constraints and temperature target constraints.



Box 16.1, Figure 1: Global Technology cost and deployment in two groups of AR6 scenarios: (1) reference and current policies including NDCs and (2) 2°C and well-below 2°C.
Panel a) Current capital costs are sourced from Table 1, (Timilsina 2020); distribution of capital costs in 2030 and 2050 (AR6 database). Blue symbols represent the mean. 'Current' capital costs for coal and gas plants with CCS are not available; Panel b) Total installed capacity in 2019 (IRENA 2020a; IEA 2020c; IRENA 2020b); distribution of total installed capacity in 2030 and 2050 (AR6 database). Blue symbols represent the mean; Panel c) Percentage of change in capital costs and installed capacity between (2010-2020) and percentage of median change (2020-2030 and 2020-2050) (Median$_{year}$-

Median$_{2020}$)/Median$_{2020}$*100. "M" indicates the number of models, "S" the number of scenarios for which this data is available. Reference and current policies' are C6 and C7 scenario categories and '2C and 1.5C' are C1, C2 and C3 scenario categories. Each model may have submitted data for more than one model version.

END BOX 16.1 HERE

16.3 A systemic view of technological innovation processes

The innovation process, which consists of a set of sequential phases (Section 16.2.1), is often simplified to a linear process. Yet, it is now well understood that it is also characterised by numerous kinds of interactions and feedbacks between the domains of knowledge generation, knowledge translation and application, and knowledge use (Kline and Rosenberg 1986). Furthermore, it is not just invention that leads to technological change but the cumulative contribution of incremental innovations over time can be very significant (Kline and Rosenberg 1986). Innovations can come not just from formal R&D but also sources such as production engineers and the shop floor (Freeman 1995a; Kline and Rosenberg 1986).

This section reviews the literature focusing on innovation as a systemic process. This now predominant view enriches the understanding of innovation as presented in section 16.2; it conceptualizes innovation as the result of actions by, and interactions among, a large set of actors, whose activities are shaped by, and shape, the context in which they operate and the user group with which they are engaging. This section aligns with the discussion of socio-technical transitions (see Chapter 1 Section 1.7.3, the Supplementary Material in Chapter 5, and Cross-Chapter Box 12 in this chapter).

16.3.1 Frameworks for analysing technological innovation processes

The resulting overarching framework that is commonly used in the innovation scholarship and even policy analyses is termed as "innovation system", where the key constituents of the systems are actors, their interactions, and the institutional landscape, including formal rules, such as laws, and informal restraints, such as culture and codes of conduct, that govern the behaviour of the actors (North 1991).

One application of this framework is that of *national innovation systems (NIS)*, which highlights the importance of national and regional relationships for determining the technological and industrial capabilities and development of a country (Nelson 1993; Lundvall 1992; Freeman 1995a). Nelson (1993) and Freeman (Freeman 1995a) highlight the role of institutions that determine the innovative performance of national firms as way to understand differences across countries, while Lundvall (1992) focuses on the "elements and relationships which interact in the production, diffusion and use of new, and economically useful, knowledge", i.e., notions of interactive learning, in which user-producer relationships are particularly important (Lundvall 1988). Building on this, various other applications of the "innovation systems" framework have emerged in the literature.

Technological Innovation systems (TIS), with technology or set of technologies (more narrowly or broadly defined in different cases) as the unit of analysis and focus on explaining what accelerates or hinders their development and diffusion. Carlsson and Stankiewicz (1991) define a technological system as "a dynamic network of agents interacting in a specific economic/ industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilisation of technology." More recent work takes a "functional approach" to TIS (Bergek et al. 2008; Hekkert et al. 2007), which was later expanded with explanations of how some of the sectoral, geographical and political dimensions intersect with technology innovation systems (Bergek et al. 2015; Quitzow 2015).

Sectoral innovation systems (SIS): based on the understanding that the constellation of relevant actors and institutions will vary across industrial sectors, with each sector operating under a different technological regime and under different competitive or market conditions. A sectoral innovation, thus, can be defined as "that system (group) of firms active in developing and making a sector's products and in generating and utilising a sector's technologies" (Breschi and Malerba 1997).

Regional and Global innovation systems (RIS, GIS), recognising that the many innovation processes have a spatial dimension, where the development of system resources such as knowledge, market access, financial investment, and technology legitimacy may well draw on actors, networks, and institutions within a region (Cooke et al. 1997). In other cases, the distribution of many innovation processes are highly internationalised and therefore outside specific territorial boundaries (Binz and Truffer 2017). Importantly, Binz and Truffer (2017) note that the GIS framework "differentiates between an industry's dominant innovation mode... and the economic system of valuation in which markets for the innovation are constructed."

Mission-oriented innovation systems (MIS), whose relevance comes into focus with the move towards mission-oriented programs as part of the increasing innovation policy efforts to address societal challenges. Accordingly, an MIS is seen as consisting of "networks of agents and sets of institutions that contribute to the development and diffusion of innovative solutions with the aim to define, pursue and complete a societal mission" (Hekkert et al. 2020).

Notably the innovation systems approach has been used in a number of climate-relevant areas such as agriculture (Echeverría 1998; Klerkx et al. 2012; Horton and Mackay 2003; Brooks and Loevinsohn 2011), energy (Sagar and Holdren 2002; OECD 2006; Gallagher et al. 2012; Wieczorek et al. 2013; Mignon and Bergek 2016; Darmani et al. 2014), industry (Koasidis et al. 2020b) and transport (Koasidis et al. 2020a), and sustainable development (Clark et al. 2016; Bryden and Gezelius 2017; Anadon et al. 2016b; Nikas et al. 2020).

A number of functions can be used to understand and characterise the performance of technological innovation systems (Hekkert et al. 2007; Bergek et al. 2008). The most common functions are in Table 16.5.

Table 16.5 Functions that the literature identified as key for well-performing technological innovation systems (based on Hekkert et al (2007) and Bergek et al (2008))

Functions	Description
Entrepreneurial activities and experimentation	Entrepreneurial activities and experimentation for translating new knowledge and/or market opportunities into real-world application
Knowledge development	Knowledge development includes both "learning-by-searching" and "learning-by-doing"
Knowledge diffusion	Knowledge diffusion through networks, both among members of a community (e.g., scientific researchers) and across communities (e.g., universities, business, policy, and users).
Guidance of search	Guidance of search directs the investments in innovation in consonance with signals from the market, firms or government
Market formation	Market formation through customers or government policy is necessary to allow new technologies to compete with incumbent technologies
Resource mobilisation	Resource mobilisation pertains to the basic inputs – human and financial capital – to the innovation process

Creation of legitimacy/counteract resistance to change	Creation of legitimacy or counteracting resistance to change, through activities that allow a new technology to become accepted by users, often despite opposition by incumbent interests
Development of external economies	Development of external economies, or the degree to which other interests benefit from the new technology

Evidence from empirical case studies indicates that all the above functions are important and that they interact with one another (Hekkert and Negro 2009). The approach therefore serves as both a rationale for and a guide to innovation policy (Bergek et al. 2010).

A much-used, complementary systemic framework is the multilevel perspective (MLP) (Geels 2002), which focuses mainly on the diffusion of technologies in relation to incumbent technologies in their sector and the overall economy. A key point of MLP is that new technologies need to establish themselves in a stable 'socio-technical regime' and are therefore generally at a disadvantage, not just because their low technological maturity, but also because of an unwelcoming system. The MLP highlights that the uptake of technologies in society is an evolutionary process, which can be best understood as a combination of "variation, selection and retention" as well as "unfolding and reconfiguration" (Geels 2002). Thus new technologies in their early stages need to be selected and supported at the micro-level by niche markets, possibly through a directed process that has been termed "strategic niche management" (Kemp et al. 1998). As at the macro landscape level pressures on incumbent regimes mount, and those regimes destabilise, the niche technologies get a chance to get established in a new socio-technical regime, which allows these technologies to grow and stabilise, shaping a changed or sometimes radically renewed socio-technical regime. The MLP takes a systematic and comprehensive view about how to nurture and shape technological transitions by understanding them as evolutionary, multi-directional and cumulative socio-technical process playing out at multiple levels over time with a concomitant expansion in the scale and scope of the transition (Elzen et al. 2004; Geels 2005b). There have been numerous studies that draw on the MLP (van Bree et al. 2010; Geels et al. 2017; Geels 2012) to understand different aspects of climate technology innovation and diffusion.

Systemic analyses of innovation have predominantly focused on industrialised countries There have been some efforts to use the innovation systems lens for the developing country context (Jacobsson and Bergek 2006; Lundvall et al. 2009; Altenburg 2009; Choi and Zo 2019; Tigabu 2018; Tigabu et al. 2015) and specific suggestions on ways for developing countries to strengthening their innovation systems (e.g., by universities taking on a "developmental" role (Arocena et al. 2015) or industry associations acting as intermediaries to build institutional capacities (Watkins et al. 2015; Khan et al. 2020), including specifically for addressing climate challenges (Sagar et al. 2009; Ockwell and Byrne 2016). But the conditions in developing countries are quite different, leading to suggestions that different theoretical conceptualisations of the innovation systems approach may be needed for these countries (Arocena and Sutz 2020), although a system perspective would still be appropriate (Boodoo et al. 2018).

16.3.2 Identifying systemic failures to innovation in climate-related technologies

Traditional perspectives on innovation policy were mostly science-driven, and focused on strengthening invention and its translation into application in a narrow sense, and a second main traditional perspective on innovation policy was focused on correcting for 'market failures' (covered in Section 16.2) (Weber and Truffer 2017). The more recent understanding of, and shift of focus to, the systemic nature on the innovation and diffusion of technologies has implications for innovation policy since innovation outcomes depend not just on inputs such as R&D but much more on the functioning of the overall innovation system (see previous section and Section 16.4). Policies can therefore be directed at innovation systems components and processes that need the greatest attention or support. This may include, for example, strengthening the capabilities of weak actors and improving interactions between actors (Jacobsson et al. 2017; Weber and Truffer 2017). At the same time, a systemic perspective also brings into sharp relief the notion of 'system failures' (Weber and Truffer 2017).

Systemic failures include infrastructural failures; hard (e.g., laws, regulation) and soft (e.g., culture, social norms) institutional failures; interaction failures (strong and weak network failures); capability failures relating to firms and other actors; lock-in; and directional, reflexivity, and coordination failures (Klein Woolthuis et al. 2005; Chaminade and Esquist 2010; Weber and Rohracher 2012; Wieczorek and Hekkert 2012; Negro et al. 2012). By far most of the literature that unpacks such failures and explores ways to overcome them is on energy-related innovation policy. For example, Table 16.6 summarizes a meta-study (Negro et al. 2012) that examined cases of renewable energy technologies trying to disrupt incumbents across a range of countries to understand the roles, and relative importance, of the 'systemic problems' highlighted in Section 16.3.1.

Table 16.6 Examination of systemic problems preventing renewable energy technologies from reaching their potential, including number of case studies in which the particular 'systemic problem' was identified Source: (Negro et al. 2012).

Systemic problems	Empirical sub-categories	No. of cases
Hard institutions	- 'Stop and go policy': lack of continuity and long-term regulations; inconsistent policy and existing laws and regulations -'Attention shift': policy makers only support technologies if they contribute to the solving of a current problem -'Misalignment' between policies on sector level such as agriculture, waste, and on governmental levels, i.e. EU, national, regional level, etc. -"Valley of Death": lack of subsidies, feed-in tariffs, tax exemption, laws, emission regulations, venture capital to move technology from experimental phase towards commercialisation phase	51
Market structures	- Large-scale criteria - Incremental/near-to-market innovation - Incumbent's dominance	30
Soft institutions	- Lack of legitimacy - Different actors opposing change	28
Capabilities/capacities	- Lack of technological knowledge of policy makers and engineers - Lack of ability of entrepreneurs to pack together, to formulate clear message, to lobby to the government - Lack of users to formulate demand - Lack of skilled staff	19
Knowledge infrastructure	- Wrong focus or not specific courses at universities knowledge institutes - Gap/Misalignment between knowledge produce at universities and what needed in practice	16

Too weak interactions	- Individualistic entrepreneurs - No networks, no platforms - Lack of knowledge diffusion between actors - Lack of attention for learning-by-doing	13
Too strong interactions	- Strong dependence on government action or dominant partners (incumbents) - Networks allows no access to new entrants	8
Physical infrastructure	- No access to existing electricity or gas grid for RETs - No decentralised, small-scale grid - No refill infrastructure for biofuels, ABG, H2, biogas	2

Depending on the sector, specific technology characteristics, and national and regional context, the relevance of these systemic problems varies (Trianni et al. 2013; Bauer et al. 2017; Wesseling and Van der Vooren 2017; Koasidis et al. 2020b,a), suggesting that the innovation policy mix has to be tailor-made to respond to the diversity of systemic failures (Rogge et al. 2017). An illustration of how such systemic failures have been addressed is given in Box 16.2, which shows how the Indian government designed its standards and labelling programme for energy-efficient air conditioners and refrigerators. The success of this program resulted from the careful attention to bring on board and coordinate the relevant actors and resources, the design of the standards, and ensuring effective administration and enforcement of the standards (Malhotra et al. 2021).

START BOX 16.2 HERE

Box 16.2: Standards and Labelling (S&L) for energy efficient refrigerators and air conditioners in India[2]

Energy efficiency is often characterised as a "low-hanging fruit" for reducing energy use. However, systemic failures such as lack of access to capital, hidden costs of implementation, and imperfect information can result in low investments into adoption and innovation in energy efficiency measures (Sorrell et al. 2004). To address such barriers, India's governmental Bureau of Energy Efficiency (BEE) introduced the Standards and Labelling (S&L) programme for promotion of innovation in energy efficient appliances in 2006 (Sundaramoorthy and Walia 2017). While context-dependent, the programme design, policies and scale-up contain lessons for addressing systemic failures elsewhere too.

Program design and addressal of early systemic barriers

To design the S&L program, BEE drew on the international experiences and technical expertise of the Collaborative Labelling and Appliance Standards Program (CLASP) – a non-profit organisation that provides technical and policy support to governments in implementing S&L programs. For example, since there was no data on the efficiency of appliances in the Indian market, CLASP assisted with early data collection efforts, resulting in a focus on refrigerators and air conditioners (ACs) (McNeil et al. 2008).

FOOTNOTE [2] This section draws on "The role of capacity-building in policies for climate change mitigation and sustainable development: The case of energy efficiency in India" (Malhotra et al. 2021)

Besides drawing from international knowledge, the involvement of manufacturers, testing laboratories, and customers was crucial for the functioning of the innovation system.

To involve manufacturers, BEE employed three strategies to set the standards at an ambitious yet acceptable level. First, BEE enlisted IIT Delhi (a public technical university) to engage with manufacturers and to demonstrate cost-effective designs of energy-efficient appliances. Second, BEE agreed to make the standards voluntary from 2006 to 2010. In return, the manufacturers agreed to mandatory and progressively more stringent standards starting in 2010. Third, BEE established a multi-stakeholder committee with representation from BEE, the Bureau of Indian Standards, appliance manufacturers, test laboratories, independent experts, and consumer groups (Jairaj et al. 2016) to ensure that adequately stringent standards are negotiated every two years.

At this time, India had virtually no capacity for independent testing of appliances. Here too, BEE used multiple approaches towards creating the actors and resources needed for the innovation system to function. First, BEE funded the Central Power Research Institute (CPRI) – a national laboratory for applied research, testing and certification of electrical equipment – to set up refrigerator and AC testing facilities. Second, they invited bids from private laboratories, thus creating a demand for testing facilities. Third, BEE developed testing protocols in partnership with universities. Australian standards for testing frost-free refrigerators were adopted until local standards were developed. Thus, once the testing laboratories, protocols and benchmark prices for testing were in place, the appliance manufacturers could employ their services.

Finally, a customer outreach program was conducted from 2006 to 2008 to inform customers regarding energy efficient appliances, to enable them to interpret the labels correctly, and to understand their purchase decisions and information sources (Joshi et al. 2019; Jain et al. 2018). BEE initiated a capacity building program for retailers to be an information source for costumers. A comprehensive document with details of different models and labels was provided to retailers, together with a condensed booklet to be shared with customers.

Adapting policies to technologies and local context

While many of India's standards and testing protocols were based on international standards, they needed to be adapted to the Indian context. For example, because of higher temperatures in India, the reference outside temperature of 32°C for refrigerators was changed to 36°C.

AC testing protocols also had to be adapted because of the emergence of inverter-based ACs. Existing testing done only at a single temperature did not value inverter-based ACs' better average performance as compared to fixed-speed ACs over a range of temperatures. Thus, the Indian Seasonal Energy Efficiency Ratio (ISEER) was developed for Indian temperature conditions in 2015 by studying ISO standards and through consultations with manufacturers (Mukherjee et al. 2020).

These measures had multiple effects on technological change. As a result of stringent standards, India has some of the most efficient refrigerators globally. In the case of ACs, the ISEER accelerated technological change by favouring inverter-based ACs over fixed-speed ACs, driving down their costs and increasing their market shares (BEE 2020).

Scaling up policies for market transformation

As the S&L program was expanded, BEE took measures to standardise, codify and automate it. For example, to process a high volume of applications for labels efficiently, an online application portal with objective and transparent certification criteria was created. This gave certainty to the manufacturers, enabling diversity and faster diffusion of energy-efficient appliances. Thus by 2019, the program expanded to cover thousands of products across 23 appliance types (BEE 2020).

Besides issuing labels, the enforcement of standards also needed to be scaled up efficiently. BEE developed protocols for randomly sampling appliances for testing. Manufacturers were given a fixed period to rectify products that did not meet the standards, failing which they would be penalised and the test results would be made public.

END BOX 16.2 HERE

16.3.3 Indicators for technological innovation

Assessing the state of technological innovation helps understanding how current efforts and policies are doing in relation to stated objectives and how we might design policies in order to do better.

Traditionally, input measures such as RD&D investments and output measures such as scientific publication and patents were used to characterise innovation activities (Freeman and Soete 2009), partly because of the successes of specialised R&D efforts (Freeman 1995a), the predominant linear model of innovation, and because such measures can (relatively) easily obtained and compared. In the realm of energy-related innovation, RD&D investments remains the single most-used indicator to measure inputs into the innovation process (Box 16.3). Patents counts are a widely used indicator of the outputs of the innovation process, especially because they are detailed enough to provide information on specific adaptation and mitigation technologies. Mitigation and adaptation technologies have their own classification (Y02) with the European Patent Office (EPO) (Veefkind et al. 2012; Angelucci et al. 2018), which can be complemented with keyword search and manual inspection (Persoon et al. 2020; Surana et al. 2020b). However, using energy-related patents as indicator of innovative activities is complicated by several issues (Haščič and Migotto 2015; Jaffe and de Rassenfosse 2017; de Rassenfosse et al. 2013), including the fact that the scope of what are to be considered climate mitigation inventions is not always clear or straightforward.

Conversely, private energy R&D investments and investments by financing firms cannot be precisely assessed for a number of reasons, including limited reporting and the difficulty of singling out energy-related investments. This inability to precisely quantify private investments in energy R&D leads to a patchy understanding of the energy innovation system, and how private energy R&D investments responds to public energy R&D investments. Overall, evidence shows that some of the industrial sectors that are important for meeting climate goals (electricity, agriculture and forestry, mining, oil and gas, and other energy-intensive industrial sectors) are investing relatively small fractions of sales on R&D (*medium evidence, high agreement*) (European Commission 2015; National Science Board 2018; American Energy Innovation Council 2017; Jasmab and Pollitt 2005; Sanyal and Cohen 2009; Jamasb and Pollitt 2008; Gaddy et al. 2017).

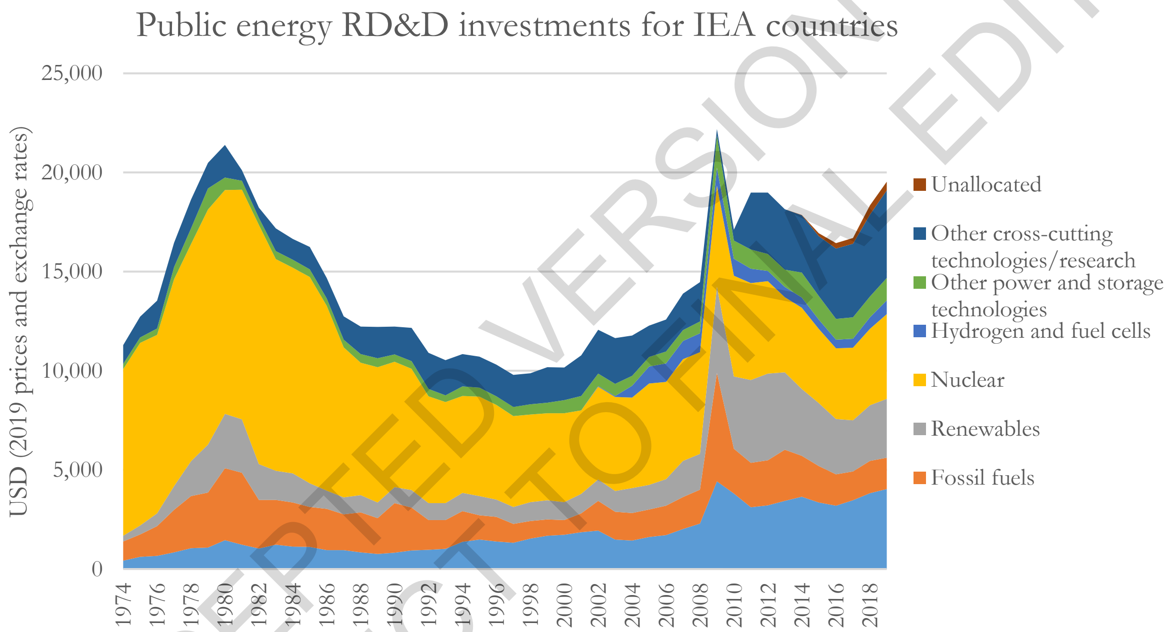
Financing firms also play an important role in the energy innovation process, but data availability is also limited. The venture capital (VC) financing model, used to overcome the "valley of death" in the biotech and IT space (Frank et al. 1996), has not been as suitable for hardware start-ups in the energy space: for example, the percentage of exit outcomes in clean-tech start-ups was almost half of that in medical start-ups and less than a third of software investments (Gaddy et al. 2017). The current VC model and other private finance do not sufficiently cover the need to demonstrate energy technologies at scale (Mazzucato 2013; Anadón 2012; Nemet et al. 2018). This greater difficulty in reaching the market compared to other sectors may have contributed to a reduction in private equity and venture capital finance for renewable energy technologies after the boom of the late 2000s (Frankfurt School-UNEP Centre/BNEF 2019).

START BOX 16.3 HERE

Box 16.3 Investments in public energy R&D

Public energy R&D investments are a crucial driver of energy technology innovation (Sections 16.2.1.1, 16.4.1). Box 16.3, Figure 1 shows the time profile of energy-related RD&D budgets in OECD countries as well as some key events which coincided with developments of spending (IEA 2019). Such data on other countries, in particular developing countries, are not available, although recent evidence suggests that expenditures are increasing there (IEA 2020c). The IEA collected partial data from China and India in the context of Mission Innovation, but this is available only starting in 2014 and thus not included in the Figure.

The figure illustrates two points. First, energy-related RD&D has risen slowly in the last 20 years, and is now reaching levels comparable with the peak of energy RD&D investments following the two oil crises. Second, over time there has been a reorientation of the portfolio of funded energy technologies away from nuclear energy. In 2019, around 80% of all public energy RD&D spending was on low-emission technologies – energy efficiency, CCUS, renewables, nuclear, hydrogen, energy storage and cross-cutting issues such as smart grids. A more detailed discussion of the time profile of RD&D spending in IEA countries, including as a share of GDP, are available in (IEA 2020b).



Box 16.3, Figure 1 Fraction of public energy RD&D spending by technology over time for IEA (largely OECD) countries between 1974 and 2018.

Sources: IEA RD&D Database, 2019 (IEA 2019). (extracted on November 11, 2020).

END BOX 16.3 HERE

Quantitative indicators such as energy-related RD&D spending are insufficient for the assessment of innovation systems (David and Foray 1995): they only provide a partial view into innovation activities, and one that is potentially misleading (Freeman and Soete 2009). Qualitative indicators measuring the more intangible aspects of the innovation process and system are crucial to fully understand the innovation dynamics in a climate or energy technologies or sectors (Gallagher et al. 2006), including in relation to adopting an adaptive learning strategy and supporting learning through demonstration projects (Chan et al. 2017).

In Table 16.7, both quantitative and qualitative indicators for systemic innovation are outlined, using clean energy innovation as an illustrative example and drawing on a broad literature base, taking into account both the input-output-outcome classification and its variations (Hu et al. 2018; Freeman and Soete 1997; Sagar and Holdren 2002), combined with the functions of technological innovation systems

(Miremadi et al. 2018), while also being cognizant of the specific role of key actors and institutions (Gallagher et al. 2012). A specific assessment of innovation may focus on part of such a list of indicators, depending on what aspect of innovation is being studied, whether the analysis takes a more or less systemic perspective, and the specific technology and geography considered. Similarly, innovation policies may be designed to specifically boost only some of these aspects, depending whether a given country/region is committed to strengthen a given technology or phase.

The systemic approach to innovation and transition dynamics (see also Cross-Chapter Box 12 in this chapter) has advanced our understanding of the complexity of the innovation process, pointing to the importance of assessing the efficiency and effectiveness in producing, diffusing and exploiting knowledge (Lundvall 1992), including how the existing stock of knowledge may be recombined and used for new applications (David and Foray 1995). There remains a crucial need for more relevant and comprehensive approaches of assessing innovation (Freeman and Soete 2009; Dziallas and Blind 2019). In the context of climate mitigation, innovation is a means to an end; therefore, there is the need to consider the processes by which the output of innovation (e.g., patents) are translated into real-world outcomes (e.g., deployment of low-carbon technologies) (Freeman and Soete 1997; Sagar and Holdren 2002). Currently, a set of quantitative metrics that, collectively, can help get a picture of innovation in a particular energy technology or set of energy technologies is not available. Also the understanding of how to systematically use qualitative indicators to characterise the more intangible aspects of the energy innovation system and to improve front-end innovation decisions is still lacking (Dziallas and Blind 2019).

Table 16.7 Commonly used quantitative innovation metrics, organized by inputs, outputs and outcomes. Based on (Sagar and Holdren 2002; Gallagher et al. 2006; Hekkert et al. 2007; Gallagher et al. 2012; Miremadi et al. 2018; Hu et al. 2018; Gallagher et al. 2011; Avelino et al. 2019; Gruebler et al. 2012)

Function	Input indicators	Output indicators	Outcome indicators	Actors	Policies	Structural and systemic indicators
Knowledge development	Higher education investments R&D investments Number of researchers R&D projects over time	Scientific publications Highly-cited publications Patents New product configurations	Number of technologies developed (proof-of-concept/prototypes) Increase in number of researchers Learning rates	Governments Private corporations Universities	Research programs and strategies IPR policies International technical norms (e.g. standards) Higher education policies	Well-defined processes to define research priorities Stakeholder involvement in priority-setting
Knowledge diffusion	R&D networks Number of research agreement Number of research exchange programs Number of scientific conferences	Citations to literature or patents Public-private co-publications Co-patenting Number of co-developed products International scientific co-publications Number of workshops and conferences	Number of licensed patents Number of technologies transferred Knowledge-intensive services exports Number of patent applications by foreigners Number of researchers working internationally	Governments Private corporations Scientific societies Universities	Development of communication centres Facilitation of the development of networks Open-access publication policies IPR policies International policy: e.g. treaties, clean development mechanism	Accessibility to exchange programs Strength of linkage among key stakeholders Participation to framework agreements ICT access
Guidance of search	Policy action plans and long-term targets Shared strategies and roadmaps	Level of media coverage Scenarios and foresight projects	Budget allocations Mission-oriented innovation programs	Governments Interest groups	Targets set by government of industry Innovation policies	Media strength

	Articulation of interest from lead customers Expectations of markets/profits			Media	Credible political support	
Resource mobilization	Access to finance Graduate in STEMS Gross expenditures on R&D/total expenditures Domestic credit to private sector Number of researchers in R&D per capita Public energy R&D expenditures/total expenditures Expenditure on education Investment in complementary assets and/or infrastructure (e.g. Charging	Number of green projects/technologies funded Share of domestic credit granted to low-carbon technology projects Share of domestic credit granted to projects developing complementary assets/infrastructure	Employment in knowledge-intensive activities Employment in relevant industries Scale of innovative activities Rate of growth of dedicated investment Availability of complementary assets and infrastructure	Governments Private firms Private investors (angel, venture capital, private equity) Banks	Financial resources support Development of innovative financing International agreements (e.g. technology agreements) Infrastructure support Project/program evaluation Innovation policies Higher education policies	

	infrastructure for EVs, smart grids) Venture capital on deals					
Entrepreneurial activities	No. of new entrants % of clean energy start-ups/incumbents access to finance for clean-tech start up	SMEs introducing product or process innovation Market introduction of new technological products Number of new businesses Experimental application projects Creative goods exports		Private firms Government Risk-capital providers Philanthropies	Ease of starting a business Risk-capital policies Start-up support programs Incubator programs	Start-up support services
Market formation	Public market support High-tech imports	Market penetration of new technologies Increase in installed capacity No of niche markets Number of technologies commercialized	Environmental performance Level of environmental impact on society Renewable energy jobs Renewable energy production Trade of energy technology and equipment High-tech exports	Private firms Governments institutions regulating trade, finance, investment, environment, development, security, and health issues	Environmental and Energy Regulation Fiscal and financial incentives Cleantech-friendly policy processes Transparency Specific tax regimes	Resource endowments Attractiveness of renewable energy infrastructure Coordination across relevant actors (e.g., renewable energy producers, grid operators, and distribution companies)

Creation of legitimacy	Youth and public demonstration Lobbying activities Regulatory acceptance and integration Technology support	Level of discussion/debate among key stakeholders (public, firms, policy-makers, etc.) Greater recognition of benefits	Public opinion Policy-maker opinion Executive opinion on regulation Environmental standards and certification	Governments Stakeholders Citizens Philanthropies	Regulatory quality Regulatory instruments Political consistency	Participatory processes

16.3.4 Emerging policy perspectives on systemic transformations

Because of the multiple market, government, system, and other failures that are associated with the energy system, a range of policy interventions are usually required to enable the development and introduction of new technologies in the market (Twomey 2012; Jaffe et al. 2005; Bürer and Wüstenhagen 2009; Veugelers 2012; Negro et al. 2012; Weber and Rohracher 2012) and used in what is termed as policy mixes (Rogge and Reichardt 2016; Rogge et al. 2020; Edmondson et al. 2020, 2019) . Empirical research shows that when in the energy and environment space new technologies were developed and introduced in the market, it was usually at least partly as a result of a range of policies that shaped the socio-technical system (Nemet 2019a; Bunn et al. 2014; Rogge and Reichardt 2016; Bergek et al. 2015) (*robust evidence, high agreement*). An example of this systemic and dynamic nature of policies is the 70-year innovation journey of solar PV, covering multiple countries, which is reviewed in Box 16.4.

START BOX 16.4 HERE

Box 16.4 Sources of cost reductions in solar photovoltaics

No single country persisted in developing solar PV. Five countries each made a distinct contribution. Each leader relinquished its lead. The free flow of ideas, people, machines, finance, and products across countries explains the success of solar photovoltaics (PV). Barriers to knowledge flow delay innovation.

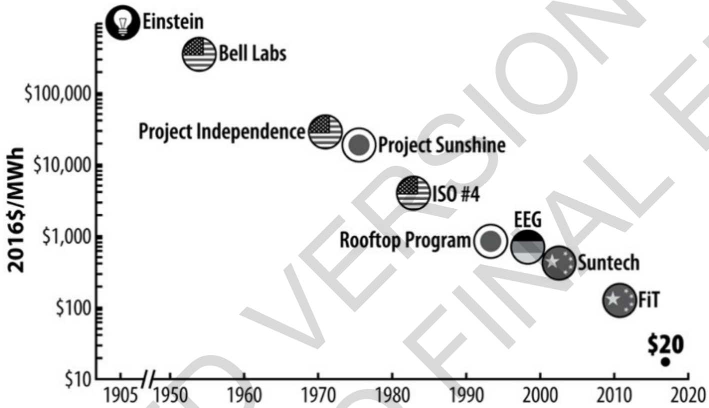
Solar PV has attracted interest for decades, and until recently was seen as an intriguing novelty, serving a niche, but widely dismissed as a serious answer to climate change and other social problems associated with energy use. Since AR5, PV has become a substantial global industry—a truly disruptive technology that has generated trade disputes among superpowers, threatened the solvency of large energy companies, and prompted reconsideration of electric utility regulation rooted in the 1930s. More favourably, its continually falling costs and rapid adoption are improving air quality and facilitating climate change mitigation. PV is now so inexpensive that it is important in an expanding set of countries. In 2020, 41 countries, in 6 continents, had installed at least 1GW of solar each (IRENA 2020a).

The cost of generating electricity from solar PV is now lower in sunny locations than running existing fossil fuel power plants (Chapter 6) (IEA 2020c). Prices in 2020 were below where even the most optimistic experts expected they would be in 2030.

The costs of solar PV modules have fallen by more than a factor of 10,000 since they were first commercialised in 1957. This four orders of magnitude cost reduction from the first commercial application in 1958 until 2018 can be summarised as the result of distinct contributions by the US, Japan, Germany, Australia, and China—in that sequence (Green 2019; Nemet 2019c). As shown in Box 16.4 Figure 1, PV improved as the result of:

1) Scientific contributions in the 1800s and early 1900s, in Europe and the US, that provided a fundamental understanding of the ways that light interacts with molecular structures, leading to the development of the p-n junction to separate electrons and holes (Einstein 1905; Ohl 1941);
2) A breakthrough at a corporate laboratory in the US in 1954 that made a commercially available PV device available and led to the first substantial orders, by the US Navy in 1957 (Gertner 2013; Ohl 1946);
3) A government R&D and public procurement effort in the 1970s in the US, that entrained skilled scientists and engineers into the effort and stimulated the first commercial production lines (Laird 2001; Christensen 1985; Blieden 1999);

4) Japanese electronic conglomerates, with experience in semiconductors, serving niche markets in the 1980s and in 1994 launching the world's first major rooftop subsidy program, with a declining rebate schedule and demonstrating there was substantial consumer demand for PV (Kimura and Suzuki 2006);
5) Germany passing a feed-in tariff in 2000 that quadrupled the market for PV catalysing development of PV-specific production equipment that automated and scaled PV manufacturing (RESA 2001; Lauber and Jacobsson 2016);
6) Chinese entrepreneurs, almost all trained in Australia and using Australian-invented passivated emitter rear cell technology, building supply chains and factories of gigawatt scale in the 2000s. China became the world's leading installer of PV from 2013 onward (Helveston and Nahm 2019; Quitzow 2015).
7) A cohort of adopters with high willingness to pay, accessing information from neighbours, and installer firms that learned from their installation experience, as well as that of their competitors to lower soft costs (Gillingham et al. 2016; Ardani and Margolis 2015).



Box 16.4, Figure 1 Milestones in the development of low-cost solar photovoltaics (Nemet 2019c)

As this evolution makes clear, no individual country persisted in leading the technology and every world leading firm lost its lead within a few years (Green 2019). Solar followed an overlapping but sequential process of technology creation, market creation and cost reductions (comparable to emergence, early adoption, diffusion and stabilisation in Cross-Chapter Box 12 in this chapter). In the technology creation phase examples of central processes include flows of knowledge from one person to another, between firms, and between countries as well as US and Japanese R&D funding in the 1970s and early 1980s. During market creation, PVs modular scale allowed it to serve a variety of niche markets from satellites in the 1950s to toys in the 1980s, when Germany transformed the industry from niche to mass market with its subsidy program that began in 2000 and became important for PV in 2004. The dramatic increase in size combined with its 20-year guaranteed contracts reduced risk for investors and created confidence in PVs long term growth. Supportive policies also emerged outside Germany, in Spain, Italy, California, and China, which spread the risk even as national policy support was more volatile. Rapid and deep cost reductions were made possible by learning-by-doing in the process of operating, optimising, and combining production equipment; investing and improving each manufacturing line to gradually scale up to massive sizes and incremental improvements in the PV devices themselves.

Central to PV development has been its modularity, which provided two distinct advantages: access to niche markets, and iterative improvement. Solar has been deployed as a commercial technology across 9 orders of magnitude: from a 1W cell in a calculator to a 1GW plant in the Egyptian desert, and almost every scale in between. This modular scale enabled PV to serve a sequence of policy-independent niche markets (such as satellites and telecom applications), which generally increased in size and decreased in willingness to pay, in line with the technology cost reductions. This modular scale also enabled a large number of iterations, such that in 2020 over three billion solar panels have been produced. Compared to, for instance, approximately 1000 nuclear reactors that were ever constructed, a million times more opportunities for learning-by-doing were available to solar PV: to make incremental improvements, to introduce new manufacturing equipment, to optimise that equipment, and to learn from failures. More generally, recent work has point to the benefits of modularity in the speed of adoption (Wilson et al. 2020) and learning rates (Sweerts et al. 2020).

While many technologies do not fit into the solar model, some, including micro nuclear reactors and direct air capture, also have modular characteristics that make them suitable for following solar's path and benefit from solar's drivers. However, PV took solar 60 years to become cheap, which is too slow for addressing climate change if a technology is now still at the lab scale. A challenge in learning from the solar model is therefore to how to use public policy to speed up innovation over much shorter time frames, e.g. 15 or less years.

END BOX 16.4 HERE

There are many definitions of policy mixes from various disciplines (Rogge et al. 2017), including environmental economics (Lehmann 2012), policy studies (Kern and Howlett 2009) and innovation studies. Generally speaking, a policy mix can be characterised by a combination of building blocks, namely elements, processes and characteristics, which can be specified using different dimensions (Rogge and Reichardt 2016). Elements include (i) the policy strategy with its objectives and principal plans and (ii) the mix of policy instruments, and (iii) instrument design. The content of these elements is the result of policy processes. Both elements and processes can be described by their characteristics in terms of the consistency of the elements, the coherence of the processes, and the credibility and comprehensiveness of the policy mix in different policy, governance, geography and temporal context (Rogge and Reichardt 2016). Other aspects in the evaluation of policy mixes include framework conditions, the type of policy instrument and the lower level of policy granularity, namely design elements or design features (del Río 2014; del Río and Cerdá 2017). In addition, many have argued the need to craft policies that affect different actors in the transition, some supporting and some 'destabilising' (see e.g. Kivimaa and Kern (2016) and Geels (2002)).

Learning from the innovation systems literature, some of the recent policy focus is not only directed on innovation policies that can optimise the innovation system to improve economic competitiveness and growth but also policies that can induce strategic directionality and guide processes of transformative changes towards desired societal objectives (Mitcham 2003; Steneck 2006). Therefore, the aim is to connect innovation policy with societal challenges and transformative changes through engagement with a variety of actors and ideas and incorporating equity, nowadays often referred to as a just transition (Newell and Mulvaney 2013; Swilling et al. 2016; Heffron and McCauley 2018; Jasanoff 2018) (see Chapter 1 and Chapter 17). This new policy paradigm is opening up a new discursive space, shapes policy outcomes, and is giving rise to the emerging idea of transformative innovation policy (Diercks et al. 2019; Fagerberg 2018).

Transformative innovation policy has a broader coverage of the innovation process with a much wider participation of actors, activities and modes of innovation. It is often expressed as socio-technical transitions (Elzen et al. 2004; Turnheim and Sovacool 2020) or societal transformations (Scoones 2015; Roberts et al. 2018). Transformative innovation policy encompasses different ideas and concepts that aim to address the societal challenges involving a variety of discussions including social innovation (Mulgan 2012), complex adaptive systems (Gunderson and Holling 2002), eco-innovation (Kemp 2011) and framework for responsible innovation (Stilgoe et al. 2013), value-sensitive design (Friedman and Hendry 2019) and social-technical integration (Fisher et al. 2006).

16.4 Innovation policies and institutions

Building on the frameworks for identifying market failures (Section 16.2) and systemic failures (Section 16.3) in the innovation system for climate-related technologies, Section 16.4 proceeds as follows. First, it considers some of the policy instruments introduced in Chapter 13 that are particularly relevant for the pace and direction of innovation in technologies for climate change mitigation and adaptation. Second, it explains why governments put in place policies to promote innovation in climate related technologies. Third, it takes stock of the overall empirical and theoretical evidence regarding the relationship between policy instruments with a direct and an indirect impact on innovation outcomes (including intellectual property regimes) and also other outcomes (competitiveness and distributional outcomes). Fourth, it assesses the evidence on the impact of trade-related policies and of sub-national policies aiming to develop cleantech industrial clusters.

This section focuses on innovation policies and institutions which are implemented at the national level. Whenever relevant, this section highlights examples of policies or initiatives that delve more deeply into the main high-level sectors: power, transport, industry, buildings, and AFOLU. Whenever possible, this section also discusses issues in policy selection, design, and implementation that have been identified as more relevant in developing countries and emerging economies.

Overall, this section shows that national and subnational policies and institutions are one of the main factors determining the redirection and acceleration of technological innovation and low-emission technological change (Åhman et al. 2017; Rogge and Reichardt 2016; Anadon et al. 2016b; Anadón et al. 2017; Roberts et al. 2018) *(robust evidence, high agreement).* Both technology push (e.g., scientific training, R&D) and demand pull (e.g., economic and fiscal support and regulatory policy instruments), as well as instruments promoting knowledge flows and especially research-firm technology transfer, can be part of the mix *(robust evidence, medium agreement)* (see also Sections 16.2 and 16.3).

Public R&D investments in energy and climate-related technologies have a positive impact on innovation outcomes (*medium evidence, high agreement*). The evidence on procurement is generally positive but limited. The record economic policy instruments that can be classified as market pull instruments when it comes to the competitiveness outcome (at least in the short term) is more mixed. The review of the literature in this section shows that market pull policy instruments had positive but also some negative impacts on outcomes in some instances on some aspects of competitiveness and distributional outcomes (*medium evidence, medium agreement*) (Peñasco et al. 2021). For several of them, carbon taxes or feed-in tariffs for example, the evidence of a positive impact on innovation is more consistent than the others. Evidence suggests that complementary policies or improved policy design can mitigate such short-term negative distributional impacts.

16.4.1 Overview of policy instruments for climate technology innovation

Government policies can influence changes in technologies, as well as changes to the systems they support (Somanathan et al. 2014) (see Chapter 13 and Sections 16.2 and 16.3).

Technology-push policy instruments stimulate innovation by increasing the supply of new knowledge through funding and performing research; increasing the supply of trained scientists and engineers which contribute to knowledge-generation and provide technological opportunities, which private firms can decide to commercialise (Mowery and Rosenberg 1979; Anadon and Holdren 2009; Nemet 2009b; Mazzucato 2013).

Governments can also stimulate technological change through demand-pull (or: market-pull) instruments which support market creation or expansion and technology transfer and thus promoting learning by doing, economies of scale, and automation (Section 16.2). Demand-pull policy instruments include regulation, carbon prices, subsidies that reduce the cost of adoption, public procurement, and intellectual property regulation. Typically, technology push is especially important for early-stage technologies, characterised by higher uncertainty and lower appropriability (see Section 16.2); demand-pull instruments become more relevant in the later stages of the innovation process (Section 16.2) (Mowery and Rosenberg 1979; Anadon and Holdren 2009; Nemet 2009b).

The second column of Table 16.8 summarises the set of policies shaping broader climate outcomes over the past few decades in many countries outlined in Chapter 13 Section 13.6, which groups them into economic and financial, regulatory, and soft instruments. Other policies, such as monetary, banking and trade policies, for instance, can also shape innovation but most government action to shape energy has not focussed on them. As Table 16.8 shows, this section discusses the set of policy instruments on innovation outcomes, or a subset of the 'Transformative Potential' criterion presented in Chapter 13, and thus complements the more general discussion presented there. Table 16.8 specifically prioritizes the impact of the subset of policy instruments on innovation outcomes for which evidence is available. This focus is complemented by a discussion of the impact of the same policy instruments on competitiveness (a subcomponent of the economic effectiveness evaluation criterion) and on distributional outcomes. Many of the policy instrument types listed in Table 16.8 have been implemented or proposed to address different types of market or systemic failures or bottlenecks described in Section 16.2 and Section 16.3 (OECD 2011a).

Table 16.8 Overview of policy instrument types covered in Chapter 13 and their correspondence to the subset of policy instrument types reviewed in Chapter 16 with a focus on innovation outcomes.

High- level categorisation	**Lower level policy instrument type in Chapter 13**	**Policy instrument types reviewed in Section 16.5 (for definitions see Peñasco et al** (2021)**)**
Economic or financial policy instrument types	R&D investments	R&D investments (including demonstration) (see Box 16.4 in Section 16.4)
	Subsidies for mitigation	Feed in tariffs or premia (set administratively)
		Energy auctions
		Other public financing options (public investment banks, loans, loan guarantees)
	Emissions trading schemes	Emissions trading scheme
	Carbon taxes	Taxes/tax relief (including carbon taxes, energy taxes and congestion taxes)
	Government provision	Government provision (focus on innovation procurement)
	Removing fossil fuel subsidies	*Not covered*
	Border carbon adjustments	*Not covered*
	Offsets	*Not covered*
Regulatory policy instrument types	Performance standards (including with tradeable credits)	Renewable obligations with tradeable green certificates
		Efficiency obligations with tradeable white certificates
		Clean energy or renewable portfolio standards (electricity)
		Building codes (building efficiency codes)
		Fuel efficiency standards
		Appliance efficiency standards

	Technology standards	*Not covered*
Soft policy instruments	Divestment and disclosure	*Not covered*
	Voluntary agreements (public voluntary programs & negotiated agreements)	Voluntary agreements
		Energy labels

Section 16.3 characterized technological innovation as a systemic, non-linear and dynamic process. Figure 16.1 below presents a stylized (and necessarily incomplete view) connecting the innovation process stages presented in Section 16.2, some of the key the mechanisms in technology innovation systems, and some of the decarbonisation policy instruments that have been assessed in terms of their impact on technological innovation outcomes in Section 16.4.4. As noted in the caption and discussed in Section16.4.4, regulatory policy instruments also shape the early stages of technology development.

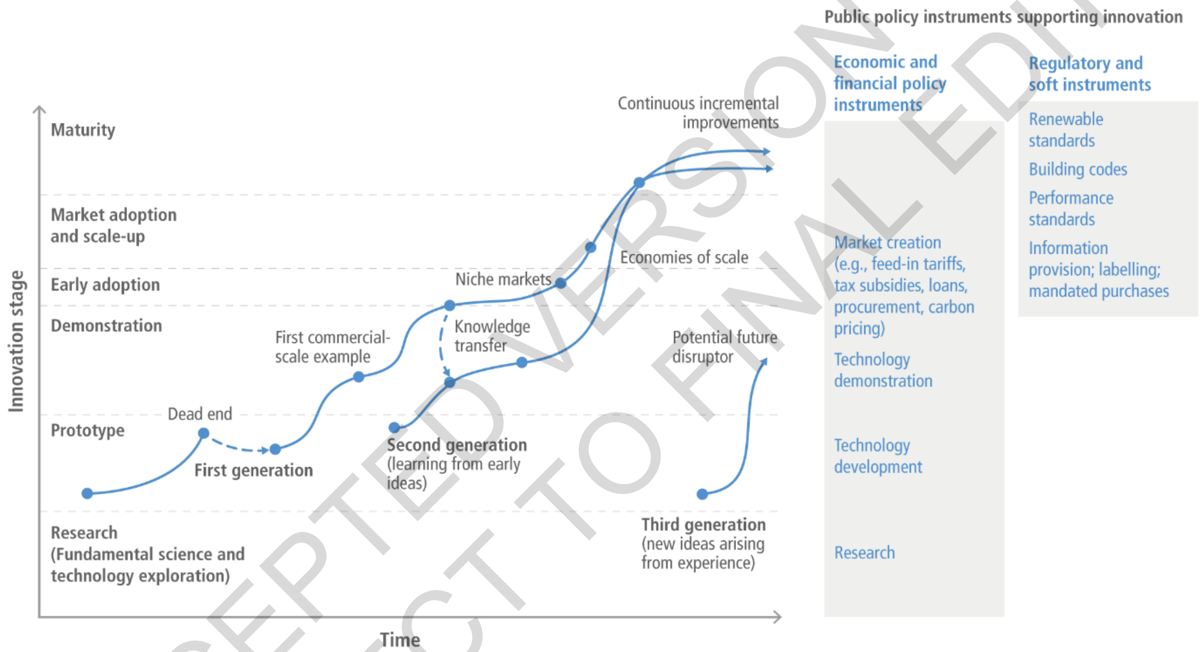


Figure 16.1 Technology innovation process and the (illustrative) and role of different public policy instruments (on the right-hand side). Adapted from IEA (IEA 2020a). Note that, as shown in section 16.4.4, demand pull instruments in the regulatory instrument category, for instance, can also shape the early stages of the innovation process. Their position on the latter stages is highlighted in this figure just because typically these instruments have been introduced in latter stages of the development of the technology.

16.4.2 The drivers and politics of national policies for climate change mitigation and adaptation

Governments around the world implement innovation policies in the energy and climate space with the aim of simultaneously advancing environmental, industrial policy (or competitiveness), and security goals (Surana and Anadon 2015; Meckling et al. 2017; Matsuo and Schmidt 2019; Anadón 2012; Peñasco et al. 2021) (*medium evidence, medium agreement*). Co-benefits of policies shaping technological innovation in climate-related technologies, including competitiveness, health, and improved distributional impacts can be drivers of climate mitigation policy in the innovation sphere

(Deng et al. 2018a; Stokes and Warshaw 2017; Probst et al. 2020). This was the case for climate and air pollution policies with local content requirements for different types of renewable energy projects, for instance. in places including China (Lewis 2014; Qiu and Anadon 2012), India (Behuria 2020), South Africa (Kuntze and Moerenhout 2012), and Canada (Genest 2014) (*robust evidence, medium agreement*).

The emergence of industries and support groups can lead to more sustained support for innovation policies (Schmid et al. 2020; Stokes and Breetz 2018; Meckling 2019; Meckling and Nahm 2019; Meckling et al. 2015a; Schmidt and Sewerin 2017a). Conversely, policies shaping technology innovation contribute to the creation and evolution of different stakeholder groups *(robust evidence, high agreement*). Most of the literature on the role of the politics and interest groups has focused on renewable energy technologies although there is some work on heating in buildings (e.g. Wesche et al. 2019).

As novel technologies become cost-competitive, opposition of incumbents usually grows, as well as the dangers of lock-in that can be posed by the new winner. Addressing this involves adapting policy (*robust evidence, high agreement*).

Three phases of politics in the development of policies to meet climate and industrial objectives can be identified, at the top, the middle and the bottom of the experience curve (Breetz et al. 2018) (see also Figure 16.1 above, and Geels (2002)). In the first phase of 'niche market diffusion', the politics of more sustained support for a technology or set of technologies become possible after a group of economic winners and 'clean energy constituencies' are created (Meckling et al. 2015a). When technologies grow out of the niche (second phase), they pose a more serious competition to incumbents who may become more vocal opponents of additional support for innovation in the competing technologies (Stokes 2016; Geels 2014a). In a third phase, path-dependence in policymaking and lock-in in institutions need to change to accommodate new infrastructure, the integration of technologies, the emergence of complementary technologies and of new regulatory regimes (Aklin and Urpelainen 2013; Levin et al. 2012).

16.4.3 Indicators to assess the innovation, competitiveness and distributional outcomes of policy instruments

If policy instruments are created to (at least partly) shape innovation for systemic transitions to a zero-carbon future, they also need to be evaluated on their impact on the whole socio-technical system (Neij and Åstrand 2006) and a wide range of goals, including distributional impacts and competitiveness and jobs (Stern 2007; Peñasco et al. 2021). Given this and the current policy focus on green recovery and green industrial policy, although we primarily focus on innovation outcomes, we assess also impacts on competitiveness and equity. Table 16.9 lists the selected set of indicators used to assess the impact of the policy instrument types covered in right hand side column in Table 16.8. The table does not include technology diffusion or deployment because these are covered in the technological effectiveness evaluation criterion in Chapter 13. As noted in section 16.2, it is very difficult to measure or fully understand innovation with one or even several indicators. In addition, all indicators have strengths and weaknesses and may be more relevant in some countries and sectors than in others. The literature assessing the impact of different policy instruments on innovation often covers just one of the various indicators listed in the second column of Table 16.9.

Table 16.9 Outcomes (first row) and indicators (second row) to evaluate the impact of policies shaping innovation to foster carbon neutral economies.

Sources: Innovation outcomes indicators are sourced from Del Rio and Cerdá (2014), and Peñasco et al (2021) Grubb et al (2021); the indicators under the competitiveness and distributional effects criteria are sourced from Peñasco et al (2021)

Policy Instrument Outcomes	**Innovation** (part of Chapter 13 'Transformative potential' evaluation criterion)	**Competitiveness** (part of Chapter 13 'Economic effectiveness' evaluation criterion)	**Distributional impacts** (defined in the same way as in Chapter13)
Examples of indicators used for each outcome in the literature	R&D investments, cost improvements, learning rates, patents, publications, reductions in abatement costs, energy efficiency improvements, other performance characteristics, firms reporting carbon saving innovation	Industry creation, net job creation, export of renewable energy technology equipment, economic growth (GNP, GDP), productivity, other investments	Level and incidence of support costs, change in spending on electricity as a % of total household spending, participation of different stakeholders, international equity (e.g., tCO_2-eq per capita), unequal access between large vs. small producers or firms

16.4.4 Assessment of innovation and other impacts of innovation policy instruments

While it is very difficult to attribute a causal relationship between a particular policy instrument implementation and different innovation indicators, given the complexity of the innovation system (see Section 16.3) there is a large quantitative and qualitative literature aiming to identify such impact.

16.4.4.1 Assessment of the impact on innovation of technology push policy instruments: public RD&D investments, other R&D incentives and public procurement

Economic and direct investment policy instrument types are typically associated with a direct focus on technological innovation: R&D grants, R&D tax credits, prizes, national laboratories, technology incubators (including support for business development, plans), novel direct funding instruments (e.g., ARPA-E), and innovation procurement.

Public RD&D investments have been found to have a positive impact on different innovation in energy and climate related technologies (*robust evidence, high agreement*), but the assessment relies almost entirely on evidence from industrialised countries. Out of 17 publications focussing on this assessment, only three found no relationship between R&D funding and innovation metrics (Peñasco et al. 2021; Goldstein et al. 2020; Doblinger et al. 2019). Sixteen out of them *used ex post* quantitative methods and one relied on theoretical *ex ante* assessment; only two of them included some non-industrialised countries, with one being the theoretical analysis. The evidence available does not point to public R&D funding for climate-related technologies crowding out private R&D (an important driver of innovation) but instead crowding it in. Box 16.6 summarizes the evidence available of the impact of ARPA-E (a public institution created in the United States in 2009 to allocate public R&D funding in energy) on innovation and competitiveness outcomes. Another institution supporting energy R&D that is the subject of much interest is the Fraunhofer Institute.

No evidence regarding the specific impact of R&D tax credits on climate mitigation or adaptation technologies has been found, but it is worth noting that generally speaking, R&D tax credits are found to incentivize innovation in firms in general, with an greater impact on small and medium firms (OECD 2020). This is consistent with the fact that most of the evidence on the positive impact of public R&D support schemes covers small and medium firms (Howell 2017; Doblinger et al. 2019; Goldstein et al. 2020). Although there is a high level of agreement in the literature regarding the impact of R&D

investments on innovation outcomes in climate-related technologies, it is important to note that this evidence comes from industrialised countries. This does not mean that public R&D investments in energy have been found to have no impact on developing countries innovation or competitiveness outcomes, but rather that we were not able to find such studies focussing on developing countries.

Overall, public procurement has high potential to incentivise innovation in climate technologies, but the evidence is mixed, particularly in developing countries (*limited evidence, medium agreement*). Public procurement accounted for 13 % of gross domestic products in OECD in 2013 and much more in some emerging and developing economies (Baron 2016). Its main goal is to acquire products or services to improve public services, infrastructures and facilities and, in some cases, to also incentivize innovation. It is important to implement several steps in the public procurement procedure to improve transparency, minimise waste, fraud and corruption of public fund. These steps range from the assessment of a need, issuance of a tender to the monitoring of delivery of the good or service. Box 16.5 outlines a public procurement program that was implemented in The Netherlands in 2005 with a focus on green technologies. In spite of the fact that green procurement policies have been implemented, the literature assessing the innovation impact of public procurement programs is relatively limited and suggests either a positive impact or no impact (Peñasco et al. 2021; Alvarez and Rubio 2015; Fernández-Sastre and Montalvo-Quizhpi 2019; Baron 2016). The majority of cases where the impact is positive are analyses of industrialised countries, while no impact emerges in the case of a developing country (Ecuador). More empirical research is needed to understand the impact of public procurement, which has the potential to support the achievement of other societal challenges (Edler and Georghiou 2007; Henderson and Newell 2011; ICLEI 2018; Baron 2016) in both developing and developed countries.

START BOX 16.5 HERE

Box 16.5 Green Public Procurement in The Netherlands

In 2005, the Dutch national government acknowledged a move in the House of Representatives to utilise their annual spending power to promote the market for sustainable goods and services as well as to play as a role model. Hence, a policy for environmentally friendly procurement was developed and implemented across the national, local and provincial governments. Subsequently, sustainable public procurement has expanded into a multidimensional policy in the Netherlands, accommodating policies on green public procurement, bio-based public procurement, international social criteria, social return on investment, innovation-oriented public procurement and circular economy.

The Green Public Procurement (GPP) policy is targeted at minimising the negative impacts of production and consumption on the nature environment (Melissen and Reinders 2012; Cerutti et al. 2016). It includes a wide range of environmental criteria for different product groups that public organisations frequently procure such as office equipment, uniforms, road works and catering. There are 45 product groups (Melissen and Reinders, 2012) and 6 product clusters part of the government's purchasing in terms of sustainability(PIANOo Expertisecentrum 2020). The six product clusters are: i) Automation & telecommunications, ii) Energy, iii) Ground, road & hydraulic engineering, iv) Office facilities and services, v) Office buildings, and vi) Transport (PIANOo Expertisecentrum 2020).The GPP 2020 Tender Implementation Plan spells out the terms and conditions for making their green public procurement. Some of these are confidential documents and are not shared online. Others are available for download. The tender implementation plan for the Netherlands is available on https://gpp2020.eu/low-carbon-tenders/open-tenders/. One of the important scenarios is that the public procurers need the details of LCA analysis carried out in a tool called DuboCalc which calculates the environmental impacts of the materials and methods of an infrastructural projects. GPP 2020 has reported that three million tonnes of CO_2 would be saved in the Netherlands alone if all Dutch public authorities applied the national Sustainable Public Procurement Criteria.

Research has been carried out to determine the prime mover for implementing Green Public Procurement. An online survey of was administered among public procurement officers that subscribed to the newsletters of two Dutch associations that provide advice and training to public procurers, yielding a sample size of over 200 (Grandia and Voncken 2019). The first association is called NEVI which is the only organisation in the Netherlands that offers certified procurement training programmes. The second association is called PIANOo which is a public procurement expertise centre paid by the Dutch national government for bringing together relevant information regarding public procurement and providing public procurers with useful tools through their websites, workshops, meetings and annual conferences. The data from the survey was then analysed using structural equations modelling (SEM) and the results show that ability, motivation and opportunities affect the implementation of GPP. Particularly, opportunity was found to affect green public procurement, innovation-oriented public procurement and circular economy but not the other types of public procurement.

END BOX 16.5 HERE

16.4.4.2 Assessment of the impact on competitiveness of technology push policy instruments: public RD&D investments, other R&D incentives and public procurement

Public R&D investments in the energy, renewables, environment space are generally associated with positive impacts on industrial development or 'competitiveness outcome' (*robust evidence, medium agreement*). In a number of cases negligible or negative impacts emerge (Peñasco et al. 2021; Goldstein et al. 2020; Doblinger et al. 2019). The majority of these 15 analyses rely on *ex post* quantitative methods, while only four use *ex ante* modelling approaches. Also, in this case, the vast majority of the evidence is from industrialised countries.

There is limited and mixed evidence regarding the (positive or negative) impact of public procurement for low-carbon or climate technologies and it emerges from developed countries (*limited evidence, low agreement*). All of the four evaluations identified in the Peñasco et al (2021) review relied on qualitative methods. One found a positive impact, another a negative impact and two others found no impact. All of the studies covered European country experiences.

R&D and procurement policies have a positive impact on distributional outcomes (*limited evidence, high agreement*). Peñasco et al (2021) identify three evaluations of the impact of RD&D funding on distributional outcomes (two using quantitative methods and one ex ante theoretical methods) and one of procurement on distributional outcomes (relying on qualitative analysis).

16.4.4.3 Emerging insights on different public R&D and demonstration funding schemes

The ability of a given R&D policy instrument to impact innovation and competitiveness depends to some extent on policy design features (*limited evidence, high agreement*). As discussed in section 16.4.4.4, this is not unique to R&D funding. Most of these assessments use a limited number of indicators (e.g., patents and publications and follow-on private financing, firm growth and survival, respectively), focusses on the energy sector and on the US and other industrialised countries. Extrapolating to emerging economies and low-income countries is difficult. There is no evidence on the impact of different ways of allocating public energy R&D investments in the context of developing countries.

Block funding, which tends to be more flexible, can lead to research that is more productive or novel, but there are other factors that can affect the extent to which block funding can lead to more or less novel outcomes (*limited evidence, medium agreement*). Research on national research laboratories, which conduct at least 30% of all research in 68 countries around the world (Anadon et al. 2016a), are a widespread mechanism to carry out public R&D and allocate funds, but assessments of their performance is limited to developed countries. R&D priorities are also guided by institutions, and research focussed on general technology innovation policy finds that institutions often do not embody the goals of the poor or marginalized (Anadon et al. 2016b).

In the case of the US Department of Energy, block funding that can be quickly allocated to novel l projects (such as that allocated to National Labs as part of the Laboratory Directed Research and Development—LDRD—funding) has been found to be associated with improved innovation indicators (Anadon et al. 2016a). Research on Japan on R&D funding in general (not for climate-related technologies) however, indicates that R&D funds allocated competitively result in higher novelty for 'high status' (the term used in the paper to refer to senior male researchers), while block funding was associated with research of higher novelty for lower status researchers (e.g., junior female researchers) (Wang et al. 2018).

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Box 16.6 ARPA-E a novel R&D funding allocation mechanism focussed on an energy mission

One approach for allocating public R&D funds in energy involves relying on active program managers and having clear technology development missions that focus on high-risk high-reward areas and projects. This approach can be exemplified by a relatively new energy R&D funding agency in the US, the Advanced Research Projects Agency for Energy (ARPA-E). This agency was created in 2009 and it was modelled on the experience of DARPA (a US government agency funding high risk high reward research in defence-related areas (Bonvillian and Van Atta 2011; Bonvillian 2018; U.S. National Academies of Sciences Engineering and Medicine 2017). DARPA program managers had a lot of discretion for making decisions about funding projects, but since energy R&D funding is usually more politically vulnerable than defence R&D funding, the ARPA-E novel involved program managers requesting external review as an informational input (Azoulay et al. 2019).

Like DARPA, ARPA-E program managers use an 'active management approach that involves empowering program manages to make decisions about funding allocation, milestones and goals. ARPA-E managers also differ from other R&D allocation mechanisms in that ARPA-E staff retained some control on the funded projects after the allocation of the funds. As argued by (Azoulay et al. 2019), even though this relative control over the project can result in a reduction in the flexibility of funded researchers, some 'exploration' happens at the program manager level.

Research on ARPA-E also sheds light on how program managers make decisions about what projects to fund: about the process of project selection. Program managers do not just follow the rankings of peer reviewers (sometimes projects with very disparate rankings were funded) and in many cases program managers reported using information from review comments instead of the rankings (Goldstein and Kearney 2020). Azoulay et al. (2019) suggest that if expert disagreement is a useful proxy for uncertainty in research, then the use of individual discretion in ARPA-E would result in a portfolio of projects with a higher level of uncertainty, as defined by disagreement among reviewers. Moreover, under the premise that uncertainty is a corollary to novelty, individual discretion is an antidote to novelty bias in peer review.

While innovation is notoriously hard to track and, particularly for emerging technologies, it can take a lot time to assess, early analysis has shown that this mission-orientation and more 'actively managed' R&D funding program may yield greater innovation patenting outcomes than other US energy R&D funding programs and a greater or similar rate of academic publications when compared to other public funding agencies in energy in the US, ranging from the Office of Science, the more applied Office of Energy Efficiency and Renewable Energy or the small grants office (Goldstein and Narayanamurti 2018; U.S. National Academies of Sciences Engineering and Medicine 2017). In addition research analysing the first cohort of cleantech start-ups has found that start-ups supported by ARPA-E had more innovative outcomes when compared to those that had applied but not received funding, with others that had not received any government support, and with others that had received other types of government R&D support (Goldstein et al. 2020). Overall, the mission-oriented ARPA approach has been successful in the United States when it comes to innovation outcomes. The extent to which it can yield the same outcomes in other geographies with different innovation and financing environments remains unknown. (*limited evidence, high agreement*).

END BOX 16.6 HERE

Public financing for R&D and research collaboration in the energy sector is important for small firms, at least in industrialised countries, and it does not seem to crowd out private investment in R&D (*medium evidence, high agreement*). Small US and UK firms accrue more patents and financing when provided with cash incentives for R&D in the form of grants (Pless 2019; Howell 2017). US cleantech start-ups which partner with government partners for joint technology development or licensing partnerships accrue more patents and follow on financing (Doblinger et al. 2019).

Overall, the body of literature on public R&D funding design in energy and climate related technologies provides some high-level guidance on how to make the most of these direct RD&D investments in energy technologies in the climate change mitigation space, including: giving researchers and technical experts autonomy and influence over funding decisions; incorporating technology transfer in research organisations; focussing demonstration projects on learning; incentivising international collaboration in energy research; adopting an adaptive learning strategy; and making funding stable and predictable (Narayanamurti and Odumosu 2016; Narayanamurti et al. 2009; Chan et al. 2017) (*medium evidence, high agreement*).

Without carefully designed public funding for demonstration efforts, often in a cost shared manner with industry, the experimentation at larger scales needed for more novel technologies needed for climate change mitigation may not take place. (*medium evidence, high agreement*). Government funding specifically for technology demonstration projects, for RD&D (research, development and demonstration) in energy technologies plays a crucial supporting role (Section 16.2.1). Governments can facilitate knowledge spill-overs between firms, between countries, and between technologies (see Section 16.2, Cohen et al (2002) and Baudry and Bonnet (2019)).

16.4.4.4 Assessment of the impact on innovation and on competitiveness and distributional outcomes of market pull policy instruments

Demand pull policies such as tradeable green certificates, taxes, or auctions, are essential to support scaling up efforts (Remer and Mattos 2003; Nahm and Steinfeld 2014; Wilson 2012). Just like for R&D investments, research has indicated that effective demand pull needs to be credible, durable, and aligned with other policies (Nemet et al. 2017) and that the effectiveness of different demand pull instruments depends on policy design (del Río and Kiefer 2021). Historical analyses of the relative importance of demand pull and technology push are clear; both are needed to provide robust incentives for investment in innovation. Interactions between them are central as their combination enables innovators to connect a technical opportunity with a market opportunity (Grubler and Wilson 2013; Freeman 1995b; Jacobsson et al. 2004). It is important to note that these market pull policies are often put in place primarily to meet security and/or environmental goals, although innovation and competitiveness are sometimes also pursued explicitly.

Emission Trading Schemes

Overall evidence suggests that the <u>emissions trading schemes</u>, as currently designed, have not significantly contributed to innovation outcomes (*medium evidence, medium/high agreement*).

Penasco et al. (2021) review 20 evaluations: eight identified a positive impact (although in at least two cases the paper indicated the impact was small or negligible), 11 no impact and one was associated with a negative impact on innovation indicators. The studies that found no impact and the studies that found some impact covered all three methods covered (quantitative *ex post*, qualitative and theoretical and *ex ante* analysis). Another review focussed only on empirical studies (mainly quantitative but also qualitative), covered a slightly longer period and identified 19 studies (15 using quantitative methods) (Lilliestam et al. 2021). With a narrower set of indicators of innovation, they concluded there was very little empirical evidence linking the emissions trading schemes studied to date and innovation (Lilliestam et al. 2021). This review focussed mainly on papers evaluating the earlier stages of the European Emissions Trading Scheme, which featured relatively low CO_2 prices and covered a small set of firms, showing that carbon pricing policy design is an important determinant of innovation outcomes. Combining both reviews, there are a total of 27 individual studies, some of them providing mixed evidence of impact, and 23 of them suggest there was no impact or (in a couple of cases) it was small. It is important to note that some researchers note that, for particular subsectors and actors, emissions trading schemes have had an impact on patenting trends (Calel and Dechezleprêtre 2016). Overall the expectation is that higher prices and coverage would result in higher impacts and that, over time, the impact on innovation would grow.

Carbon and environmental taxes

The impact of <u>carbon taxes</u> on innovation outcomes is more positive than that for ETS schemes but the evidence is more limited (*limited evidence, medium agreement*). Assessments of their impact on innovation metrics have been very limited, with only four studies (three quantitative and one *ex ante*). Three of the studies found a positive impact of carbon taxes on innovation outcomes and one found no impact (Peñasco et al. 2021).

Depending on the design (including the value and coverage of the tax), carbon taxes can either have positive, negative or null impact on competitiveness and distributional outcomes (*medium evidence, medium agreement*). The evidence on the impact of carbon taxes on competitiveness is significant (a total of 27 evaluations) and mixed, with six of them reporting some positive impacts, ten reporting no impact, and 11 reporting negative impacts (so 59% were not associated with negative impacts). Most of the evaluations reporting negative impacts were theoretical assessments, and only three *ex post* quantitative analysis (Peñasco et al. 2021). 24 evaluations covered distributional impacts of carbon taxes and other environmental taxes and the majority (15) found the existence of some negative distributional impacts, six found positive impacts and three no distributional impacts. Differences in the result of the assessments stem from the design of the taxes (Peñasco et al. 2021). It is important to note that, once again, the evidence comes from industrialized countries and emerging economies.

Feed-in-Tariffs

Many factors affect the impacts of feed in tariffs on outcomes other than innovation (*robust evidence, high agreement*). While FITs have been generally associated with positive innovation outcomes, some of the differences found in the literature may arise from differences in the evaluation method (Peñasco et al. 2021) or differences in policy design (e.g., the level and the rate of decrease of the tariff) (Hoppmann et al. 2014), the policy mixes (Rogge et al. 2017), the technologies targeted and their stage of development (Huenteler et al. 2016b), and the geographical and temporal context of where the policy was put in place (Section 16.3). Research has also found that, particularly for less mature technologies, a higher technology specificity in the design of FITs is associated with more innovation (Del Río 2012). Feed-in-tariffs yield better results if they account for the specificities of the country; else, the technology and the policy could result in negative distributional and (to a lesser extent) competitiveness impacts. Meckling et al (2017) indicate that an 'enduring challenge' of technology-specific industrial policy such as some feed-in-tariffs is to avoid locking in suboptimal clean technologies—a challenge which, among other options, could be overcome with targeted niche procurement for next generation technologies.

Other authors have cautioned that the move from renewable feed-in-tariffs to auctions may favour existing PV (e.g., polysilicon) over more novel solar power technologies (Sivaram 2018b) such as thin-film PV, amorphous PV, and perovskites.

Policy design, policy mixes, and domestic capacity and infrastructure are important factors determining the extent to which economic policy instruments in industrialised countries and emerging economies can also lead to positive (or at least not negative) competitiveness outcomes and distributional outcomes (*medium evidence, medium agreement*) (Section 16.3). Prioritising low cost energy generation in the design of FIT schemes can result in a lower focus of innovation efforts on more novel technologies and greater barriers to incumbents in less mature technologies (Hoppmann et al. 2013). Similarly, case study research from Mexico and South Africa indicates that focusing on low-cost renewable energy generation only can result in a greater reliance on existing foreign value chains and capital, and thus in lower or negative impacts on domestic competitiveness—in other words, some approaches can hinder the development of the local capabilities that could result in greater long-term benefits domestically (Matsuo and Schmidt 2019). Evidence for developing countries indicates that local and absorptive capacity also play an important role in particular on the ability of policies to contribute to competitiveness or industrial policy goals (e.g., Binz and Anadon 2018). Research comparing China's and India's policies and outcomes on wind also suggest that policy durability and systemic approaches can affect industrial outcomes (Surana and Anadon 2015).

Energy auctions

The evidence of the impact of renewable energy auctions on innovation outcomes is very small and provides mixed results *(limited evidence, low agreement*). Out of six evaluations, three of them identify positive impacts, two no impacts, and one negative impacts. All of the evaluations but one were qualitative or theoretical and the quantitative assessment indicated no impact (Peñasco et al. 2021). There is more evidence covering emerging economies analysing the impacts of auctions when compared to other policy instrument types. For example, there is work comparing the approaches to renewable energy auctions in South Africa and Denmark (Toke 2015) finding a positive impact on the latter stages of innovation (mainly deployment), and broader work on auctions covering OECD countries as well as Brazil, South Africa and China not finding a significant impact on innovation (Wigand et al. 2016), and work comparing renewable energy auctions in different countries in South America finding generally a positive impact on innovation outcomes (Mastropietro et al. 2014). The body of evidence on the impact of auctions on competitiveness is also limited (six evaluations) and indicates negative outcomes of renewable auctions of competitiveness (*limited evidence, low agreement*). As with other policies, the design of the auctions can affect innovation outcomes (del Río and Kiefer 2021). Only two studies investigated distributional outcomes and both were negative.

Other financial instruments

There is no explicit literature on the ability of green public banks, and targeted loans, and loan guarantees to lead to upstream innovation investments and activities, although there is evidence on their role in deployment (see e.g. Geddes et al (2018)). This notwithstanding the key role of these institutions in the innovation system (Sections 16.2.1 and 16.3) (OECD 2015c; Geddes et al. 2018) and the belief that they can de-risk scale-up and the testing of business models (Probst et al. 2021; Geddes et al. 2018) (see Chapter 17).

Renewable obligations with tradeable green certificates

There is mixed evidence of the impact of tradeable green certificates (TGCs) on innovation (*limited evidence, low agreement)* and competitiveness (*limited evidence, low agreement)*. Out of the 11 evaluations in Peñasco et al (2021), six found no impact, two a positive impact, and three a negative impact. All of them used a qualitative research approach. Of the six studies focusing on competitiveness outcomes, three conclude TGCs have had no impact on competitiveness, while two indicate negative impact and one a positive impact. Only one of the studies was quantitative and did not identify an impact on competitiveness.

TGC are associated with the existence of negative distributional impacts in most applications (*medium evidence, high agreement*). Ten out of 12 studies identify the existence of some negative impacts. All but one of these studies (which focussed on India) are based on analysis of policies implemented in industrialised countries.

Clean Energy and renewable Portfolio Standards
The impact of renewable portfolio standards without tradeable credits on innovation outcomes is negligible or very small (*medium evidence, medium agreement*). Out of the nine studies, seven reported no impact on innovation outcomes and two a positive impact (Peñasco et al. 2021). Most of these papers focussed on patenting and private R&D innovation indicators and not cost reductions. Impact on competitiveness is found to be negligible or positive (*limited evidence, medium agreement*). Out of eight evaluations, five report positive impact and three negligible impact; only two are quantitative studies (Peñasco et al. 2021). Negative distributional impacts from renewable portfolio standards can emerge in some cases (*limited evidence, low agreement*). Out of eight evaluations, four identified positive impacts, and four negative impacts; all of the studies identifying a positive impact were theoretical. There are efforts focussed on clean energy portfolio standards which include technologies beyond renewables.

Efficiency obligations with tradeable credits
The impact of tradeable white certificates in innovation is largely positive, but the evidence is limited (*limited evidence, medium/high agreement*). Out of four evaluations, only one of which was quantitative, three report positive impact and one no impact (Peñasco et al. 2021). The impact of white certificates on competitiveness is positive (*limited evidence, high agreement*) while that on distributional outcomes is very mixed (*limited evidence, low agreement*). Two theoretical studies report positive competitiveness impacts. Out of 11 evaluations of distributional outcomes, eight rely on theoretical *ex ante* approaches. Seven evaluations reported positive impacts (four of them using theoretical methods), three of them (using theoretical methods) indicated negative impacts and one of them no impact.

Building codes
There is evidence of the impact of building codes on innovation outcomes (Peñasco et al. 2021). Only two studies assessed competitiveness impacts (one identifying positive impacts and one negligible ones) and three studies identifying distributional impacts, all positive.

Overall, the evidence on the impact of the market pull policy instruments covered in Section 16.4.4.4 when it comes to the competitiveness outcome (at least in the short term) is more mixed. For some of them, the evidence of a positive impact on innovation is more consistent than the others (for carbon taxes or FITs, for example). Peñasco et al (2021) found that the disagreements in the evidence regarding the positive, negative or no impact of a policy on competitiveness or distributional outcomes can often be explained by differences in policy design, differences in geographical or temporal context (since the review included evidence from countries from all over the world), or on how policy mixes may have affected the ability of the research design of the underlying papers to separate the impact of the policy under consideration from the others.

16.4.4.5 Assessment of the impact on innovation, competitiveness and distributional outcomes of regulatory policy instruments targeting efficiency improvements

There is medium evidence that the introduction of flexible, performance-based environmental regulation on energy efficiency in general (e.g., efficiency standards) can stimulate innovative responses in firms (Ambec et al. 2013; Popp 2019) *(medium evidence, high agreement)*. Evidence comes from both observational studies that examine patenting, R&D or technological responses to regulatory interventions, and from surveys and qualitative case studies in which firms report regulatory compliance as a driving force for the introduction of environmentally-beneficial innovations (Grubb et al. 2021). While the literature examining the impact of environmental regulation on innovation is large, there have been fewer studies on the innovation effects of minimum energy or emissions performance regulations specifically relating to climate mitigation. We discuss in turn two types of efficiency regulations: on vehicles, and on appliances.

Relationship between automotive efficiency regulations and innovation

The announcement, introduction and tightening of vehicle fleet efficiency or GHG emission standards either at the national or sub-national level positively impacts innovation as measured by patents (Barbieri 2015) or vehicle characteristics (Knittel 2011; Kiso 2019) as summarised in a review by Grubb et al (2021). Detailed studies on the innovation effects of national pollutant (rather than energy) regulations on automotive innovation also indicate that introducing or tightening performance standards has driven technological change (Lee et al. 2010). Some studies in the US that examine periods in which little regulatory change took place have found that the effects of performance standards on fuel economy have been small (Knittel 2011) or not significant relative to the innovation effects of prices (Crabb and Johnson 2010). This is at least in part because ongoing efficiency improvements during this period were offset by increases in other product attributes. For example, Knittel (2011) study observed that size and power increased without a corresponding increase in fuel consumption. It has also been observed that regulatory design may introduce distortions that affect automotive innovation choices: in particular, fuel economy standards based on weight classes have been observed to distort light-weighting strategies for fuel efficiency in both China (Hao et al. 2016) and Japan (Ito and Sallee 2018).

A number of studies have focused on the impacts of a sub-national technology-forcing policy: the California Zero Emission Vehicle (ZEV) mandate. When it was introduced in 1990, this policy required automotive firms to ensure that 2% of the vehicles they sold in 1998 would be zero emissions. In the years immediately after introduction of the policy, automotive firms reported that it was a significant stimulus to their R&D activity in electric vehicles (Brown et al. 1995). Quantitative evidence examining patents and prototypes has indicated that the stringency of the policy was a significant factor in stimulating innovation, though this was in part dependent on firm strategy (Sierzchula and Nemet 2015). Like in the previous instruments, most of the evidence comes from industrialised countries and additional research on other countries would be beneficial.

Relationship between appliance efficiency standards and innovation

Regulation-driven deployment of existing technologies can generate innovation in those technologies, through learning-by-doing, induced R&D and other mechanisms, although not in all cases (Grubb et al. 2021) *(medium evidence, medium agreement)*. The introduction or tightening of minimum energy performance standards for appliances (and in the case of Noailly (2012) for buildings) have driven innovation responses, using direct measures of product attributes (Newell et al. 1999) and patents (Noailly 2012; Kim and Brown 2019), though not all studies have found a significant relationship (Girod et al. 2017). There is also evidence of a correlation between regulation-driven deployment of energy-efficient products with accelerated learning in those technologies (Van Buskirk et al. 2014; Wei et al. 2017).

In addition to observational studies, evidence on the relationship between innovation and regulation comes from surveys in which survey respondents are asked whether they have engaged in innovation leading to energy saving or reduced GHG emissions, and what the motivations were for such innovation. Survey evidence has found that expected or current regulation can drive both R&D investment and decisions to adopt or introduce innovations that reduce energy consumption or CO_2 emissions (Horbach et al. 2012; Grubb et al. 2021). Survey-based studies, however, tend not to specify the type of regulation.

Competitiveness and distributional impacts associated with vehicles and appliance performance standards

Minimum energy performance standards and appliance standards have been known to result in negative distributional impacts *(limited evidence, medium/high agreement*). Several studies focused on the US have highlighted that minimum energy performance standards for vehicles tend to be regressive, with poorer households disproportionately affected (Levinson 2019; Jacobsen 2013), particularly when second-hand vehicles are taken into account (Davis and Knittel 2019). Similar arguments, though with less evidence, have been made for appliance standards (Sutherland 2006).

Overall, the extent to which regulations in energy efficiency result in positive or negative competitiveness impacts in firms is mixed (*limited evidence, high disagreement*). A meta-analysis of 107 studies, of which 13 focused on regulations relating to energy consumption or GHG emissions, found that around half showed that regulations resulted in competitiveness impacts, while half did not (Cohen and Tubb 2018). Cohen and Tubb (2018) also found that studies examining performance-based regulations were less likely to find positive competitiveness impacts than those that examined market-based instruments.

Insights into causal mechanisms and co-evolutionary dynamics from case studies on efficiency regulations

While most of the literature addresses the extent to which regulation can induce innovation, a number of case studies highlight that innovation can also influence regulation, as the costs of imposing regulation are reduced and political interests emerge that seek to exploit competitive advantages conferred by successfully developing energy-efficient or low-carbon technologies (*medium evidence, high agreement*). Case studies map the causal mechanisms relating regulations and innovation responses in specific firms or industries (Ruby 2015; Wesseling et al. 2015; Kemp 2005; Gann et al. 1998).

16.4.4.6 Assessment of the impact on innovation and on competitiveness and distributional outcomes of soft instruments

Energy labels and innovation

The literature specifically focusing on the impacts of labels is very limited and indicates positive outcomes (*limited evidence, high agreement).* Energy labels may accompany a minimum energy performance standard and the outcomes of these policies are often combined in literature (IEA 2015). But again, given the limited evidence more research is needed. Although there are many studies on energy efficiency more broadly and for both standards and labels, only eight studies specifically focus on labels. Furthermore, seven of them report positive outcomes and one negative outcomes. Six of the studies used qualitative methods mentioning the impacts of labelling on the development of new products (Wiel et al. 2006). Research specifically comparing voluntary labels with other mechanisms found a significant and positive relationship between labels and the number of energy-efficient inventions (Girod et al. 2017). More research is needed especially in developing countries that have extensive labelling programs in place, and also with quantitative methods, to develop evidence on the impacts of labelling on innovation. Box 16.7 discusses an example of a combination of policy instruments in China including labelling, bans and financial support.

START BOX 16.7 HERE

Box 16.7 China Energy Labelling Policies, combined with sale bans and financial subsidies

From 1970 to 2001, China was able to significantly limit energy demand growth through energy-efficiency programs. Energy use per unit of gross domestic product (GDP) declined by approximately 5% yr^{-1} during this period. However, between 2002 and 2005, energy demand per unit of GDP increased on average by 3.8% yr^{-1}. To curb this energy growth, in 2005, the Chinese government announced a mandatory goal of 20% reduction of energy intensity between 2006 and 2010 (Zhou et al. 2010; Lo 2014).

An Energy Labelling System was passed in 2004. It requires the manufacturers to provide information about the efficiency of their electrical appliances to consumers. From 2004 to 2010, 23 electrical appliances (including refrigerators, air conditioners and flat-screen TVs) being labelled as energy efficient with 5 different grades, with Grade 1 being the most energy efficient and grade 5 the least efficient. Any appliances with an efficiency grade higher than 5 cannot be sold in the market.

In addition to providing information to consumers, the National Development Reform Commission, which was in charge of designing the policies, and the Ministry of Finance launched in 2009 the "energy-saving products and civilian-benefiting project" (Zhan et al. 2011). It covered air conditioners, refrigerators, flat panel televisions, washing machines, electrical efficient lighting, energy saving and new energy vehicles with the energy grades at 1 or 2 and it consisted of financial subsidies for enterprises producing these products. The standard design of these financial subsidies involved the government paying for the price difference of energy efficiency products and general products. The manufacturers which produce the energy efficient products can get the financial subsidies directly from the government (Wang et al. 2017b).

Before 2008, the market share of grade 1 and grade 2 air conditioners was about 5%, and about 70% of all air conditioners were grade 5 (the most inefficient). Driven by the financial subsidies, the selling price of the highly efficient air conditioners became competitive with that of the general air conditioners. Hence, the sales of energy efficient air conditioners increased substantially, making the market share of air conditioners at grade 1 and 2 to be about 80% in 2010 (Wang et al. 2017b). According to the information from energy efficiency labelling management centre of China National Institute of Standardisation, under the energy label system implemented 5 years ago, more than 1.5 hundred billion kWh power was saved by March 2010, equivalent to more than 60 million tons of standard coal, 1.4 billion tons of carbon dioxide emissions, and 60 tons of sulphur dioxide emissions (Zhan et al. 2011), which significantly contributed to energy saving goals of the 11th Five-Year Plan.

END BOX 16.7 HERE

Voluntary approaches and innovation

Voluntary approaches have a largely positive impact on innovation for those that choose to participate (*robust evidence, medium agreement*). Research on voluntary approaches focuses on firms adopting voluntary environmental management systems that can be certified based on standards of the widely adopted International Standards Organisation (ISO 14001) or the European Union Environmental Management and Auditing Scheme (EMAS), which is partly mandatory today. Out of 16 analyses, 70% report positive innovation outcomes in terms of patents, or product and process innovation. 17% report negligible impacts and 13% report negative impact. Positive innovation outcomes have been linked to firms' internal resource management practices and were found to be strengthened in firms with mature environmental management systems and in the presence of other environmental regulations (He and Shen 2019; Inoue et al. 2013; Li et al. 2019a). Overall, studies are concentrated in a few countries that do not fully capture where environmental management systems have been actually adopted (Boiral et al. 2018). There is a need for research in analyses of such instruments in emerging economies including China and India, and methodologically in qualitative and longitudinal analyses (Boiral et al. 2018).

Competitiveness and distributional outcomes of soft instruments

The outcomes for performance or endorsement labels have been associated with positive competitiveness outcomes *(medium evidence, medium agreement).* Out of 19 studies, 89% report positive impact and 11% negligible impact. Although there are several studies analysing competitiveness related metrics, evidence on most individual metrics is sporadic, except for housing premiums. A large number of studies quantitatively assessing competitiveness find that green labels in buildings are associated with housing price premium in multiple countries and regions (Fuerst and McAllister 2011; Kahn and Kok 2014; Zhang et al. 2017). 32% of the studies were qualitative, associating appliance labelling programs with employment and industry development (European Commission 2018). There is a research gap in analyses of developing countries, and also in quantitatively assessing outcomes beyond housing price premiums.

A few studies on the distributional outcomes of voluntary labelling programs point to positive impacts *(limited evidence, high agreement).* All four studies focusing benefits for consumers and tenants, report positive impacts (Devine and Kok 2015). Although there are benefits for utilities and other stakeholders, more research is needed specifically attribute these benefits to voluntary labels rather than energy efficiency programs in general.

Voluntary agreements are associated with positive competitiveness outcomes *(medium evidence, medium agreement)*, 14 out of 19 evaluations identified were associated with positive outcomes while three were associated with negligible outcomes, and two with negative outcomes. Research found an increase in perceived firm financial performance (de Jong et al. 2014; Moon et al. 2014). Studies also show an association with higher exports as more environmentally conscious trade partners increasingly value environmental certifications (Bellesi et al. 2005). More research is needed to develop evidence on metrics of competitiveness besides firms' financial performance, and especially in developing countries.

Voluntary agreements are associated with a positive impact on distributional outcomes *(limited evidence, high agreement)*. Five studies, mainly using qualitative approaches, report a positive association between a firm adopting an environmental management system and impacts on its supply chains. There is a need for more studies with quantitative assessments and geographical diversity.

16.4.4.7 Summary of the size and direction of the evidence of all policy instrument types on innovation outcomes

Positive impacts have been identified more frequently in some policies than in others. There is also a lot of variation in the density of the literature. Developing countries are severely underrepresented in the decarbonisation policy instrument evaluation literature aiming to understand the impact on innovation. (*high evidence, high agreement).*

Figure 16.2 below indicates the extent to which some decarbonisation policy instruments have been more or less investigated in terms of their impact on innovation outcomes as described in Table 16.9 above. For example, it indicates the extent to which there has been a greater focus of evaluations of the impact of R&D investments, emissions trading schemes and voluntary approaches on innovation. It also shows a limited amount of evidence on procurement, efficiency obligations with tradeable green certificates (TGCs), building codes and auctions.

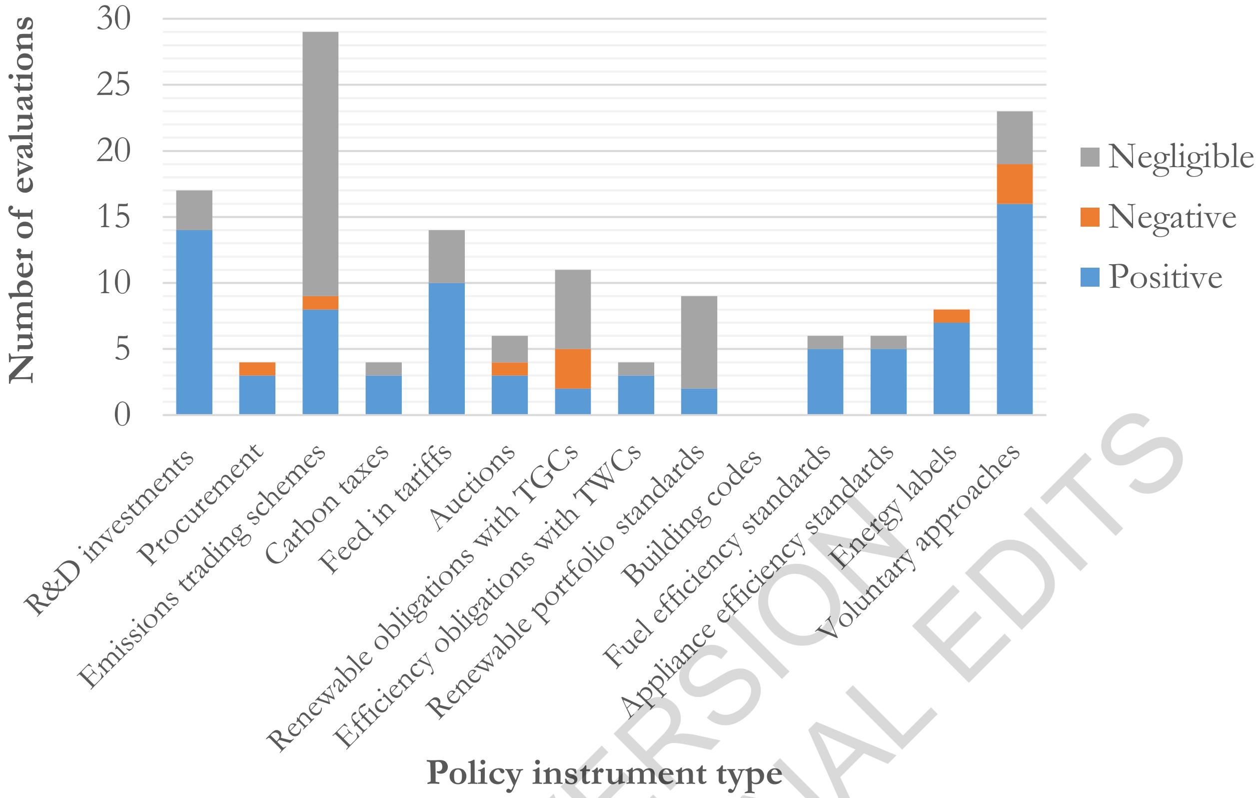

Figure 16.2 Number of evaluations available for each policy instrument type covered regarding their impact on innovation and direction of the assessment. The vertical axis displays the number of evaluations claiming to isolate the impact of each policy instrument type on innovation outcomes as listed in Table 16.9. The colour indicates whether each evaluation identified a positive impact on the innovation outcome (blue), the existence of a negative impact (in orange), and no impact (in grey). It builds on Peñasco et al (2021), Grubb et al (2021), Lilliestam et al (2021) and additional studies identified as part of these reviews. TGC stands for tradeable green certificates. TWC stands for tradeable white certificates.

16.4.5 Trade instruments and their impact on innovation

There has been a long interest on the impact of Foreign Direct Investment (FDI) on domestic capacity on innovation and on environmental outcomes. This section does not cover the much larger body of evidence on the relationship between FDI and economic development and growth.

Overall, research indicates that trade can facilitate the entrance of new technologies, but the impact on innovation is less clear (*limited evidence, low agreement*). A recent study indicates that for countries with high environmental performance FDI has a negligible impact on environmental performance, while on the lower end of the spectrum (countries with a lower environmental performance) may benefit from FDI in terms of their environmental performance (Li et al. 2019b). One analysis on China links FDI not just with improved environmental performance and energy efficiency but also innovation outcomes in general (Gao and Zhang 2013). Other work links FDI with increased productivity across firms (not just those engaged in climate-related technologies) through spill-overs (Newman et al. 2015). In addition, Brandão and Ehrl (2019) indicate that productivity of the electric power industry is more influenced by the transfer of embodied technology from other industries than by investments of the power industry and that countries with high R&D stocks are the main sources of these international technology spillovers and that the source countries may also benefit from the spillover.

Other emerging work investigates the role of local content requirements on innovation outcomes and suggests that it can lead to increased power costs (negative distributional impacts) and the domestic innovation system benefits, measured by patents or exports are unclear if the policies are not part of a holistic and longer lasting policy framework (Probst et al. 2020).

16.4.6 Intellectual property rights, legal framework and the impact on innovation

Virtually all countries around the world have instituted systems for the protection of creations and inventions, known as Intellectual Property (IP) rights systems (WIPO 2021). While several types of intellectual property exist – patents, copyright, design rights, trademarks, and more –, this section will focus on patents, as the most relevant property right for technological innovations (World Intellectual Property Organization 2008), and hence the most relevant for policy instruments in this context.

Patent systems aim to promote innovation and economic growth, by stimulating both the creation of new knowledge and diffusion of that knowledge (*high evidence, high agreement*). National patent systems, as institutions, play a central role in theories on national innovation systems (*high evidence, strong agreement).* Patent systems are usually instituted to promote innovation and economic growth (Nelson and Mazzoleni 1996; Machlup and Penrose 1950; Encaoua et al. 2006). Some countries explicitly refer to this purpose in their law or legislation – for instance, the US Constitution states the purpose of the US IP rights system to "promote the progress of science and useful arts". Patent systems aim to reach their goals by trying to strike a balance between the creation of new knowledge and diffusion of that knowledge (Scotchmer and Green 1990; Devlin 2010; Anadon et al. 2016b). They promote the creation of new knowledge (e.g. technological inventions) by providing a temporary, exclusive right to the holder of the patent, thus providing incentives to develop such new knowledge and helping parties to justify investments in research and development. They promote the diffusion of this new knowledge via the detailed disclosure of the invention in the patent publication, and by enabling a 'market for knowledge' via the trading of patents and the issuance of licenses (Arora et al. 2004). Although IP protections provide incentives to invest in innovation, they have the double effect of restricting the use of new knowledge by raising prices or blocking follow-on innovation (Stiglitz 2008; Wallerstein et al. 1993). National patent systems, as institutions, feature prominently in models and theories of National Innovation Systems (Edquist 1997; Klein Woolthuis et al. 2005).

The degree to which patent systems actually promote innovation is subject to debate. Patent protection has been found to have a positive impact on R&D activities in patent-intensive industries, but this effect was found to be conditional on access to finance (Maskus et al. 2019). Patents are believed to be especially important to facilitate innovation in selected areas like pharmaceuticals, where investments in developments and clinical trials are high, imitation costs are low, and there is often a 1:1 relationship between a patent and a product, referred to as a "discrete" product industry (Cohen et al. 2000). At the same time, there is an increasing body of theoretical and empirical literature that suggests that the proliferation of patents also discourages innovation (*medium evidence, low agreement)*. Theoretical contributions note that a too stringent appropriability regime may greatly limit the diffusion of advanced technological knowledge and eventually block the development of differentiated technological capabilities within an industry, in what is called an 'appropriability trap' (Edquist 1997; Klein Woolthuis et al. 2005). There has been a long-standing debate on the impact of patents and other IP rights on innovation and economic development (Hall and Helmers 2019; Machlup 1958). Jaffe and Lerner (2004) and Bessen & Meurer (2009) highlight how IP rights also hamper innovation in a variety of ways. Other more specific contributions in the literature focus on specific factors. For example, Shapiro (2001) discusses patent thickets, where overlapping sets of patent rights mean that those seeking to commercialize new technology, need to obtain licenses from multiple patentees. Heller and Eisenberg (1998) argue that a 'tragedy of the anticommons' is likely to emerge when too many parties obtain the right to exclude others from using fragmented and overlapping pieces of knowledge, with ultimately no one having the effective privilege of using the results of biomedical research. Reitzig et al. (2007) describe the damaging effects of extreme business strategies employing patents, such as patent trolling.

IP protection and enforcement in general may have different impacts on economic growth in different types of countries *(limited evidence, high agreement*). There has been a significant degree of harmonisation and cooperation between national IP systems over time. The most recent milestone is the 1994 WTO agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS Agreement) , entered into by all members of the World Trade Organisation (WTO), and which sets down minimum standards for the regulation by national governments of many forms of intellectual property as applied to nationals of other WTO member nations (WTO 1994). Developing countries successfully managed to include some flexibilities into TRIPS both in terms of timing of legislative reform and in terms of the content of the reforms. In an attempt to understand the effects of the introduction of TRIPS, Falvey et al. (2006) find that the effect of IP protection on growth is positively and significantly related to growth for low- and high-income countries, but not for middle-income countries. They argue that low-income countries benefit from increased technology flows, but middle-income countries may have offsetting losses from the reduced scope for imitation. Note that Falvey et al. (2006) do not break down their results in different technological areas and they do not focus on innovation, but instead growth. It has been argued that the increasingly globalised IP regime through initiatives like the TRIPS agreement will diminish prospects for technology transfer and competition in developing countries, particularly for several important technology areas related to meeting sustainable development needs (Maskus and Reichman 2017).

In principle, patent holders are not required to take their protected invention into use, and neither have the obligation to allow (i.e., license) others to use the inventions in question *(high evidence, high agreement)*. Studies have shown that the way patent holders use their patent differs considerably across industrial sectors: in pharmaceutics, patents are typically used to be the only producer of a certain good (and obtain monopoly rents), while in industries like computers, semiconductors, and communications, patents are often used to strengthen positions in cross-licensing negotiations and to generate licensing income (Cohen et al. 2000; Foray 2004). There are also companies that predominantly obtain patents for defensive reasons: they seek freedom to design and manufacture, and by owning a patent portfolio themselves, they hope to prevent that they become the target of litigation by other patent holders (Hall and Ziedonis 2001). Patents are often used strategically to impede the development and diffusion of competing, alternative products, processes or services, by employing strategies known as 'blanketing' and 'fencing' (Grandstrand 2000), although the research is not specific to the climate space.

There are notable but specific exceptions to the general principle that patent holders are not obliged to license their patent to others. These exceptions include the compulsory license, Fair, Reasonable and Non-discriminatory (FRAND) policies, and statement on licences of right *(high evidence, high agreement).* While patent holders are, as stated above, in principle free to choose not to license their innovation, there are three important exceptions to this. First, most national patent laws have provisions for compulsory licensing, meaning that a government allows someone else to produce a patented product or process without the consent of the patent holder, or plans to use the patent-protected invention itself (WTO 2020). Compulsory licenses may be issued in cases of public interest or events of abuse of the patent (Biadgleng 2009; World Intellectual Property Organization 2008). Compulsory licensing is explicitly allowed in the WTO TRIPS agreement, and its use in context of medicine (for instance to control diseases of public health importance, including HIV, tuberculosis and malaria) is further clarified in the 'DOHA Declaration' from 2001 (Reichman 2009; WHO 2020). Second, standard-setting organisations have policies to include patented inventions in their standards only if the patent holder is willing to commit FRAND licensing conditions for those patents (Contreras 2015). While a patent holder can still choose not to make such a commitment, by doing so, its patent is no candidate anymore for inclusion in the standard. In the (many) fields where standards are of key importance, it is very unusual for patent holders not to be willing to enter into FRAND commitments (Bekkers 2017). Third, when a patent holder, at the time of filing at the patent office, opts for the "licence of right" regime, in return for reduced patent fees, it enters into a contractual agreement that obliges to license the patent to those that request it. While not all national patent systems feature this regime, it is a feature present in the new European Community patent (EPO 2017), and may therefore increase in importance.

For a discussion on the impact of IPR on international technology diffusion, see Box 16.9 in Section 16.5.

16.4.7 Sub-national innovation policies and industrial clusters

Research examining the impacts of sub-national policies on innovation and competitiveness is sporadic – regional variations have been quantitatively assessed in US or China, or with case studies in these and other countries. Research on wind energy in the United States, distributed PV balance of systems in China, and renewable energy technologies in Italy have found that policies that incentivised local demand were associated with inducing innovation, measured with patents (Fu et al. 2018; Gao and Rai 2019; Corsatea 2016). Different policies may have different impacts – for example, in the United States state-level tax incentives and subsidies induced innovation within the state; but for renewable portfolio standards policies in other states were associated with innovation, because of impact on demand, but own-state policies were not (Fu et al. 2018). Research has also noted that the outcomes of policy and regulation on innovation are spatially heterogenous, because of differences in local planning authorities and capabilities (Song et al. 2019; Corsatea 2016).

Sub-national deployment policies have been associated with different impact on competitiveness metrics (*limited evidence, medium agreement)*. Research on green jobs show positive association between sub-national policies and green jobs or green firms at the metropolitan level as well as the state of provincial level, in both China and the United States (Yi 2013; Yi and Liu 2015; Lee 2017), while others find no impact of renewable portfolio standards on green job growth in the state (Bowen et al. 2013). Other examples of competitiveness are in the impact of regional green industrial policy in Brazil's Rio Grande do Sul region in attracting auctioned contracts for wind energy (Adami et al. 2017) or in the changes in net positive state revenues associated with removing tax incentives for wind producers in Idaho in the US (Black et al. 2014).

Sub-national policies also directly support innovation and competitiveness through green incubators and direct grants or R&D funding for local companies working on clean energy, intending to promote local economic development *(limited evidence, medium agreement*). The literature on the impacts of such policies on innovation and competitiveness is sparse. Some case studies and program evaluation reports, primarily in the United States, have identified the impacts of sub-national policies on competitiveness — for example, job creation from direct R&D funding in North Carolina (Hall and Link 2015), perceptions for local industry development and support for follow-on financing for companies receiving state-funded grants in Colorado (Surana et al. 2020b), and return on investments for the state in research and innovation spending from the New York state's energy agency (NYSERDA 2020). There is a general paucity of metrics on innovation and competitiveness for systematic assessments of such programs in developed countries, and even more so in India and other developing countries where such programs have been increasing (Surana et al. 2020a; Gonsalves and Rogerson 2019).

Although states and local governments increasingly support clean energy deployment as well as directly support innovation given its link with economic development goals, there is a lack of systematic research on the impacts of these policies at the subnational level. More research—both qualitative and quantitative, and in both developed and developing countries—is needed to systematically develop evidence on these impacts and to understand the reasons behind regional differences in terms of the type of policy as well as the capabilities in the region.

16.4.8 System-oriented policies and instruments

Although previous sections summarised the research disentangling the role of individual policies in advancing or hindering innovation (as well as impacts on other objectives), other research has tried to characterise the impact of a policy mix on a particular outcome. Although the outcome studied was not innovation, but diffusion (technology effectiveness is in the set of criteria outlined above), it seems relevant to discuss overall findings. Reviewing renewable energy policies in nine OECD countries, research concludes that, over time, a broad set of policies characterized by a 'balance' metric has been put in place. This research also identifies a significant negative association between the balance of policies in renewable energy and the diffusion of total renewable energy capacity but no significant effect of the overall intensity (coded as the 46 weighted average of six indicators) on renewable capacity (Schmidt and Sewerin 2019), indicating that a neutral conception of balance across all possible policies may not be desirable and that policy mix intensity by itself does not explain technology diffusion.

A growing body of research aims to understand how different policies interact and how to characterise policy mixes (del Río and Cerdá 2017; del Río 2010; Howlett and del Rio 2015; Rogge and Reichardt 2016). The empirical impact on the innovation outcomes is not yet discussed. A more detailed discussion of this literature is located in Chapter 13.

An emerging stream of research in complex systems has suggested that relatively small changes in policy near a possible tipping point in climate impacts in areas including changing strategies related to investments in innovation, could trigger large positive societal feedbacks in the long term (Farmer et al. 2019; Otto et al. 2020a).

16.5 International technology transfer and cooperation for transformative change

This section covers international transfer and cooperation in relation to climate-related technologies, "the flows of know-how, experience and equipment for mitigating and adapting to climate change amongst different stakeholders" (IPCC 2000) as well as innovation to support transformative change compared to the AR5 (IPCC 2014) and the SR1.5 (IPCC 2018a). This complements the discussion on international cooperation on science and technology in Chapter 14.

This section first outlines the needs for and opportunities of international transfer and cooperation on low-emission technologies. It then describes the main objectives and roles of these activities, and then reviews recent institutional approaches within and outside the UNFCCC to support international technology transfer and cooperation. Finally, it discusses emerging ideas on international transfer and cooperation on technology, and possible modifications to support the achievement of climate change and sustainable development goals, building up to Section 16.6.

16.5.1 International cooperation on technology development and transfer: needs and opportunities

With the submission of their NDCs as part of the Paris Agreement, most developing countries are now engaged in climate mitigation and adaptation. While technology is seen as one of the 'means of implementation' of climate action, developing countries often have relatively limited technology innovation capabilities, which requires them to access technologies developed in higher-income countries with stronger innovation systems (Popp 2011; Binz et al. 2012; Urban 2018). In many cases, these technologies require adaptation for the local context and needs (Sagar 2009; Anadon et al. 2016b), and, once again, innovation capabilities are required to suitably adapt these technologies for local use and also to create new markets and business models that are required for successful deployment (Ockwell et al. 2015; Ockwell and Byrne 2016; Sagar 2009). This can lead to dependencies on foreign knowledge and providers (Ockwell and Byrne 2016), negative impacts in terms of higher costs (Huenteler et al. 2016a), and balance of payments constraints and vulnerability to external shocks (Ebeling 2020).

The climate technology transition can also yield other development benefits, for instance better health, increased energy access, poverty alleviation and economic competitiveness (Deng et al. 2018a), including industrial development, job creation and economic growth (Altenburg and Rodrik 2017; Porter and Van der Linde 1995; Lema et al. 2020; Pegels and Altenburg 2020) (See Section 16.6). The growing complexity of technologies and global competition have made the development of a technology into a globalized process involving the flow of knowledge and products across borders (Koengkan et al. 2020; Lehoux et al. 2014). For instance, in production of electronics, Asian economies have captured co-location synergies and dominate production and assembly of product components, whereas American firms have adopted "design-only" strategies (Tassey 2014). In the context of renewable energy technologies, "green global division of labour" has been observed, with countries specialising in investments in R&D, manufacturing or deployment of renewables (Lachapelle et al. 2017). In the case of solar PV, for example, while many of the technical innovations emerged from the US, Japan and China emphasized the manufacture of physical modules (Deutch and Steinfeld 2013) (see also Box 16.4).

Such globalization of production and supply chains opens up economic development opportunities for developing countries (Lema et al. 2020). At the same time, not all countries benefit from the globalisation of innovation, as barriers remain related to finance, environmental performance, human capabilities and cost (Egli et al. 2018; Weiss and Bonvillian 2013), with developing countries being particularly disadvantaged at leveraging these opportunities. The gap in low-carbon technology innovation between countries appears to have been reducing only amongst OECD countries (Yan et al. 2017; Du and Li 2019; Du et al. 2019) and the lower-income countries are not able to benefit as much from low-carbon technologies. For instance, in the case of agriculture, Fuglie (2018) notes out that international R&D spillovers seem to have benefited developed countries more than developing countries. Gross et al (2018)also argue that the development timescales for new energy technologies can extend up to 70 years, even within one country, and recommend that innovation efforts be balanced between on the one hand commercialising already low-emission technologies in the demonstration phase, and diffusing them globally, and on the other hand early-stage R&D spending.

Thus international cooperation on technology development and transfer can enable developing countries to achieve their climate goals more effectively, while also addressing other sustainable development goals, taking advantage, where possible, of the globalization of innovation and production (Lema et al. 2020). Earlier assessments in the AR5 and SR1.5 have made it clear that international technology transfer and cooperation could play a role in climate policy at both the international and the domestic policy level (IPCC 2018b; Stavins et al. 2014; Somanathan et al. 2014) and for low-carbon development at the regional level (Agrawala et al. 2014). The Paris Agreement also reflects this view by noting that countries shall strengthen cooperative action on technology development and transfer regarding two main aspects: 1) promoting collaborative approaches to research and development and 2) facilitating access to technology to developing country Parties (UNFCCC 2015). Furthermore, both in literature and in UNFCCC deliberations, South-South technology transfer is highlighted (Khosla et al. 2017) as a complement to the transfer of technology and know-how from North to the South.

This is consistent with literature that suggests that GHG mitigation in developing countries can be enhanced by (1) technology development and transfer collaboration and a 'needs-driven' approach, (2) development of the specific types of capacity required across the entire innovation chain and (3) strengthening of the coordination and agendas across and between governance levels (including domestic and international levels) (Upadhyaya et al. 2020; Zhou 2019; Khosla et al. 2017).

16.5.2 Objectives and roles of international technology transfer and cooperation efforts

International efforts involving technology transfer can have different objectives and roles. These include access to knowledge and financial resources as well as promotion of new industries in both the developed and recipient country (Huh and Kim 2018). Based on an econometric analysis of international technology transfer factors and characteristics of Clean Development Mechanism (CDM) projects, Gandenberger et al (2016) find that complexity and novelty of technologies explain whether CDM project includes hardware technology transfer, and that factors like project size and absorptive capacity of the host country do not seem to be drivers. Halleck Vega and Mandel (2018) argue that 'long-term economic relations', for instance being part of a customs union, affects technological diffusion between countries for the case of wind energy, and indicate that this has resulted in low-income countries being largely overlooked.

There is some literature studying whether technology cooperation could complement or replace international cooperation based on emission reductions, such as in the Kyoto Protocol, and whether that would have positive impacts on climate change mitigation and compliance. A handful of papers conducted game-theoretic analysis on technology cooperation, sometimes as an alternative for cooperation on emission reductions, and found partially positive effects (Rubio 2017; Narita and Wagner 2017; Bosetti et al. 2017; Verdolini and Bosetti 2017). However, Sarr and Swanson (2017)model that, due to the rebound effect, technology development and transfer of resource-saving technologies may not lead to envisioned emission reductions.

While technology cooperation can be aimed at emission reduction through mitigation projects, as indicated above, not all cooperative actions directly result in mitigation outcomes. Overall, technology transfer broadly has focused on i) enhanced climate technology absorption and deployment in developing countries and ii) enhanced RD&D through cooperation and knowledge spill-overs.

16.5.2.1 Enhancing low-emission technology uptake in developing countries

Real-world outcomes in terms of low-emission technology deployment in developing countries may vary significantly depending on both the nature of the international engagement and the domestic context. While there have been some success in the enhancement of technology deployment through technology transfer in some developing countries (de la Tour et al. 2011; Zhang and Gallagher 2016), many others, and particularly least-developed countries, are lagging behind (Glachant and Dechezleprêtre 2017). They indicate that this is due to the lack of participation in economic globalisation and that climate negotiations could facilitate technology transfer to those countries through the creation of global demand for low-emission technologies through stronger mitigation targets that will result in lowering of costs and therefore enhanced technology diffusion. A broader perspective presents a host of other factors that govern technology diffusion and commercialization in developing countries, including, investment; social, cultural and behavioural, marketing and market building; macroeconomics; and support policy (Bakhtiar et al. 2020). Ramos Mejía et al (2018) indicate that the governance of low-emission technology transfer and deployment in developing countries is frequently negatively affected by a mixture of well- and ill-functioning institutions, in a context of, for instance, market imperfection, clientelist and social exclusive communities and patrimonial and/or marketized states. Furthermore, existing interests, such as fossil fuel production, may also impede the deployment of low-emission technologies, as highlighted in case studies of Vietnam and Indonesia (Dorband et al. 2020; Ordonez et al. 2021). It is for such reasons that both domestic efforts and international engagement are seen as necessary to facilitate technology transfer as well as deployment in developing countries (Boyd 2012). The same has been seen as true in the case of agriculture where the very successful international research efforts of the CGIAR (with remarkably favourable benefit-cost ratios (Alston et al. 2021) were complemented by the national agricultural research systems for effective uptake of high-yielding varieties of crops (Evenson and Gollin 2003).

One key area for underpinning effective technology uptake in developing countries relates to capabilities for managing technological change that includes the capabilities to innovate, implement, and undertake integrated planning. There is much research to indicate that the ability of a country's firms to adopt new technologies is determined by its absorptive capacity, which includes its own R&D activities, human capacity (e.g., technical personnel), government involvement (including institutional capacity), and the infrastructure in the country (Kumar et al. 1999), and that knowledge and capacity are part of the 'intangible assets' or the 'software' of a firm or a country (Corsi et al. 2020; da Silva et al. 2019; Ockwell et al. 2015). For sustainable development, capacity to plan in an integrated way and implement the SDGs (Elder et al. 2016; Khalili et al. 2015), including using participatory approaches (Disterheft et al. 2015), are conditional means of implementation. It also is argued that, if human capital were at the focus of international climate negotiations as well as national climate policy, it could change the political economy in favour of climate mitigation, which is needed for developing such capabilities in advance to keep up with the required speed of transformation (Hsu 2017; Upadhyaya et al. 2020; Ockwell et al. 2015; IPCC 2018b). Halleck-Vega et al (2018), in a global analysis of wind energy using econometric analysis, lend quantitative credibility to the claim that a technology skill base is a key determinant of technological diffusion. Activities to enhance capabilities include informational contacts, research activities, consulting, education & training and activities related to technical facilities (Huh and Kim 2018; Khan et al. 2020).

There are multiple studies drawing on empirical work also support this conclusion. For South-South technology transfer between India and Kenya, not just technical characteristics, but also mutual learning on how to address common problems of electricity access and poverty, was suggested as an important condition for success (Ulsrud et al. 2018). Specifically for Africa, Olawuyi (2018)discusses the capability gap in Africa, despite decades of technology transfer efforts under various mechanisms and programmes of the UNFCCC. The study suggests that barriers need to be resolved by African countries themselves, in particular inadequate access to information about imported climate technologies, lack of domestic capacities to deploy and maintain imported technologies, the weak regulatory environment to stimulate clean technology entrepreneurship, the absence or inadequacy of climate change laws, and weak legal protection for imported technologies. Moreover, Ziervogel et al (2021) indicate that for transformative adaptation, transdisciplinary approaches and capacity building shifting "the co-creation of contextual understandings" instead of top-down transferal of existing knowledge would deliver better results. Despite the understanding of the importance of the capacity issue, significant gaps still remain on this front (Technology Executive Commitee 2019); see also 16.5.4).

16.5.2.2 Enhancing RD&D and knowledge spill-overs

As mentioned earlier, RD&D can aid both the development of new technologies as well as their adoption for new use contexts. Therefore it is not surprising that international cooperation on RD&D is identified as a mechanism to promote low-carbon innovation (see, for example, Suzuki (2015), Technology Executive Committee (2021), Mission Innovation (2019)). This has resulted in a variety of international initiatives to cooperate on technology in order to create knowledge spill-overs and develop capacity. For example, the UNFCCC Technology Mechanism, amongst other things, aims to facilitate finance for RD&D of climate technologies by helping with readiness activities for developing country actors. In particular preparing early-stage technologies for a smoother transition to deployment and commercialisation has been emphasised in the context of the Technology Executive Committee (Technology Executive Committee 2017). There are numerous programmes, multilateral, bilateral and private, that have facilitated RD&D, biased mostly towards mitigation (as opposed to adaptation) activities, and many programmes that seemed to be about RD&D were in reality dialogues about research coordination (Ockwell et al. 2015). There also are a variety of possible bilateral and multilateral models and approaches for engaging in joint R&D (Mission Innovation 2019). An update by the Technology Executive Committee (2021) reviewing good practices in international cooperation of technology confirmed the conclusions of Ockwell et al(2015), and moreover highlighted that most initiatives are led by the public sector, and that the private sector tended to get involved only in incubation, commercialisation and diffusion phases. It also concluded that, although participation of larger, higher-income developing countries seems to have increased, participation of least-developed countries is still very low.

16.5.3 International technology transfer and cooperation: recent institutional approaches

In the sections below, the literature on various categories of international technology cooperation and transfer is discussed.

16.5.3.1 UNFCCC technology and capacity building institutions

Technology development and transfer are a part of the UNFCCC since its agreement in 1992 and has undergone discussions and developments in the context of the international climate negotiations ever since, as assessed in AR5 (Stavins et al. 2014). The support on "Technology Needs Assessment" to developing countries was the first major action undertaken by the UNFCCC, and has undergone different cycles of learning (Nygaard and Hansen 2015; Hofman and van der Gaast 2019). Since 2009, the UNFCCC discussions on technology development and transfer have focussed on the Technology Mechanism under the Cancun Agreements of 2010, which can be seen as the global climate governance answer to redistributive claims by developing countries (McGee and Wenta 2014). The Technology Mechanism consists of a Technology Executive Committee (TEC) and a Climate Technology Centre and Network (CTCN). An independent review of CTCN evaluated it on five dimensions – relevance, effectiveness, efficiency, impacts and sustainability – indicated that the organization is achieving its mandate in all these dimensions, although there are some possible areas of improvement. The review also specifically noted that "the lack of predictability and security over financial resources significantly affected the CTCN's ability to deliver services at the expected level, as did the CTCN's lack of human and organizational resources and the capacity of NDEs." (Technology Executive Committee 2017). The CTCN has overcome some of the limitations imposed by resource constraints by acting as a matchmaker from an open-innovation perspective (Lee and Mwebaza 2020). The lack of financial sustainability of the CTCN has been a recurring issue, which may potentially be resolved by deepening the linkage between the CTCN and GCF (Oh 2020). In the meanwhile, the GCF is planning to establish the Climate Innovation Facility to support and accelerate early-stage innovations and climate technologies through the establishment of regional innovation hubs and climate accelerators as well as a climate growth fund (Green Climate Fund 2020).

The 'technology' discussion has been further strengthened by the Paris Agreement, in which Article 10 is fully devoted to technology development and transfer (UNFCCC 2015). However, the political discussions around technology continue to be characterised by viewing technology mostly as hardware (Haselip et al. 2015), and relatively limited in scope (de Coninck and Sagar 2017). The workplans of the Technology Executive Committee (TEC) and the CTCN do, however, indicate a broadening of the perspective on technology (CTCN 2019; Technology Executive Commitee 2019).

Since the Kyoto Protocol's Clean Development Mechanism (CDM) has been operational, studies have assessed its hypothesised contribution to technology transfer, including transfer of knowledge. Though not an explicit objective of the CDM, numerous papers have investigated whether CDM projects contribute to technology transfer (Michaelowa et al. 2019). The literature varies in its assessment. Some find extensive use of domestic technology and hence lower levels of international technology transfer (Doranova et al. 2010), while other indicate that around 40% of projects feature hardware or other types of international transfer of technology (Murphy et al. 2015; Seres et al. 2009), depending on the nature of technology, the host country and region (Cui et al. 2020) and the project type (Karakosta et al. 2012). Although the CDM would generally be positively evaluated on the technology transfer contribution, it was also regarded critically as the market-responsiveness and following of export implies a bias to larger, more advanced economies rather than those countries most in need of technology transfer (Gandenberger et al. 2016), although some countries have managed to correct that by directing the projects, sub-nationally, to provinces with the greatest need (Bayer et al. 2016). Also, the focus on hardware transfer of technology in evaluations of technology transfer under the CDM has been criticised (Michaelowa et al. 2019; Haselip et al. 2015). Indeed, although many studies do go beyond hardware in their evaluations (e.g. Murphy et al (2015)), the degree to which the project leads to a change in the national system of innovation or institutional capacity development is not commonly assessed, or assessed as limited (de Coninck and Puig 2015).

There is significantly less literature on capacity building under the UNFCCC, especially as it relates to managing the technology transition. D'Auvergne and Nummelin (2017)(D´Auvergne and Nummelin 2017), in a legal analysis, indicate the nature, scope and principles of Article 11 on capacity building of the Paris Agreement as being demand- and country-driven, following a needs approach, fostering national, subnational and local ownership, and being iterative, incorporating the lessons learned, as well as participatory, cross-cutting and gender-response. They also highlight that it is novel that least-developed countries and SIDS are called out as the most vulnerable and most in need of capacity building, and that it raises a "legal expectation" that all parties "should" cooperate to enhance the capacity in developing countries to implement the Paris Agreement. These aspects are reflected in the terms of reference of the Paris Committee on Capacity Building (PCCB) that was established in 2015 at the 21st Conference of the Parties (UNFCCC 2016; D´Auvergne and Nummelin 2017), which was extended by five years at the 25th Conference of the Parties in 2019 (UNFCCC 2020a,b). In its work plan for 2020-2024, amongst other things, it aims to "identifying capacity gaps and needs, both current and emerging, and recommending ways to address them".

An example of how innovative technologies combined with capacity development and institutional innovation is combined in the context of adaptation to extreme weather in SIDS can be found in Box 16.8.

START BOX 16.8 HERE

Box 16.8 Capacity building and innovation for early warning systems in Small Island Developing States

One of the areas of international cooperation on capacity building is adaptation, which has been highlighted by both the Technology Executive Committee (Technology Executive Committee 2015; Ockwell et al. 2015) and the Paris Committee on Capacity Building (UNFCCC 2020b) as an area where capacity gaps remain, especially in Small Island Developing States (SIDS).

While adaptation was initially conceived primarily in terms of infrastructural adjustments to long-term changes in average conditions (e.g., rising sea levels), a key innovation in recent years has been to couple such long-term risk management to existing efforts to manage disaster risk, specifically including early warning systems enabling early action in the face of climate- and weather-risk at much shorter timescales (e.g., IPCC 2012), with potentially significant rates of return (e.g., Rogers and Tsirkunov 2010; Hallegatte 2012; Global Commission on Adaptation 2019).

In recent years, deliberate international climate finance investments have focused on ensuring that developing countries (and especially SIDS and LDCs) have access to improvements in hydrometeorological observations, modelling, and prediction capacity, sometimes with a particular focus on the people intended to benefit from the information produced (e.g., CREWS 2016). For instance, on the Eastern Caribbean SIDS of Dominica, researchers took a community-based approach to identify the mediating factors affecting the challenges to coastal fishing communities in the aftermath of two extreme weather events (in particular hurricane Maria in 2017) (Turner et al. 2020). Adopting an adaptive capacity framework (Cinner et al. 2018), they identified 'intangible resources' that people relied on in their post-disaster response as important for starting up fishery, but also went beyond that framework to conclude that the response ability on the part of governmental organisations as well as other actors (e.g. fish vendors) in the supply chain is also a requirement for rebuilding and restarting income-generating activity (Turner et al. 2020). Numerous other studies have highlighted capacity building as adaptation priorities (Williams et al. 2020; Kuhl et al. 2020; Vogel et al. 2020; Basel et al. 2020; Sarker et al. 2020).

One of several helpful innovations in these efforts is impact-based forecasting (Harrowsmith et al. 2020), which provides forecasts targeted at the impact of the hazard rather than simply the meteorological variable, enabling a much easier coupling to early action in response to the information, enabling a more appropriate response afterwards. Automatic responses to warnings have also been adopted in the humanitarian field for anticipatory action ahead (rather than simply in response to) disasters triggered by natural hazards (Coughlan de Perez et al. 2015), resulting in a rapid scale-up of such anticipatory financing mechanisms to tens of countries over the past few years, and emerging evidence of its effectiveness. Still, the response is lacking in coherence and comprehensiveness, resulting in calls for a more systematic evidence agenda for anticipatory action (Weingärtner et al. 2020).

END BOX 16.8 HERE

From the broader assessment above, despite limitations of available information, it is clear that the number of initiatives and activities on international cooperation and technology transfer and capacity building seem to have been enhanced since both the Cancun Agreements and the Paris Agreement (Technology Executive Committee 2021). However, given the complexity and magnitude of the requirements in terms of coverage of activities, the amount of committed funding, and effectiveness, much more can be done. Some assessments of UNFCCC instruments specifically for technology transfer to developing countries had indicated that functions such as knowledge development, market formation and legitimacy in developing countries' low-emission technological innovation systems would need much more support to fulfil the Paris goals. (de Coninck and Puig 2015; Ockwell et al. 2015); such areas would benefit from continued attention, given their role in the overall climate technology transition.

16.5.3.2 International RD&D cooperation and capacity building initiatives

Besides the UNFCCC mechanisms, there are numerous other initiatives that promote international cooperation on RD&D as well as capacity building. Some of them are based on the notion of "mission-oriented innovation policy" (Mazzucato and Semieniuk 2017; Mazzucato 2018), which shapes markets rather than merely correcting market failures.

For instance, "Mission Innovation" (MI) is a global initiative consisting of 23 member countries and the European Commission working together to reinvigorate and accelerate global clean energy innovation with the objective to make clean energy widely affordable with improved reliability and secured supply of energy. The goal is to accelerate clean energy innovation in order to limit the rise in the global temperature to well below 2°C. The members to seek to increase public investments in clean energy R&D with the engagement of private sectors, and foster international collaboration amongst its members. A recent assessment shows that, although expenditures are rising, the aims are not met by 2020 (Myslikova and Gallagher 2020). Gross et al (2018)caution against too much focus on R&D efforts for energy technologies to address climate change, including Mission Innovation. They argue that given the timescales of commercialisation, developing new technologies now would mean they would be commercially too late for addressing climate change. Huh and Kim (2018) discuss two 'knowledge and technology transfer' projects that were eventually not pursued through beyond the feasibility study phase due to cooperation and commitment problems between national and local governments and highlight the need for ownership and engagement of local residents and recipient governments.

The intellectual property right regime (see Box 16.9) can be an enabler or a barrier to energy transition. For more background on IPR and impact on innovation, see Section 16.4.6.

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Box 16.9 Intellectual property rights (IPR) regimes and technology transfer

In the global context of climate mitigation technologies, it has been noted that technologies have been developed primarily in industrialised countries but are urgently required in fast-growing emerging economies (Dechezleprêtre et al. 2011). International technology transfer of such technologies can primarily take place via three channels: (i) trade in goods, where technology is embedded in products; (ii) direct foreign investments (FDI), where enterprises transfer firm-specific technology to foreign affiliates, and (iii) patent licenses, where third parties obtain the right to use technologies. IPRs are relevant for all these three channels.

Not surprisingly, then, the role of IPRs in international technology transfer of climate mitigation technologies has been much discussed but also described as particularly controversial (Abdel-Latif 2015). The relationships between IP rights, innovation, international technology transfer and local mitigation and adaptation are complex (Maskus 2010; Li et al. 2020; Abdel-Latif 2015) and there is no clear consensus on what kind of an IPR regime will be most beneficial for promoting technology transfer.

Several studies argue that, particularly in developing nations, the global IP regime has resulted in delayed access, reduced competition and higher prices (Littleton 2008; Zhuang 2017) and that climate-change-related technology transfer is insufficiently stimulated under the current IPR regime. Compulsory licensing (as already used in medicine) is one of the routes proposed to repair this (Abdel-Latif 2015; Littleton 2008).

There is little systematic evidence that patents and other IPRs restrict access to environmentally sound technologies, since these technologies mostly are in sectors based on mature technologies where numerous substitutes among global competitors are available (Maskus 2010). This might however change in the future, for instance with new technologies based on plants, via biotechnologies and synthetic fuels (Maskus 2010), for which Correa et al (2020) already find some evidence.

There also is literature that suggests weak IPR regimes have a "strong and negative impact on the international diffusion of patented knowledge" (Dechezleprêtre et al. 2013; Glachant and Dechezleprêtre 2017). Also, patents may support market transactions in technology, including international technology transfer, especially to "middle-income" countries and larger developing countries (Maskus 2010; Hall and Helmers 2019) but LDCs may be better served by building capacity to absorb and implement technology (Sanni et al. 2016; Hall and Helmers 2010; Maskus 2010; Glachant and Dechezleprêtre 2017). It is also argued that it is not even clear that the patent system as it exists today is the most appropriate vehicle for encouraging international access (Sanni et al. 2016; Hall and Helmers 2010; Maskus 2010; Glachant and Dechezleprêtre 2017). Given the large variation in perspectives on the role of IPRs in technology transfer, there is a need for more evidence and analysis to better understand if, and under what conditions, IPRs may hinder or promote technology transfer (see also Technology Executive Committee (2012)).

In terms of ways forward to meet the challenge of climate change, different suggestions are made in the context of IPRs that can help to further improve international technology transfer of climate mitigation technologies, including through the TRIPS agreement, by making decisions on IPR to developing countries on a case-by-case basis, by developing countries experimenting more with policies on IPR protection, or through brokering or patent-pooling institutions (Littleton 2009; Dussaux et al. 2018; Maskus and Reichman 2017). Others also suggests that distinctions among country groups be made on basis of levels of technological and economic development, with least developed countries getting particular attention (Abbott 2018; Zhuang 2017).

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16.5.4 Emerging ideas for international technology transfer and cooperation

As with the broader innovation literature (as highlighted in Section 16.3), and, in fact, drawing on such literature, there has been an emergence of a greater understanding of, and emphasis on, the role of innovation systems (at a national, sectoral, and technological level) as a way to help developing countries with the climate technology transition (Technology Executive Committee 2015; Ockwell and Byrne 2016). This has given rise to several proposals, discussed here and summarised in Figure 16.3.

Enhancing deployment and diffusion of climate technologies in developing countries would require a variety of actors with sufficient capabilities (*robust evidence, medium agreement*) (Ockwell et al. 2018; Kumar et al. 1999; Sagar et al. 2009). This may include strengthening existing actors (Malhotra et al. 2021), supporting science, technology, and innovation-based start-ups to meet social goals (Surana et al 2020b), and developing entities and programs that are intended to address specific gaps relating to technology development and deployment (Ockwell et al. 2018; Sagar et al. 2009).

There also is an increasing emphasis on the relevance of participative social innovation, local grounding and policy learning as a replacement of the expert-led technological change (Kowarsch et al. 2016; Chaudhary et al. 2012; Disterheft et al. 2015). Others have suggested a shift to international innovation cooperation rather than technology transfer, which implies donor-recipient relationship. The notion of innovation cooperation also makes more explicit the focus on innovation processes and systems (Pandey et al. 2021). A broad transformative agenda therefore proposes that contemporary societal challenges are complex and multi-variegated in scope and will require the actions of a diverse set of actors to both formulate and address the policy, implying social, institutional and behavioural changes next to technological innovations are the possible solutions (Geels 2004) (see also Cross-Chapter Box 12 in this chapter).

Several authors have proposed new mechanisms for international cooperation on technology. Ockwell and Byrne (2016) argue that a role for the UNFCCC Technology Mechanism could be to support climate relevant innovation-system builders (CRIBs) in developing countries, institutions locally that develop capabilities that "form the bedrock of transformative, climate-compatible, technological change and development". Khan et al (2020) propose a specific variant with universities in developing countries serving as 'central hubs' for capacity building to implement the NDCs as well as other climate policy and planning instruments; they also suggest that developing countries outline their capacity building needs more clearly in their NDCs.

Building on an earlier discussion of technology-oriented and sectoral agreements (Meckling and Chung 2009) and the potential for international cooperation in energy-intensive industry (Åhman et al. 2017), where deep emission reduction measures require transformative changes (see also Chapter 11), Oberthür et al (2021) propose that the global governance for energy-intensive industry through sub-sector 'clubs' that include governmental, private and societal actors could be effective way forward (Oberthür et al. 2021).

Examples of emerging ideas for international cooperation on climate technology, as well as their relation to the objectives and existing efforts, and in relation to the level of development of the innovation system around a technology (Bergek et al. 2008; Hekkert et al. 2007) or in nations (Lundvall et al. 2009) are summarized in Figure 16.3.

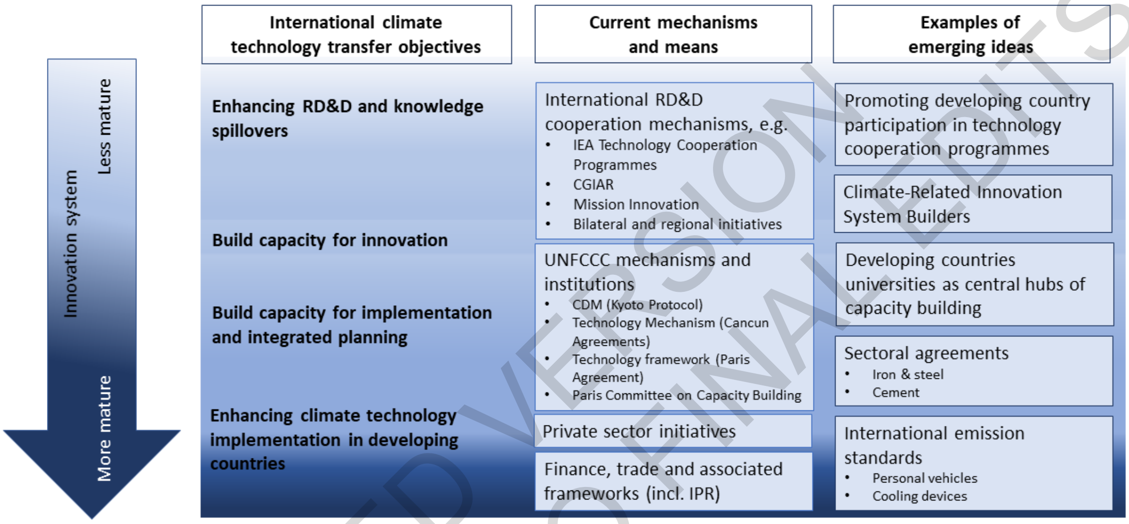

Figure 16.3 Examples of recent mechanisms and emerging ideas (right column) in relation to level of maturity of the national or technological innovation system, objectives of international climate technology transfer efforts and current mechanisms and means. Sources: (Oberthür et al. 2021; Khan et al. 2020; Ockwell and Byrne 2016; Sagar 2009)

16.6 Technological change and sustainable development

This section considers technological innovation in the broader context of sustainable development, recognising that technological change happens within social and economic systems, and therefore technologies are conceived and applied in relation to those systems (Grübler 1998). Simplifications of complex interactions between physical and social systems and incomplete knowledge of technological innovation indirect effects may systematically lead to underestimation of environmental impacts and overestimation of our ability to mitigate climate change (Arvesen et al. 2011; Hertwich and Peters 2009).

In previous sections, the chapter discussed how a systemic approach, appropriate public policies and international cooperation on innovation can enhance technological innovation. This section provides more details on how innovation and technological change, sustainable development and climate change mitigation intertwine.

16.6.1 Linking sustainable development and technological change

Sustainable development and technological change are deeply related (UNCTAD 2019). Technology has been critical for increasing productivity as the dominant driving force for economic growth but also, the concentration of technology in few hands has boosted consumption of goods and services which are not necessarily aligned with sustainable development goals (Walsh et al. 2020). It has been suggested that, in order to address sustainable development challenges, science and technology actors would have to change their relation to policymakers (Ravetz and Funtowicz 1999) as well as the public (Jasanoff 2003). This has been further elaborated for the SDGs. The scale and ambition of the SDGs call for a change in development patterns that require a fundamental shift in both current best practices and guidelines for technological and investment decisions and in the wider socio-institutional systems (UNCTAD 2019; Pegels and Altenburg 2020). This is needed as not all innovation will lead to sustainable development patterns (Altenburg and Pegels 2012; Lema et al. 2015).

Current Sustainable Development Goals (SDG) implementation gaps reflect, to some extent, inadequate understanding of the complex relationships among the goals (Skene 2020; Waiswa et al. 2019), as well as their synergies and trade-offs, including how they limit the range of responses available to communities and governments, and potential injustices (Thornton and Comberti 2017). These relationships have been approached by focusing primarily on synergies and trade-offs while lacking the holistic perspective necessary to achieve all the goals (Nilsson et al. 2016; Roy et al. 2018).

A more holistic framework could envisage the SDGs as outcomes of stakeholder engagement and learning processes directed at achieving a balance between human development and environmental protection (Gibbons 1999; Jasanoff 2003), to the extent that the two can be separated. From a science, technology and innovation (STI) perspective, Fu et al (2019) distinguish three categories of SDGs. The first category comprises those SDGs representing essential human needs for which inputs that put pressure on sustainable development would need to be minimized. These include food (SDG 2), water (SDG 6) and energy (SDG 7) resources, which continue to rely on production technologies and practices that are eroding ecosystem services, hampering the realization of SDG goals 15 (land) and 14 (oceans) (Díaz et al. 2019). The second are those related to governance and which compete with each other for scarce resources, such as infrastructure (SDG 9) and climate action (SDG 13), which require an interdisciplinary perspective. The third category are those that require maximum realization, include no poverty (SDG 1), quality education (SDG 4) and gender equality (SDG 5) (Fu et al. 2019).

Resolving tensions between the SDGs requires adoption and mainstreaming of novel technologies that can meet needs while reducing resource waste and improving resource-use efficiency, and while acknowledging the systemic nature of technological innovation, which involve many levels of actors, stages of innovation and scales (Anadon et al. 2016b). Changes in production technology have been found effective to overcome trade-offs between food and water goals (Gao and Bryan 2017). Innovative technologies at the food, water and energy nexus are transforming production processes in industrialized and developing countries, such as developments in agrivoltaics, which is co-development of land for agriculture and solar with water conservation benefits (Barron-Gafford et al. 2019; Schindele et al. 2020; Lytle et al. 2020), and other renewably powered low- to zero-carbon food, water and energy systems (He et al. 2019). Silvestre and Ţîrcă (Silvestre and Ţîrcă 2019) indicate that maximising both social and environmental aims is not possible, but that sustainable innovations include satisfactory solutions for social, environmental and economic pillars (see Figure 16.4).

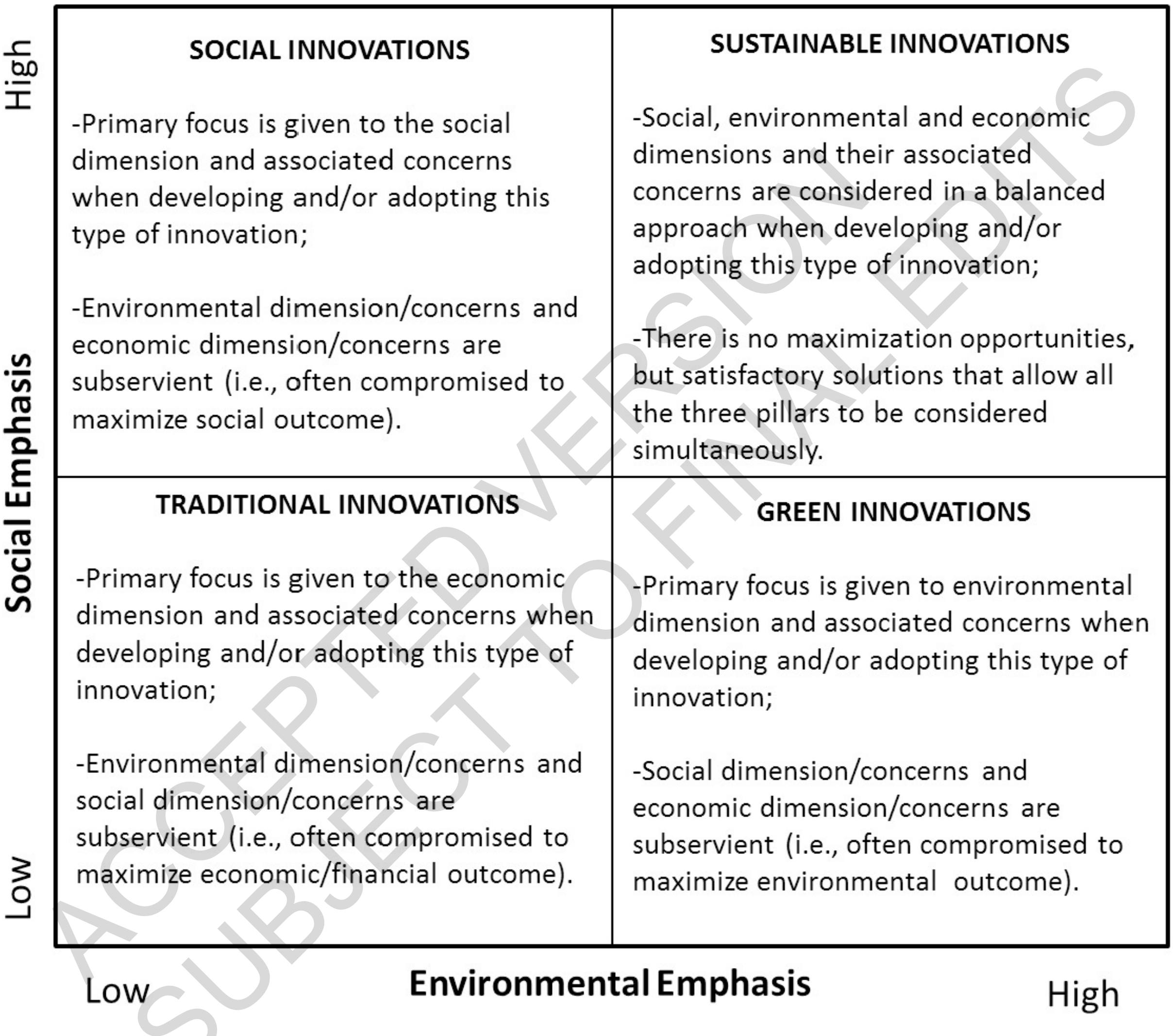

Figure 16.4: Considerations and typology of innovations for sustainable development (Silvestre and Ţîrcă 2019).

There is evidence that technological changes can catalyse implementation of the reforms needed to the manner in which goods and services are distributed among people (Fu et al. 2019). A recently developed theoretical framework based on a capability approach (CA) has been used to evaluate the quality of human life and the process of development (Haenssgen and Ariana 2018). Variations of the CA have been applied to exploratory studies of the link between technological change, human development, and economic growth (Mayer 2001; Mormina 2019). This suggests that the transformative potential of technology as an enabling condition is not intrinsic, but is assigned to it by people within a given technological context. A failure to recognize and account for this property of technology is a root cause of many failed attempts at techno-fixing sustainable development projects (Stilgoe et al. 2013; Fazey et al. 2020).

The basic rationale for governance of technological change is the creation and maintenance of an enabling environment for climate and SDG-oriented technological change (Avelino et al. 2019). Such an environment poses high demands on governance and policy to coordinate with actors and provide a direction for innovation and technological change. Cross-Chapter Box 12 illustrates how the dynamics of socio-technical transitions and shifting development pathways towards sustainable development offer options for policymakers and other actors to accelerate the system transitions needed for both climate change mitigation and sustainable development. Governance interventions to implement the SDGs will need to be operationalized at sub-national, national and global levels and support integration of resource concerns in policy, planning and implementation (UNEP 2015; Williams et al. 2020).

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Cross-Chapter Box 12 Transition Dynamics

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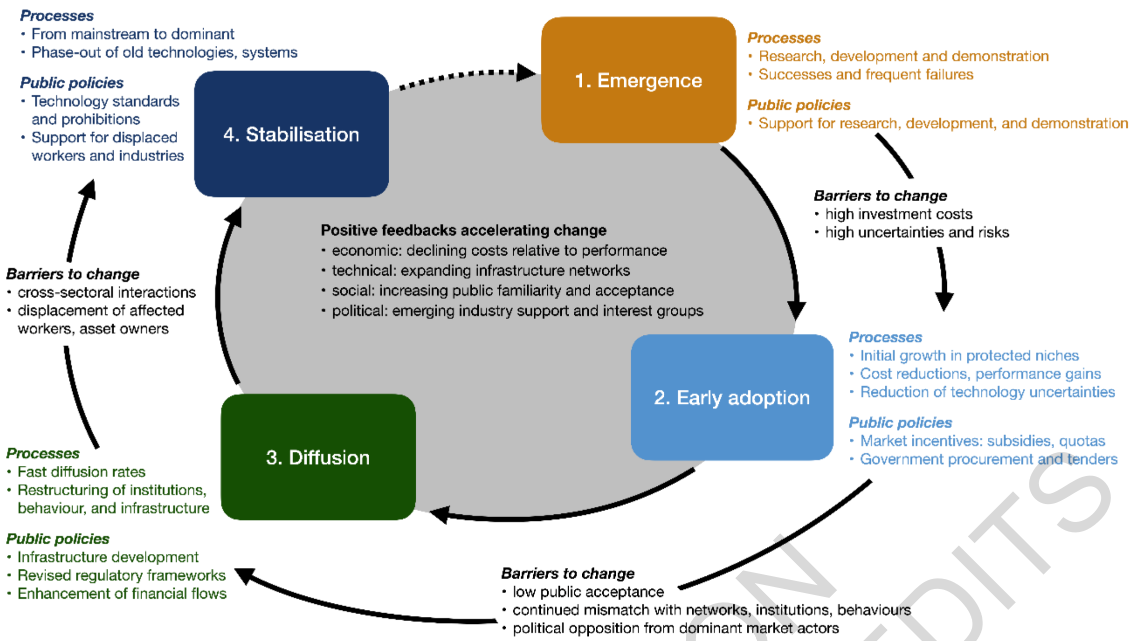
Introduction: Numerous studies suggest that transformational changes would be required in many areas of society if climate change is to be limited to 2°C warming or less. Many of these involve shifts to low carbon technologies, such as renewable energy, which typically involve changes in associated regulatory and social systems; others more explicitly concern behavioural shifts, such as towards plant-based diets or cleaner cooking fuels, or, at the broadest level, a shift in development pathways. Chapter 1 establishes an analytic framework focusing on transitions, which chapters 5, 13, 14, 15 and 16 further develop. In this cross-chapter box, we provide a complementary overview of the dynamics of different kinds of transformational changes for climate mitigation and sustainable development. We first focus on insights from socio-technical transitions approaches, and then expand to broader system transitions.

Dynamics of socio-technical transitions: A large literature documents the processes associated with transformational changes in technology and the social systems associated with their production and use (Köhler et al. 2019; Geels 2019). Transformational technological change typically goes hand-in-hand with shifts in knowledge, behaviour, institutions, and markets (Markard et al. 2012, p. 956; Geels and Schot 2010); stickiness in these factors often keeps society "locked-in" to those technologies already in widespread use, rather than shift to new ones, even those that offer benefits (David 1985; Arthur 1994). Exceptions often follow consistent patterns (Unruh 2002; Geels 2002); since AR5 a growing number of scholars have suggested using these insights to design more effective climate policies and actions (Geels et al. 2017). Chapter 1 (see Section 1.7 and Figure 1.6) represents technology diffusion and a corresponding shift in policy emphasis as a continuous process; it is also useful to identify a sequence of distinct stages that typically occur, associating each stage with a distinct set of processes, challenges, and effective policies (Patt and Lilliestam 2018; Victor et al. 2019). Consistent with elsewhere in this report (section 5.5.2 and SM.5.5.3 in Chapter 5, and section 16.3 in Chapter 16), Cross-Chapter Box 12 Figure 1 elaborates four distinct stages. Recognizing that even transformative technologies will eventually be replaced with newer ones, the figure portrays these as occurring in a cycle.



Cross-Chapter Box 12, Figure 1 Stages of socio-technical transition processes

The *emergence* stage is marked by experimentation, innovation in the laboratory, and demonstration in the field, to produce technologies and system architectures (Geels 2005a). By its very nature, experimentation includes both successes and failures, and implies high risks. Because of these risks, especially in the case of fundamentally new technologies, government funding for research, development and demonstration (RD&D) projects is crucial to sustaining development (Mazzucato 2015b).

The second stage is *early adoption*, during which successful technologies jump from the laboratory to limited commercial application (Pearson and Foxon 2012). Reaching this stage is often described as crossing the "Valley of Death", because the cost/performance ratio for these new market entrants is too low for them to appear viable to investors (Murphy and Edwards 2003). A key process in the early adoption phase is induced innovation, a result of incremental improvements in both design and production processes, and of mass-production of a growing share of key components (Grubb et al. 2021; Nemet 2006). There is diversity across classes of technologies, and learning tends to occur faster for technologies that are modular (Wilson et al. 2020), such as photovoltaics, and slower for those that require site- or context-specific engineering, such as in the shift to low carbon materials production (Malhotra and Schmidt 2020). Public policies that create a secure return on investment for project developers can lead to learning associated with industry expansion (See Chapter 16, Figure 16.1); typically these are economically and politically viable when they promote growth within a market "niche", causing little disruption to the mainstream market (Roberts et al. 2018). Direct support mechanisms, including cross-subsidies, such as feed-in tariffs, and market quotas such as renewable portfolio standards, are effective (Patt and Lilliestam 2018; Geels et al. 2017b; see Chapter 9 for assessment of early adoption policies in the building sector). The value of these policies is less in their immediate emissions reductions, but more in generating the conditions for self-sustaining transformational change to take place as technologies later move from niche to mainstream (Hanna and Victor 2021).

The third stage, *diffusion*, is where niche technologies become mainstream, with accelerating diffusion rates (see Chapter 1, Sections 1.7 and 16.4), and is marked by changes to the socio-technical "regime", including infrastructure networks, value chains, user practices, and institutions. This stage is often the most visible and turbulent, because more widespread adoption of a new technology gives rise to structural changes in institutions and actors' behaviour (e.g. increased adoption of smart phones to new payment systems and social media), and because when incumbent market actors become threatened, they often contest policies promoting the new technologies (Köhler et al. 2019). In the diffusion stage, policy emphasis is shifted from financial support during the early adoption stage, towards supporting regime-level factors needed to sustain, or cope with, rapid and widespread diffusion (Markard 2018). These factors and policies are context specific. For example, Patt et al. (Patt et al. 2019) document that the policies needed to expand residential charging networks for electric vehicles depend on the local structure of the housing market.

The fourth stage is *stabilisation*, in which the new technologies, systems, and behaviours are both standardized and insulated from rebound effects and backsliding (Andersen and Gulbrandsen 2020). Sectoral bans on further investment in high carbon technologies may become politically feasible at this point (Breetz et al. 2018; Economidou et al. 2020). The decline of previously dominant products or industries can lead to calls for policy-makers to help those negatively affected, enabling a just transition (Newell and Simms 2020; McCauley and Heffron 2018). Political opposition to the system reconfiguration that comes with integration and stabilization can also be overcome by offering incumbent actors an attractive exit strategy (de Gooyert et al. 2016).

Because different sectors are at different stages of low-carbon transitions, and because the barriers that policies need to address are stage- and often context-specific, effective policies stimulating socio-technical transitions operate primarily at the sectoral level (Victor et al. 2019). This is particularly the case during early adoption, where economic barriers predominate; during diffusion, policies that address regime-level factors often need to deal with cross-sectoral linkages and coupling, such as those between power generation, transportation, and heating (Patt 2015; Bloess 2019; Fridgen et al. 2020). The entire cycle can take multiple decades. However, later stages can go faster by building on the earlier stages' having taken place elsewhere. For example, early RD&D into wind energy took place primarily in Denmark, was followed by early adoption in Denmark, Germany, and Spain, before other countries, including the United States, India, and China leapfrogged directly to the diffusion stage (Lacal-Arántegui 2019; Chaudhary et al. 2015; Dai and Xue 2015). A similar pattern played out for solar power (Nemet 2019b). International cooperation, geared towards technology transfer, capacity and institution-building, and finance, can help ensure that developing countries leapfrog to low-carbon technologies that have undergone commercialization elsewhere (Adenle et al. 2015; Fankhauser and Jotzo 2018)(see also Chapter 5, Box 5.9, Chapter 15, Section 15.5 and Section 16.5 in this chapter)..

This report contains numerous examples of the positive feedbacks in the centre of Cross-Chapter Box 12, Figure 1, predominantly arising during the early adoption and diffusion stages, and leading to rapid or unexpected acceleration of change. Public acceptance of alternatives for meat leads to firms improving the products, increasing political and economic feedbacks (Chapter 5, Section 5.4, Box 5.5). Declining costs in solar and wind cause new investment in the power generation sector being dominated by those technologies, leading to increased political support and further cost reductions (Chapter 6). In buildings (Chapter 9) and personal mobility (Chapter 10), low-carbon heating systems and electric passenger vehicles are gaining public acceptance, leading to improved infrastructure and human resources, more employment in those sectors, and behavioural contagion. Some have argued that technologies cross societal tipping points on account of these feedbacks (Obama 2017; Sharpe and Lenton 2021).

Dynamics between enabling conditions for system transitions: Abson et al. (2017) argue that it is possible to make use of "leverage points" inherent in system dynamics in order to accelerate sustainability transitions. Otto et al. (2020b) argue that interventions geared towards the social factors driving change can "activate contagious processes" leading towards the transformative changes required for climate mitigation. These self-reinforcing dynamics involve the interaction of enabling conditions including public policy and governance, institutional and technological innovation capacity, behaviour change, and finance. For example, Mercure et al. (2018) simulated financial flows into fossil-fuel extraction, and showed how investors' taking into account transition risk in combination with technological innovation would lead to the enhancement of investments in low-carbon assets and further enhanced innovation. As another example, behaviour, lifestyle, and policy can also initiate demand-side transitions (Chapter 5) (Tziva et al. 2020), such as with food systems (Rust et al. 2020) (Chapter 7, section 7.4.5), and can contribute to both resilience and carbon storage (Sendzimir et al. 2011) (Chapter 16, Box 16.5).

In the urban context, the concept of sustainability experiments has been used to examine innovative policies and practices adopted by cities that have significant impact on transition towards low-carbon and sustainable futures (Bai et al. 2010; Castán Broto and Bulkeley 2013). Individual innovative practices can potentially be upscaled to achieve low-carbon transition in cities (Peng and Bai 2018), leading to a process of broadening and scaling innovative practices in other cities (Peng et al. 2019). Such sustainability experiments give rise to new actor networks, which in some cases may accelerate change, and in others may lead to conflict (Bulkeley et al. 2014). As in the diffusion phase in Cross-Chapter Box 12, Figure 1, contextual factors play a strong role. Examining historical transitions to cycling across European cities, Oldenziel et al. (2016) found contextual factors including specific configurations of actors to lead to very different outcomes. Kraus and Koch (2021) found a short-term social shock – the COVID crisis – to lead to differential increases in cycling behaviour, contingent on other enabling conditions.

Linking system dynamics to development pathways and broader societal goals: Transition dynamics insights can be broadened to shifting development pathways. Development paths are characterised by particular sets of interlinking regime rules and behaviours, including inertia and cascading effects over time, and are reinforced at multiple levels, with varied capacities and constraints on local agency occurring at each level (Burch et al. 2014)(See also Cross-Chapter Box 5 in Chapter 4). This is also observed by Schot and Kanger (2018), who identify a needed change in a "meta-regime", crossing sectoral lines in linking value-chains or infrastructure and overall development objectives. In the context of the UN climate change regime, international cooperation can bring together such best practices and lessons learnt (Pandey et al. 2021; Adenle et al. 2015). This is especially relevant for developing countries, which often depend on technologies and financial resources from abroad, witnessing their pace and direction influenced by transnational actors (Bhamidipati et al. 2019; Marquardt et al. 2016), and benefiting little in terms of participating in high value-added activities (Whittaker et al. 2020).

System transitions differ according to context, such as across industrialized and developing countries (Ramos-Mejía et al. 2018), and within countries. Lower levels of social capital and trust negatively impact niche commercialization (Lepoutre and Oguntoye 2018). In contexts of poverty and inequality, stakeholders' – including users' – capabilities for meaningful participation are limited and transition outcomes can end up marginalizing or further excluding social groups (Osongo and Schot 2017; Hansen et al. 2018). Many studies of transitions in developing countries make note of the importance of innovation in the informal sector (Charmes 2016, Box 5.10). Facilitating informal sector access to renewable energy sources, safe and sustainable buildings, and finance can advance low-carbon transitions (McCauley et al. 2019; Masuku and Nzewi 2021). Contrary, disregarding its importance can result in misleading or ineffective innovation and climate strategies (Maharajh and Kraemer-Mbula 2010; Mazhar and Ummad 2014; de Beer et al. 2016; Masuku and Nzewi 2021).

Policies shifting innovation in climate-compatible directions can also reinforce other development benefits, for instance better health, increased energy access, poverty alleviation and economic competitiveness (Deng et al. 2018b; Karlsson et al. 2020; IPCC 2018a). Development benefits, in turn, can create feedback effects that sustain public support for subsequent policies and hence help to secure effective long-term climate mitigation (Meckling et al. 2015b; Geels 2014b; Schmidt and Sewerin

2017b; Breetz et al. 2018), increasing legitimacy of environmental sustainability actions (Hansen et al. 2018; van Welie and Romijn 2018; Herslund et al. 2018) and addressing negative socio-economic impacts (Eisenberg 2019; McCauley and Heffron 2018; Henry et al. 2020a; Deng et al. 2018b).

Summary and gaps in knowledge: Strategies to accelerate climate mitigation can be most effective at accelerating and achieving transformative change when they are synchronized with transition processes in systems. They address technological stage characteristics, take advantage of high-leverage intervention points, and respond to societal dynamics (Abson et al. 2017; Köhler et al. 2019; Geels et al. 2017). Gaps in knowledge remain on how to tailor policy mixes, the interaction of enabling conditions, the generalizability of socio-technical transition insights to other types of systems, and how to harness these insights to better shift development pathways.

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16.6.2 Sustainable development and technological innovation: Synergies, trade-offs and governance

16.6.2.1 Synergies and trade-offs

Policies that shift innovation in climate compatible directions can promote other development benefits, for instance better health, increased energy access, poverty alleviation and economic competitiveness (Deng et al. 2018a, see also Cross-Chapter Box 12). Economic competitiveness co-benefits can emerge as climate mitigation policies trigger innovation that can be leveraged for promoting industrial development, job creation and economic growth, both in terms of localizing low-emission energy technologies value chains as well as of increased energy efficiency and avoided carbon lock-ins (Section 16.4). However, without adequate capabilities, co-benefits at the local level would be minimal, and they would probably materialize far from where activities take place (Vasconcellos and Caiado Couto 2021; Ockwell and Byrne 2016). Innovation and technological change can also empower citizens. Grass-roots innovation promotes the participation of grass-roots actors, such as social movements and networks of academics, activists and practitioners, and facilitate experimenting with alternative forms of knowledge creation (UNCTAD 2019; Seyfang and Smith 2007). Examples of ordinary people and entrepreneurs adopting and adapting technologies to local needs to address locally defined needs have been documented in the development literature (van Welie and Romijn 2018) (See also Box 16.10). Digital technologies can empower citizens and communities in decentralized energy systems contributing not only to a more sustainable but also to a more democratic and fairer energy system (Van Summeren et al. 2021) (See also Cross-Chapter Box 11 in this chapter, and Section 5.4 in Chapter 5).

Therefore, even though STI is an explicit focus of SDG 9, it is in fact an enabler of most SDGs (UNCTAD 2019). Striving for synergies between innovation and technological change for climate change mitigation with other SDGs can help to secure effective long-term climate mitigation, as development benefits can create feedback effects that sustain public and political support for subsequent climate mitigation policies (Meckling et al. 2015a; Geels 2014a, also Cross-Chapter Box 12). However, innovation is not always geared to sustainable development, for instance, firms tend to know how to innovate when value chains are left intact (Hall and Martin 2005), which tend to not be the case in systemic transitions.

A comprehensive study of these effects distinguishes among "…anticipated-intended, anticipated-unintended, and unanticipated-unintended consequences" (Tonn and Stiefel 2019). Theoretical and empirical studies have demonstrated that unintended consequences are typical of complex adaptive systems, and while a few are predictable, a much larger number are not (Sadras 2020). Even when unintended consequences are unanticipated, they can be prevented through actor responses, for instance rebound effects following the introduction of energy efficient technologies. Other examples of unintended consequences include worse-than-expected physical damage to infrastructure and resistance from communities in the rapidly growing ocean renewable energy sector (Quirapas and Taeihagh 2020), and gaps between expected and actual performance of building integrated photovoltaic (BIPV) technology (Boyd and Schweber 2018; Gram-Hanssen and Georg 2018). In the agricultural sector, new technologies and associated practices that target the fitness of crop pests have been found to favour resistant variants. Unintended consequences of digitalisation are reported as well (Lynch et al. 2019) (see Cross-Chapter Box 11 in this chapter).

Innovation and climate mitigation policies can also have negative socio-economic impacts and not all countries, actors and regions around the world benefit equally from rapid technological change (UNCTAD 2019; Eisenberg 2019; McCauley and Heffron 2018; Henry et al. 2020b; Deng et al. 2018a). In fact, socio-technical transitions often create winners and losers (Roberts et al. 2018). Technological change can reinforce existing divides between women and men, rural and urban populations, and rich and poor communities, as older workers displaced by technological change will not qualify for jobs if they were unable to acquire new skills, weak educational systems may not prepare young people for emerging employment opportunities, and disadvantaged social groups, including women in many countries, often have fewer opportunities for formal education (UNCTAD 2019; McCauley and Heffron 2018). That is a risk regarding technological change for climate change mitigation, as emerging evidence suggests that the energy transition can create jobs and productivity opportunities in the renewable energy sector, but will also lead to job losses in fossil fuel and exposed sectors (Le Treut et al. 2021). At the same time these new jobs may use more intensively high-level cognitive and interpersonal skills compared to regular, traditional jobs, requiring higher levels of human capital dimensions such as formal education, work experience and on-the-job training (Consoli et al. 2016). Despite the empowerment potentials of decentralized energy systems, not all societal groups are equally positioned to benefit from energy community policies, with issues of energy justice taking place within initiatives, between initiatives and related actors, as well as beyond initiatives (van Bommel and Höffken 2021; Calzadilla and Mauger 2018).

The opportunities and challenges of technological change can also differ within country regions and between countries (e.g. Garcia-Casals et al. 2019). Within countries, Vasconcellos and Caiado Couto (2021) show that, in the absence of policies and capacity building activities which promote local recruiting, a significant part of total benefits of wind projects, especially high-income jobs and high value-added activities, is captured by already higher income regions. Between countries, developing countries usually have lower innovation capabilities, which means they need to import low-emission technology from abroad and are also less able to adapt these technologies to local conditions and create new markets and business models. This can lead to external dependencies and limit opportunities to leverage economic benefits from technology transfer (Section 16.5.1).

This means that in countries below the technological frontier, the contribution of technological change to climate change mitigation can happen primarily through the adoption and less through the development of new technologies, which can reduce potential economic and welfare benefits from rapid technological change (UNCTAD 2019). The adoption of consumer ICT technologies (Baller et al. 2016) or renewable energy technologies (Lema et al. 2021) cannot bring least developed economies close to the technological frontier without appropriate technological capabilities in other sectors and an enabling innovation system (UNCTAD 2019; Malhotra et al. 2021; Vasconcellos and Caiado Couto 2021; Sagar and Majumdar 2014; Ockwell and Mallett 2012; Ockwell et al. 2018). It has been argued widely that both hard and soft infrastructure, as well as appropriate policy frameworks and capability building, would facilitate developing countries engagement in long-term technological innovation and sustainable industrial development, and eventually in achieving the SDGs (UNCTAD 2019; Ockwell and Byrne 2016; Altenburg and Rodrik 2017).

16.6.2.2 Challenges to governing innovation for sustainable development

Dominant economic systems and centralized governance structures continue to reproduce unsustainable patterns of production and consumption, reinforcing many economic and governance structures from local through national and global scales (Johnstone and Newell 2018). Technological change, as an inherently complex process (Funtowicz 2020), poses governance challenges (Bukkens et al. 2020) requiring social innovation (Repo and Matschoss 2019) (See also Section 5.6 in Chapter 5, and Chapter 13).

Prospects for effectively governing SDG-oriented technological transformations require at a minimum balanced views and new tools for securing the scientific legitimacy and credibility to connect public policy and technological change in our society (Sadras 2020; Jasanoff 2018). Many frameworks of governance have been proposed, such as reflexive governance (Voss et al. 2006), polycentric governance (Ostrom 2010), collaborative governance (Bodin 2017), adaptive governance (Munene et al. 2018) and transformative governance (Rijke et al. 2013; Westley et al. 2013) (see also Chapters 13 and 14).

A particular class of barriers to the development and adoption of new technologies comprises entrenched power relations dominated by vested interests that control and benefit from existing technologies (Chaffin et al. 2016; Dorband et al. 2020). Such interests can generate balancing feedbacks within multi-level social-technological regimes that are related to technological lock-in, including allocations of investment between fossil and renewable energy technologies (Unruh 2002; Sagar et al. 2009; Seto et al. 2016).

Weaker coordination and implementation capacity in some developing countries can undermine ability to avoid trade-offs with other development objectives, like reinforced inequalities or excessive indebtedness and increased external dependency, and can limit the potential of leveraging economic benefits from technologies transferred from abroad (Section 16.5, Cross-Chapter Box 12). Van Welie and Romijn (2018) show that in a low-income setting the exclusion of some local stakeholders from the decision-making process may undermine sustainability transitions efforts. Countries with high levels of inequality can be more prone to elite capture, non-transparent political decision making processes, relations based on clientelism and patronage, and no independent judiciary (Jasanoff 2018), although in particular contexts, non-elites manage to exert influence (Moldalieva and Heathershaw 2020). The dominance of incumbents however implies that sustainable technological transitions could be achieved without yielding any social and democratic benefits (Hansen et al. 2018). In the cultural domain, a recurrent policy challenge that has been observed in most countries is the limited public support for development and deployment of low carbon technologies (Bernauer and McGrath 2016). The conventional approach to mobilizing such support has been to portray technological change as a means of minimizing climate change. Empirical studies show that simply reframing climate policy is highly unlikely to build and sustain public support (Bernauer and McGrath 2016).

Finally, there is a link between social and technological innovation; any innovation is grounded in complex socio-economic arrangements, to which governance arrangements would need to respond (see Sections 5.5 and 5.6, Chapter 13, and Cross-Chapter Box 12 in this chapter). Social innovation can contribute to maximizing synergies and minimizing trade-offs in relation to technological innovation and other innovative practices, but for this to materialize, national, regional and local circumstances need to be taken into account and, if needed, changed. Even in circumstances of high capabilities, the extent social innovation might help to promote synergies and avoid trade-offs is not easy to evaluate (Grimm et al. 2013).

16.6.3 Actions that maximise synergies and minimise trade-offs between innovation and sustainable development

Technological innovation may bring significant synergy in pursuing sustainable development goals, but it may also create challenges to the economy, human well-being, and the environment (Thacker et al. 2019; Schillo and Robinson 2017; Walsh et al. 2020). The degree of potential synergies and trade-offs among SDG differs from country to country and over time (see section 16.6.1.1). These potentials will depend upon available resources, geographical conditions, development stage and policy measures. Even though synergies and trade-offs related to technological innovation have received the least attention from researchers (Deng et al. 2018a), literature show that higher synergy was found where countries' policies take into account the linkages between sectors (Mainali et al. 2018). For technology innovation to be effective in enhancing synergies and reducing trade-offs, its role and nature in production and consumption patterns, as well as in value chains and in the wider economy, requires clarification. Technology ownership and control together with its current orientation and focus towards productivity needs to be revised if a meaningful contribution to the implementation of the SDGs in a transformative way is to be achieved (Walsh et al. 2020). Responsible innovation, combining anticipation, reflexivity, inclusion and responsiveness, has been suggested as a framework for conducting innovation (Stilgoe et al. 2013). Also inclusive innovation (Hoffecker 2021) could make sure that unheard voices and interests are included in decision-making, and methods for this have been implemented in practice (Douthwaite and Hoffecker 2017).

There are several examples on how to maximize synergies and avoid or minimize trade-offs when bringing technological innovation to the ground. When implementing off-grid solar energy in Rwanda, synergies were found between 80 of the 169 SDG targets, demonstrating how mainstreaming off-grid policies and prioritising investment in the off-grid sector can realise human development and well-being, build physical and social infrastructures, and achieve sustainable management of environmental resources (Bisaga et al. 2021). Another example is related to wind power in Northeast of Brazil where the creation of direct and indirect jobs has been demonstrated in areas where capabilities are high, as well as associated improvements in wholesale and retail trade and real estate activities, though this also emphasises the need for capacity development along with international collaboration projects (Vasconcellos and Caiado Couto 2021). Other examples are studies raising awareness on solar energy and women empowerment (Winther et al. 2018) and recycling and waste (Cross and Murray 2018).

Other actions with the potential to maximize synergies are those related to community or "grassroot" technological innovation. The importance of the link between technological innovation and community action and its contribution to sustainable development is usually underestimated, and requires further research and, most importantly, its inclusion in the political agenda on sustainable development (Seyfang and Smith 2007). On the other hand, when technological innovation occurs far from where is implemented and participation in the production, and hence training activities of local actors is minimal, co-benefits and synergies among SDGs are limited and usually far below expectations (Vasconcellos and Caiado Couto 2021; Bhamidipati and Hansen 2021). Actions by policymakers that safeguard environmental and social aspects can boost synergies and maximize those co-benefits (Lema et al. 2021). Given that technological change impacts countries, regions and social groups differently, just transition policies can be designed to ensure all regions and communities are able to take advantage of the energy and other transitions (Henry et al. 2020b; McCauley and Heffron 2018).

Box 16.10 provides insights on how a systemic approach to technological innovation can contribute to reconcile synergies and trade-offs to achieve sustainable development and mitigation goals.

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Box 16.10 Agroecological approaches: the role of local and indigenous knowledge and innovation

Major improvements in agricultural productivity have been recorded over recent decades (FAO 2018a). However, progress has also come with social and environmental costs, high levels of greenhouse gas emissions and rising demand for natural resources (UNEP 2017; Bringezu 2019; UNEP 2013; Díaz et al. 2019; FAO 2018a).

Trend analysis indicate that, of global demand for land, a large share is projected to be supplied by South America, in particular the Amazon (Lambin and Meyfroidt 2011; TEEB 2018) and Chaco forests (Grau et al. 2015). In developing countries, land use change for satisfying international meat demand is leading to deforestation. In Brazil, the amount of GHG emitted only by the beef cattle sector represents 65% of the emissions of the agricultural sector and 15% of the overall emissions of the country (May 2019).

Agricultural and food systems are complex and diverse; they include traditional food systems, mixed food systems and modern food systems (Pengue et al. 2018). Multiple forms of visible and invisible flows of natural resources exist in global food systems (Pascual et al. 2017; IPBES 2019; TEEB 2018).

Technological practices, management and changes in the food chain could help adapt to climate change, reduce emissions and absorb carbon in the soils, thus contributing to carbon dioxide removal (IPCC, 2018, 2019). A range of technologies can be implemented, from highly technological options such as transgenic crops resistant to drought (González et al. 2019), salt or pesticides resistance (OECD 2011b; Kim and Kwak 2020) or smart and 4.0 agriculture (Klerkx et al. 2019), to more frugal, low-cost technologies such as agroecological approaches adapted to local circumstances (Francis et al. 2003; FAO 2018b). These agroecological approaches are the subject of this box.

For developing countries, agroecological approaches could tackle both climate change challenges and food security (WGII-report, Chapter 5, Box 5.10). In SIDSs, they support livelihoods to develop local food value chains can promote sustainable management of natural resources, preserve biodiversity and help build resilience to climate change impacts and natural disasters (FAO 2019). Other advantages of agroecological practices include their adaptation to different social, economic and ecological environments (Altieri and Nicholls 2017), the fact that they are physical and financial capital-extensive, and are well-integrated with the social and cultural capital of rural territories and local resources (knowledge, natural resources, etc.), without leading to technological dependencies (Côte et al. 2019).

Agroecology is a dynamic concept that has gained prominence in scientific, agricultural and political discourses in recent years (Wezel et al. 2020; Anderson et al. 2021) (Chapter 7 - Agroecology (including Regenerative Agriculture); Chapter 5 WGII Box 5.10). There are different agroecological approaches, three of which will be briefly discussed here: agroecological intensification, agroforestry and biochar use in rice paddy fields.

Agricultural intensification provides ways to use land, water and energy resources to ensure adequate food supply while also addressing concerns about climate change and biodiversity (Cassman and Grassini 2020). The term ecological intensification (Tittonell 2014) focuses on biological and ecological processes and functions in agroecosystems. In line with the development of the concept of agroecology, agroecological intensification integrates social and cultural perspectives (Wezel et al. 2015). Agroecological intensification (Mockshell and Villarino 2019) for sub-Saharan Africa aims to address both employment and food security challenges (Pretty et al. 2011; Altieri et al. 2015).

Another example of an agroecological approach is agroforestry. Agroforestry provides examples of positive agroecological feedbacks, such as ‘the regreening of the Sahel’ in Niger. The practice is based on the assisted natural regeneration of trees in cultivated fields, an old method which was slowly dying out but which innovative public policies (the transfer of property rights over trees from the state to farmers) helped restore (Sendzimir et al. 2011).

Rice paddy fields are a major source of methane. Climate change impacts and adaptation strategies can affect rice production and net income of rice farmers. Biochar use in rice paddy fields has been advocated as a potential strategy to reduce GHG emissions from soils, enhance soil carbon stocks and nitrogen retention, and improve soil function and crop productivity (Mohammadi et al. 2020).

Contributions of indigenous people (Díaz et al. 2019), heritage agriculture (Koohafkan and Altieri 2010) and peasants agroecological knowledge (Holt-Giménez 2002) to technological innovation offer a wide array of options for management of land, soils, biodiversity and enhanced food security without depending on modern, foreign agricultural technologies (Denevan 1995). In farming agriculture and food systems, innovation and technology based on nature could help to reduce climate change impacts (Griscom et al. 2017). Evidence suggests that there are benefits to integrating tradition with new technologies in order to design new approaches to farming, and that these are greatest when they are tailored to local circumstances (Nicholls and Altieri 2018).

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16.6.4 Climate change, sustainability development and innovation

This section gives a synthesis of this chapter on innovation and technology development and transfer, connecting it to sustainable development.

In conjunction with other enabling conditions, technological innovation can support system transitions to limit warming, help shift development pathways, and bring about new and improved ways of delivering goods and services that are essential to human well-being *(high confidence)*. At the same time, however, innovation can result in trade-offs that undermine both progress on mitigation and progress towards other sustainable development goals. Trade-offs include negative externalities such as environmental impacts and social inequalities, rebound effects leading to lower net emission reductions or even increases in emissions, and increased dependency on foreign knowledge and providers *(high confidence)*. Digitalisation, for example, holds both opportunity for emission reduction and emission-saving behaviour change, but at the same time causes significant environmental, social and GHG impacts *(high confidence)*.

A systemic view of innovation, that takes into account the roles of actors, institutions, and their interactions, can contribute to both enhanced understanding of processes and outcomes of technological innovation, and to interventions and arrangements that can help innovation. It can also play a role in clarifying the synergies and trade-offs between technological innovation and the SDGs. Effective governance and policy, implemented in an inclusive, responsible and holistic way, could both make innovation policy more effective, and avoid and minimise misalignments between climate change mitigation, technological innovation, and other societal goals *(medium evidence, high agreement)*.

A special feature is the dynamics of transitions. Like other enabling conditions, technological innovation plays both a balancing role, by inhibiting change as innovation strengthens incumbent technologies and practices, and a reinforcing role, by allowing new technologies and practices to disrupt the existing socio-technical regimes *(high confidence)*. Appropriate innovation policies can help organise innovation systems better, while other policies (technology push and demand pull) can provide suitable resources and incentives to support and guide these innovation systems towards societally-desirable outcomes, ensure the innovations are deployed at scale, and direct these dynamics not just towards system transitions for climate change mitigation, but also towards addressing other SDGs. This means taking into account the full life-cycle or value chain as well as analysis of synergies and trade-offs.

Against this backdrop, international cooperation on technological innovation is one of the enablers of climate action in developing countries on both mitigation and adaptation *(high confidence)*. Experiences with international cooperation on technology development and deployment suggest that such activities are most effective when approached as "innovation cooperation" that engenders a holistic, systemic view of innovation requirements, is done in equitable partnership between donors and recipients, and develops local innovation capabilities *(medium evidence, high agreement)*.

Chapter 17, in particular Section 17.4, connects technological innovation with other enabling conditions, such as behaviour, institutional capacity and multi-level governance, to clarify the actions that could be taken, holistically and in conjunction, to strengthen and accelerate the system transitions required to limit warming to be in line with the Paris Agreement and to place countries in sustainable development pathways.

16.7 Knowledge gaps

Filling gaps in literature availability, data collection, modelling, application of frameworks and further analysis in several sectors will improve knowledge on innovation and technology development and transfer, including R&D to support policy making in climate change mitigation as well as adaptation. These policies and related interventions need to benefit from data and methodologies for the ex-post evaluation of their effectiveness.

This section addresses identified knowledge gaps related to what extent developing countries are represented in studies on innovation and technology development and transfer; to national contexts and local innovation capacity; to potential and actual contributions of businesses; to literature emphasis on mitigation; to indicators to assess innovation systems; to non-technical barriers for the feasibility of decarbonisation pathways; to the role of domestic IPR policy; to digitalisation in low-emissions pathways; to the compliance of Paris Agreement in regard to technology and capacity building.

One of knowledge gap identified when assessing the literature is on the representation of developing countries in studies on innovation and technology development and transfer. This includes the conceptual core disciplines of the economics of innovation, innovation systems and sustainability transitions. This goes both for studies on developing countries, and for authors originating from, or active in, developing countries contexts. The evidence of the impact of decarbonisation policy instruments applied to developing countries or SIDS is limited. Expanding the knowledge base with studies with a focus on developing countries would not only allow for testing whether the theories (developed by predominantly by developed-country researchers for industrialised countries) hold in developing country contexts, but also yield policy insights that could help both domestic and international policymakers working on climate-related technology cooperation.

While a growing literature has shown how technology characteristics and complexity, national context and innovation capacity can influence the capacity of a country's innovation ecosystem as a result of incentive and attraction policies, more research is needed to help prioritise and design policies in different national contexts while filling important knowledge gaps regarding the impact of "green" public procurement, lending, "green" public banking and building code policies on innovation outcomes.

There is also a superficial understanding of the potential and actual contributions of businesses, educational institutions and socially responsible programmes, particularly in developing countries, as sources of innovation and early adopters of new technologies, and a notable lack of knowledge about indigenous practices.

Besides the strong bias of literature to studies originating from and based on developed countries, innovation and technology literature is also skewed to mitigation, and within mitigation to energy. Literature on technology innovation for adaptation is largely missing.

In the area of innovation studies, data are limited on the different indicators used to assess the strength of the innovation system, even for energy, including global figures on R&D and demonstration spending, also for developing countries, and their effectiveness. There is also a lack of a comprehensive framework and detailed data to assess the strengths of low-emission innovation systems, including interactions among actors, innovation policy implementation, and strength of institutions.

Another gap in knowledge remains between the results from energy-climate-economy models and those emerging from systems transition and sustainability transition approaches, empirical case studies, and the innovation system literature. If this gap is filled, the understanding of the feasibility of decarbonisation pathways in light of the many non-technical barriers to technology deployment and diffusion could be improved.

In the field of policy instruments, existing evaluations provide insufficient evidence to assess the impact of decarbonisation policy instruments on innovation, as these evaluations mainly focus on environmental or technological effects. The potential positive or negative role of domestic IPR policy in technology transfer to least developed countries remains unclear as the literature does not show agreement. Moreover, gaps remain in impact evaluations of sub-national green industrial policies, which are of growing importance. The interaction between subnational and national decarbonisation policies to advance innovation would also benefit from further research, particularly in developing countries.

The understanding of the role of digitalisation in decarbonisation pathways is lacking and needs to be studied from several angles. Existing studies do not sufficiently take into account knowledge on the energy impact of digital technologies, in particular the increase in energy demand by digital devices, and the increase in energy efficiency. They would benefit from being technology/sector/country-specific.

The way in which digitalisation will influence the framework conditions under which decarbonisation will occur, the socio-economic and behavioural barriers influencing the diffusion of technologies in the long-term scenarios and the relationship with society and its effects need to be further explored.

Given the implications of the digital revolution for sustainability, a better characterisation of governance aspects would increase understanding of the implications and possibilities of digitalisation and other GPTs for policymakers.

Relatedly, research (both theoretical and empirical) on the impacts of imitation, or adaptation of new technological solutions invented in one region and used in other regions, could fill knowledge gaps, in order to accelerate the diffusion of climate-related technologies, while taking care not to reduce the incentive for inventors to invest in the search for new solutions.

Lastly, an independent assessment about the compliance of the Paris Agreement with regard to technology and capacity building as means of implementation is starting under the Enhanced Transparency Framework for action and support, where a methodology of monitoring, reporting and verification are being developed. There is also a lack of analysis of the full landscape of international cooperation, of what is needed to meet the objectives of the UNFCCC and the Paris Agreement, and of its effectiveness.

Frequently Asked Questions (FAQs)

FAQ 16.1 Will innovation and technological changes be enough to meet the Paris Agreement objectives?

The Paris Agreement stressed the importance of development and transfer of technologies to improve resilience to climate change and to reduce greenhouse gas emissions. However, innovation and even fast technological change will not be enough to achieve Paris Agreement mitigation objectives. Other changes are necessary across the production and consumption system and the society in general, including behavioural changes.

Technological changes never happen in a vacuum, they are always accompanied by, for instance, people changing habits, companies changing value chains, or banks changing risk profiles. Therefore, technological changes driven by holistic approaches can contribute to accelerate and spread those changes towards the achievement of climate and sustainable development goals.

In innovation studies, such systemic approaches are said to strengthen the functions of technological or national innovation systems, so that climate-friendly technologies can flourish. Innovation policies can help respond to local priorities and prevent unintended and undesirable consequences of technological change, such as unequal access to new technologies across countries and between income groups, environmental degradation and negative effects on employment.

FAQ 16.2 What can be done to promote innovation for climate change and the widespread diffusion of low-emission and climate-resilient technology?

The speed and success of innovation processes could be enhanced with the involvement of a wider range of actors from the industry, research and financial communities working in partnerships at national, regional and international levels. Public policies play a critical role to bring together these different actors and create the necessary enabling conditions, including financial support through different instruments as well as institutional and human capacities.

The increasing complexity of technologies requires cooperation if their widespread diffusion is to be achieved. Cooperation includes the necessary knowledge flow between within and between countries and regions. This knowledge flow can take the form of exchanging experiences, ideas, skills, practices, among others.

FAQ 16.3 What is the role of international technology cooperation in addressing climate change?

Technologies that are currently known but not yet widely used need to be spread around the world, and adapted to local preferences and conditions. Innovation capabilities are required not only to adapt new technologies for local use but also to create new markets and business models. International technology cooperation can serve that purpose.

In fact, evidence shows that international cooperation on technology development and transfer can help developing countries to achieve their climate goals more effectively, and if this is done properly can also help addressing other sustainable development goals. Many initiatives exist both regionally and globally to help countries in achieving technology development and transfer through partnerships and research collaboration that include developed and developing countries, with a key role for technological institutions and universities. Enhancing current activities would help an effective, long-term global response to climate change, while promoting sustainable development.

Globalization of production and supply of goods and services, including innovation and new technologies, may open up opportunities for developing countries to advance technology diffusion; however, so far not all countries have benefited from the globalisation of innovation due to different barriers such as access to finance and technical capabilities. These asymmetries between countries in the globalization process can also lead to dependencies on foreign knowledge and providers.

Not all technology cooperation directly results in mitigation outcomes. Overall, technology transfer broadly has focused on enhancing climate technology absorption and deployment in developing countries as well as RD&D and knowledge spill-overs.

Paris Agreement also reflects this view by noting that countries shall strengthen cooperative action on technology development and transfer regarding two main aspects: 1) promoting collaborative approaches to research and development and 2) facilitating access to technology to developing country Parties.

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Chapter 17: Accelerating the transition in the context of sustainable development

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Date of Draft: 28/11/2021

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Executive summary

Accelerating climate actions and progress towards a just transition is essential to reducing climate risks and addressing sustainable development priorities, including water, food and human security *(robust evidence, high agreement)*. Accelerating action in the context of sustainable development involves not only expediting the pace of change (speed) but also addressing the underlying drivers of vulnerability and high emissions (quality and depth of change) and enabling diverse communities, sectors, stakeholders, regions and cultures (scale and breadth of change) to participate in just, equitable and inclusive processes that improve the health and well-being of people and the planet. Looking at climate change from a justice perspective means placing the emphasis on a) the protection of vulnerable populations and low income countries from the impacts of climate change, b) mitigating the effects of the transformations, and c) ensuring an equitable decarbonized world {17.1.1}.

While transition pathways will vary across countries, they are likely to be challenging in many contexts. (*robust evidence, high agreement*). Climate change is the result of decades of unsustainable production and consumption patterns (for example energy production and land-use), as well as governance arrangements and political economic institutions that lock in resource-intensive development patterns (*robust evidence, high agreement*). Reframing development objectives and shifting development pathways towards sustainability can help transform these patterns and practices, allowing space for transitions to transform unsustainable systems (*medium evidence, high agreement*). {17.1.1.2}.

Sustainable development can enhance sectoral integration and social inclusion (*robust evidence, high agreement*). Inclusion merits attention because equity within and across countries is critical to transitions that are not simply rapid but also sustainable and just. Resource shortages, social divisions, inequitable distributions of wealth, poor infrastructure and limited access to advanced technologies can constrain the options and capacities for developing countries to achieve sustainable and just transitions (*medium evidence, high agreement*) {17.1.1.2}.

Concrete actions aligning sustainable development and climate mitigation and partnerships can support transitions. Strengthening different stakeholders' "response capacities" to mitigate and adapt to a changing climate will be critical for a sustainable transition (*robust evidence, high agreement*). Response capacities can be increased by means of alignment across multiple stakeholders at different levels of decision-making. This alignment will also help achieve synergies and manage trade-offs between climate and sectoral policies by breaking down sectoral silos and overcoming the multiple barriers that prevent transitions from gaining traction and gathering momentum (*medium evidence, high agreement)* {17.1.1.1}.

Economics, psychology, governance and systems research have pointed to a range of factors that influence the speed, scale and quality of transitions (*robust evidence, high agreement*). Views nonetheless differ on how much market-correcting policies, shift preferences (economics) and shifts in individual and collective mindsets (psychology) and multi-level governance arrangements and inclusive political institutions (governance) contribute to system transitions (*medium evidence, high agreement*) {17.2}.

While economics, psychology, governance and systems thinking emphasize different enablers of transitions, they often share a view that strengthening synergies and avoiding trade-offs between climate and sustainable development priorities can overcome barriers to transitions (*medium evidence, high agreement*). A growing body of research and evidence can show which factors in the views from economics, psychology, governance and systems affect how interrelationships are managed between climate, mitigation policies and sustainable development. Greater integration between studies based on different methodological approaches can show how to construct an enabling environment that increases the feasibility and sustainability of transitions {17.2, 17.3 and 17.4}.

Short- and long-term studies of transformations using macroeconomic models and integrated assessment models (IAMs) have identified synergies and trade-offs of mitigation options in the context of development pathways that align sustainable development and climate change (*robust evidence, high agreement*). IAMs often look at climate change mitigation and SDGs in an aggregate manner: supplementing this aggregate view with detail-rich studies involving SDGs can build support for transitions within and across countries (*medium evidence, medium agreement*). {17.3.2}.

The impacts of climate-change mitigation and adaptation responses, are highly context-specific and scale-dependent. There are synergies and trade-offs between adaptation and mitigation as well as synergies and trade-offs with sustainable development(*robust evidence, high agreement*). A strong link exists between sustainable development, vulnerability and climate risks, as limited economic, social and institutional resources often result in low adaptive capacities and high vulnerability, especially in developing countries. Resource limitations in these countries can similarly weaken the capacity for climate mitigation and adaptation. The move towards climate-resilient societies requires transformational or deep systemic change. This has important implications countries' sustainable development pathways *(medium evidence, high agreement)* {17.3.3.6}.

Sectoral mitigation options present synergies with the SDGs, but there are also trade-offs, which can become barriers to implementation. Such trade-offs are particularly identified in relation to the use of land for bioenergy crops, water and food access, and competition for land between forest or food production (*robust evidence, high agreement*). Many industrial mitigation options, like efficiency improvements, waste management and the circular economy, have synergies with the SDGs relating to access to food, water and energy (*robust evidence, high agreement*). The promotion of renewable energy in some industrial sectors, can imply stranded energy supply investments, which need to be taken into consideration *(medium evidence, medium agreement)*. The Agriculture, Forestry, and Other Land Uses (AFOLU) sector offers many low-cost mitigation options, but actions aimed at producing bioenergy, extending food access and protecting biodiversity can also create trade-offs between different land-uses (*robust evidence, high agreement*). Some options can help to minimize these trade-offs, for example, integrated land management, cross-sectoral policies and efficiency improvements. Lifestyle changes, including dietary changes and reduced food waste, have several synergies with climate mitigation and the SDGs (*medium evidence, medium agreement*). Cross-sectoral policies are important in avoiding trade-offs, to ensure that synergies between mitigation and SDGs are captured, and to ensure local people are involved in the development of new products, as well as production and consumption practices. There can be many synergies in urban areas between mitigation policies and the SDGs, but capturing these depends on the overall planning of urban structures and on local integrated policies, where, for example, affordable housing and spatial planning as a climate mitigation measure are combined with walkable urban areas, green electrification and clean renewable energy. Such integrated options can also reduce the pressures on agricultural land by reducing urban growth, thus improving food security. Access to green electricity can also support quality education *(medium evidence, medium agreement).* {17.3.3, 17.3.3.1, 17.3.3.3}.

Digitalization could facilitate a fast transition to sustainable development and low-emission pathways by contributing to efficiency improvements, cross-sectoral coordination and a circular economy with new IT services and decreasing resource use (*low evidence, medium agreement*)**.** Several synergies with SDGs could emerge in terms of energy, food and water access, health and education, as well as trade-offs, for example, in relation to reduced employment, increasing energy demand and increasing demand for services, all implying increased GHG emissions. However, developing countries with limited internet access and poor infrastructure could be excluded from the benefits of digitalization *(medium evidence, medium agreement).* {17.3.3}.

Actions aligning sustainable development and climate mitigation and partnerships can support transitions. Strengthening different stakeholders' "response capacities" to mitigate and adapt to a changing climate will be critical for a sustainable transition (*robust evidence, high agreement*). Response capacities can be increased by means of alignment across multiple stakeholders at different levels of decision-making. This alignment will also help achieve synergies and manage trade-offs between climate and sectoral policies by breaking down sectoral silos and overcoming the multiple barriers that prevent transitions from gaining traction and gathering momentum (*medium evidence, high agreement)* {17.1.1.1}.

The landscape of transitions to sustainable development is changing rapidly, with multiple transitions already underway. This creates the room to manage these transitions in ways that prioritise the needs for workers in vulnerable sectors (land, energy) to secure their jobs and maintain secure and healthy lifestyles, especially as the risks multiply for those exposed to heavy industrial jobs and associated outcomes (*medium evidence, high agreement*). {17.3.2.3}. A just transition incorporates key principles, such as respect and dignity for vulnerable groups, the creation of decent jobs, social protection, employment rights, fairness in energy access and use, and social dialogue and democratic consultation with the relevant stakeholders, while coping with the effects of asset-stranding and the transition to green and clean economies *(medium evidence, medium agreement).* The economic implications of the transition will be felt especially strongly by developing countries, with high dependence on hydrocarbon products for revenue streams, as they will be exposed to reduced fiscal incomes given a low demand for oil and consequent fall in oil prices *(limited evidence, medium agreement).* {17.3.2}.

Countries with assets that are at risk becoming stranded may lack the relevant resources, knowledge, autonomy or agency to reorientate, or to decide on the speed, scale and quality of the transition (*limited evidence, medium agreement*). The urgency of mitigation might overshadow some of the other priorities related to the transition, like climate change adaptation and its inherent vulnerabilities. Consequently, the transition imperative could reduce the scope and autonomy for local priority-setting and could ignore the additional risks in countries with a low capacity to adapt. A just transition will depend on local contexts, regional priorities, the starting points of different countries in the transition and the speed at which they want to travel. Both mitigation and adaptation warrant urgent and prompt action given current and continuing greenhouse gas emissions and associated negative impacts on humanity and ecosystems. *(limited evidence, medium agreement).* {17.3.2}.

A wide range of factors have been found to enable sustainability transitions, ranging from technological innovations to shifts in markets, and from policies and governance arrangements to shifts in belief systems and market forces (*robust evidence, high agreement*). Many of these factors come together in a co-evolutionary process that has unfolded globally, internationally and locally over several decades (*low evidence, high agreement*). Those same conditions that may serve to impede the transition (i.e., organizational structure, behaviour, technological lock-in) can also 'flip' to enable both it and the framing of sustainable development policies to create a stronger basis and policy support (*robust evidence, high agreement*). It is important to note that strong shocks to these systems, including accelerating climate change impacts, economic crises and political changes, may provide crucial openings for accelerated transitions to sustainable systems. For example, re-building more sustainably after an extreme event, or renewed public debate about the drivers of social and economic vulnerability to multiple stressors *(medium evidence, medium agreement)* {17.4}.

Sustainable development and deep decarbonization will involve people and communities being connected through various means, including globally via the internet and digital technologies, in ways that prompt shifts in thinking and behaviour consistent with climate change goals (*medium evidence, medium agreement*). Individuals and organizations like institutional entrepreneurs can function to build transformative capacity through collective action (*robust evidence, high agreement)*, but private-sector entrepreneurs can also play an important role in fostering and accelerating the transitions to sustainable development (*robust evidence, medium agreement*). Ultimately, the adoption of coordinated, multi-sectoral policies targeting new and rapid innovation can help national economies take advantage of widespread decarbonization. Green industrial policies that focus on building domestic supply chains and capacities can help states prepare for the influx of renewable, CDR-methods, or mechanisms for carbon capture and storage (*medium evidence, medium agreement*){17.4.2}.

Accelerating the transition to sustainability will be enabled by explicit consideration being given to the principles of justice, equality and fairness. Interventions to promote sustainability transitions that account for local context (including unequal access to resources, capacity and technology) in the development process are necessary but not sufficient in creating a just transition (*low evidence, high agreement)*. {17.4.6}

17.1 Introduction

This chapter focuses on the opportunities and challenges for "accelerating the transition in the context of sustainable development." The chapter suggests that accelerating transitions in the context of sustainable development requires more than concentrating on speed. Rather, it involves expediting the pace of change (speed) while also removing the underlying drivers of vulnerability and high emissions (quality and depth) and aligning the interests of different communities, regions, sectors, stakeholders and cultures (scale and breadth). One key to enabling deep and broad transitions is integrating the views of different government agencies, businesses and non-governmental organizations (NGOs) in transition processes. Another critical driver of deep and broad transitions is engaging and empowering workers, youth, women, the poor, minorities and marginalized stakeholders in just, equitable and inclusive processes. The result of such processes will be the transformation of large-scale socioeconomic systems to restore the health and well-being of the planet and the people on it.

Section 17.1 begins by reviewing how climate and sustainability issues have been discussed in the Intergovernmental Process on Climate Change (IPCC), as well as international climate change and sustainable development processes at different levels. It further introduces key themes addressed in the chapter's remaining subsections. Section 17.2 provides an overview of how key theories understand transitions and transformation, and notes a shared concern over leveraging synergies and managing trade-offs between climate change and sustainable development across different disciplines. Section 17.3 provides an assessment of the mitigation options that can help achieve these synergies and avoid trade-offs. 17.4 pulls together the theoretical and empirical aspects by detailing the essential elements of an enabling environment that helps drive forward transitions that are quick, deep, broad and, ultimately, sustainable.

17.1.1 Integrating Climate Change and Sustainable Development in International Assessments

Climate change not only poses a profound challenge to sustainable development, it is inexorably linked to it. From the early stages of the IPCC assessment process, this challenge and the inherent link between climate change and sustainable development have been well recognized. For example, the First Assessment Report (FAR) highlighted the relevance of sustainable development for climate policy. The Second Assessment Report (SAR) went further to include equity issues in its presentation of sustainable development. The Third Assessment Report (TAR) (Banuri et al. 2001) made the link even stronger, noting that "parties have a right to and should promote sustainable development" (as stated in the text of the UNFCCC 2015 (Article 3.4)), and offering an early review of studies integrating sustainable development and climate change. The Fourth Assessment Report (AR4) (Sathaye et al. 2007) added an additional perspective to these interconnections, acknowledging the existence of a two-way relationship between sustainable development and climate change.

The Fifth Assessment Report (AR5) (Denton et al. 2014; Fleurbaey et al. 2014) and the Special Report on Global Warming of 1.5°C (IPCC 2018; Roy et al. 2018a) have arguably made the strongest links between climate and sustainable development to date. One of the key messages of AR5 was that the implementation of climate mitigation and adaptation actions could help promote sustainable development, and it emphasized the need for transformational changes in this regard. AR5 also concluded that the link between climate change and sustainable development is cross-cutting and complex, and that thus the impacts of climate change are threatening the efforts being made to achieve sustainable development. The IPCC special report on Global Warming of 1.5°C helped systematize these links by mapping the synergies and trade-offs between selected SDG indicators and climate mitigation (IPCC 2018; Roy et al. 2018b) (see also sect. 17.3).

Despite the clear links between sustainable development and climate change being recognised from the early stages of the IPCC, climate change has often been portrayed as an environmental problem to be addressed chiefly by environmental ministries (Brown et al. 2007; Munasinghe 2007; Swart and Raes 2007). However, this perception has evolved over time. It is now increasingly common to see governments and other actors understand the wider ramifications of a changing climate for sustainable development. In a growing number of studies, work on climate policies and just transitions towards sustainable development are framed as going hand in hand (Fuso Nerini et al. 2019; Dugarova and Gülasan 2017; Sanchez Rodriguez et al. 2018; Schramade 2017; Zhenmin and Espinosa 2019).

17.1.2 Integrating Climate Change and Sustainable Development in International Policymaking Processes

Among the reasons for the growing realization of these interdependencies are milestones in international climate and sustainable development processes. As outlined in Chapter 14, the year 2015 was a turning point due to two agreements: 1) the Paris Agreement; and 2) the 2030 Agenda on Sustainable Development and its seventeen Sustainable Development Goals (SDGs) (Farzaneh et al. 2021).

Following a long history of references to sustainable development in the UNFCCC and related agreements, the Paris Agreement helped to strengthen the links between climate and sustainable development by emphasizing that sustainability is related to its objectives (Sindico 2016; UNFCCC 2016). One of the ways that it helped tighten this link is by institutionalizing bottom-up pledges and the review architecture. Toward this end, the Paris Agreement instituted nationally determined contributions (NDCs) as vehicles through which countries make pledges and demonstrate their commitment to climate action. Although there was no clear guidance on what should be included in the NDCs, some of the requirements were elaborated in the Paris Rule Book (see above, Chapter 14). Some of the submitted NDCs included only mitigation efforts, but others set out mitigation and adaptation goals aligning NDC commitments to national planning processes, while yet others mentioned links with the SDGs.

Another way that the Paris Agreement and the NDCs could strengthen their links to sustainable development is to update country-specific climate pledges. Countries are free to choose their targets and the means and instruments with which to implement them. A core feature of the NDCs was that countries submit NDCs every five years, giving them an opportunity to assess themselves relative to other countries, raise their ambitions and learn from their peers. Moreover, it was emphasized that countries should not “backslide” in subsequent NDCs, thus ensuring that countries should always be forward-looking in respect of increasing their ambitions to deliver the Paris Goals. Höhne et al. (2017) found that, in developing countries especially, the NDC preparation process has improved national climate policy-making.

Despite some favourable reviews, several assessments of specific countries’ NDCs (Andries et al. 2017; Rogelj et al. 2016; Vandyck et al. 2016) have assessed that those submitted for 2020-2030 are insufficient for delivering on the Paris goals. Updated and/or new NDCs were therefore submitted by end of 2020. However, an assessment of those NDCs revealed that the level of ambition was significantly lower than the goals of the Paris Agreement (UNFCCO 2020; see also this Chapter). One of the urgent calls in Paris was to assess the impacts and efforts that need to be undertaken to keep global warming well below 2°C in relation to pre-industrial levels and evaluate related global greenhouse-gas emission pathways (UNFCCC 2015). Although the initial NDCs fell short of these goals, the idea was that NDCs would be living documents that could ratchet up climate action and ambition.

Countries have also started to take actions on the SDGs themselves (Antwi-Agyei et al. 2018a; UNDESA 2016, 2017, 2018). The SDGs were perceived as a novel approach to development and as establishing a universal agenda for the transformation of development patterns and socioeconomic systems. At their core, the SDGs hold that building an integrated framework for action necessitates addressing the economic, social and environmental dimensions of sustainable development in an integrated manner (Biermann et al. 2017; Kanie and Biermann 2017). The SDGs take multiple elements of development into account in aiming to offer coherent, well-integrated, overarching approaches to a range of sustainability challenges, including climate change.

One way a link is made between climate and the SDGs is through Voluntary National Reviews (VNRs). Paralleling the bottom-up orientation of the Paris Agreement and the NDCs, every year approximately forty countries voluntarily share their VNRs with the international community at the High-Level Political Forum (HLPF). Even more flexible than the NDCs, the VNRs can include content such as a summary of key policies and measures that are intended to achieve the SDGs, a list of the means of implementation that support the SDGs, and related challenges and needs. The VNRs also often cover SDG 13 (on climate change) as well as many other issues connected with climate change. Even with these links, implementation of the SDGs should be mentioned as part of national development processes reflecting different countries' different priorities, visions and plans (Hanson and Puplampu 2018; Marcotullio et al. 2018; OECD 2016; Puplampu et al. 2017; Srikanth 2018).

Yet another way that the 2030 Agenda for Sustainable Development underlines the importance of capturing synergies is its calls for policy coherence (goals 17 and 14). Policy coherence and integration between sectors are two of the most critical factors in breaking down the silo mode of working of different sectors. Working across climate and other sustainability agendas is essential to coherence.

A final way that the sustainability and climate agendas have been linked is through vertical integration. Following a similar trend that appeared with Agenda 21, for which many cities adopted local plans, a growing number of cities have introduced Voluntary Local Reviews. The VLRs resemble the VNRs, but place the emphasis on local actions and needs regarding the SDGs (and some links to climate change) (Ortíz-Moya et al. 2021). The 2019 SDG Report shows that 150 countries have developed national urban plans, almost half of them also being in the implementation phase (United Nations General Assembly 2019).

17.1.3 Integrating Climate Change and Sustainable Development in Other Policymaking Processes

Other non-UN-led initiatives involving international organizations or clusters of countries have also helped to raise the issue of sustainable development as a framework for mitigation. The OECD, for instance, assesses different types of investments and economic activities with reference to their significance for environmental sustainability (OECD 2020), while G20 countries have drawn up action agendas with sustainable development at the (UToronto 2016). Meanwhile, the Petersberg Climate Dialogue, a political movement convened by major country-group representatives launched in 2010 by the German government, has also called for sustainability to be an intrinsic part of the transition (UNFCCO 2020; BMU 2018).

Due in part to the shifting orientation of these international processes, there is growing evidence of action on climate change and sustainable development at other levels of decision-making. National policies often aim to implement climate change policies in the context of sustainable development (Chimhowu et al. 2019; Chirambo 2018; ECLAC 2017; Fuseini and Kemp 2015; Galli et al. 2018; Haywood et al. 2019; Ministry of Environment of Jordan 2016; McKenzie and Abdulkadri 2018; UNDESA 2016, 2017, 2018; UN Women 2017). Some countries are adjusting their existing policies to build on themes familiar to sustainable development (Lucas et al. 2016), including renewable energy and energy efficiency (Fastenrath and Braun 2018; Kousksou et al. 2015), urban planning (Gorissen et al. 2018; Loorbach et al. 2016; Mendizabal et al. 2018), health systems (Pencheon 2018; Roschnik et al. 2017) and agricultural systems (Lipper and Zilberman 2018; Shaw and Roberts 2017). Cross-cutting and integrated approaches, such as the circular economy, have also been gaining traction in some European countries (EESC 2015) and G20 countries (Noura et al. 2020). Many of these efforts have also extended up to the regional and down to the local level (Gorissen et al. 2018; Hess 2014; Shaw and Roberts 2017).

There has also been a shift to actors outside government aligning climate with sustainable development. An assessment by Hoyer (2020) found that collective action against climate change by businesses, governments and civil society, reinforced through partnerships and coalitions across departments, industries and supply chains, can deliver significant development impacts. In order for this diverse collection of stakeholders to take action, a fundamental paradigm shift is needed from a linear model of knowledge-generation to an interdisciplinary model that co-produces knowledge (Liu et al. 2019). In fact, some have argued that accelerating just transitions for purposes of sustainable development requires the involvement of several actors, institutions and disciplines (Delina and Sovacool 2018). Not only do these roles need to be discussed more thoroughly (Kern and Rogge 2016; den Elzen et al. 2019), but it is also important to survey different views on transitions and transformations. A variety of theories that are useful for explaining the causes and constraints regarding transitions are examined in Section 17.2.

17.2 Accelerating Transitions in the Context of Sustainable Development: Definitions and Theories

This section focuses on how different theoretical frameworks can help us understand and explain what is meant by accelerating transitions in the context of sustainable development. As suggested in sect. 17.1, the reference to "*in the context of sustainable development*" suggests that sustainable transitions require more than speed, also necessitating removing the underlying drivers of vulnerability and high emissions (quality and depth of transitions) while also aligning the interests of different individuals, communities, sectors, stakeholders and cultures (scale and breadth of transitions).

The outcome of sustainable transitions is a sustainable *transformation*. While transitions involve *processes that shift development pathways and reorient energy, transport, urban and other subsystems* (Loorbach et al. 2017; Chapter 16), transformation is the resulting *fundamental reorganization of large-scale socioeconomic systems* (Hölscher et al. 2018). Such a fundamental reorganization often requires dynamic multi-stage transition processes that change everything from public policies and prevailing technologies to individual lifestyles, and social norms to governance arrangements and institutions of political economy. This set of factors can lock in development pathways and prevent transitions from gathering the momentum needed for transformations. Chapter 16 (above) provides an overview of the multistage transition dynamics involved in moving from experimentation to commercialization to integration to stabilization. That overview describes how transitions can break through lock-ins and result in a transformation.

While there may be a relatively consistent set of transition dynamics for all countries, pathways are likely to vary across and even within countries. This variation is due to different development levels, starting points, capacities, agencies, geographies, power dynamics, political economies, ecosystems and other contextual factors. Given the diversity of contributing factors, a sustainable transition is likely to be a complex and multi-faceted process which cannot be reduced to a single dimension (Köhler et al. 2019). Even with this multi-dimensionality, transition processes are likely to gain speed and become more sustainable as decision-makers adopt targeted policies and other interventions. Many disciplines have reflected on the roles of and relative influence on the policies and interventions that can drive transitions. The following discussion describes this diversity of views with a survey of how prominent lines of economic, psychological, institutional and systems thinking explain transitions. Though these disciplines differ greatly, they often stress that leveraging synergies and managing trade-offs between climate change and sustainable development can help advance a transition.

17.2.1 Economics

This section concentrates on economic explanations for transitions. At the core of many of these explanations is the assumption that economic development can deliver multiple economic, social and environmental benefits. Many modern economic systems may nonetheless struggle to deliver these benefits due to major disruptions and shocks such as climate change (Heal 2020). One way to limit disruptions to free markets are targeted interventions in free markets such as taxes or regulation. These targeted interventions motivate firms and other entities to internalize GHGs and other pollutants, potentially paving the way for a sustainable transition (Arrow et al. 2004; Chichilnisky and Heal 1998).

A related line of thought common to economic explanations involves the principles of "weak sustainability". These principles suggest that the substitution of exhaustible resources is, to some extent, feasible (Arrow et al. 2004). One way to capitalize on this substitution is to target investments at technological change, green growth, and research and development. Targeted investments in the form of subsidies can encourage the substitution of exhaustible by non-exhaustible resources. To illustrate with a concrete example, investments in renewable energy can not only mitigate climate change but also offset the use of exhaustible fossil fuels and boost energy security (Heal 2020). It is nonetheless important to note that the principles of "weak sustainability" contrasts with "strong sustainability" or "integrated sustainability" principles. These stronger principles suggest that constraints on resources restrict such substitutions (Rockström et al. 2009). These constraints merit attention because some scarce non-substitutable forms of natural capital can be exhausted (Bateman and Mace 2020). There is hence a need to capitalize on possible synergies such as those with other development priorities and trade-offs, for example, the exhaustion of non-substitutable resources. Capturing these synergies and managing these trade-offs is consistent with sustainable development, a state where the needs of the present generation do not compromise the ability of future generations to meet their own needs (Bruntland, WCED 1987).

As suggested above, aligning climate investments with other sustainable development objectives is critical to a transition. In order to support better investments in sustainable development, financing schemes, including environmental, social and governance (ESG) disclosure schemes and the Task Force on Climate-Related Financial Disclosures (TCFD), can play important roles (Executive Summary in Chapter 15). After COVID-19, economic recovery packages have increased government-led investments (Section 1.3.3 in Chapter 1), which could potentially be aligned with sustainable development. Technological change and innovation are considered key drivers of economic growth and of many aspects of social progress (Section 16.1 in Chapter 16), but if technological innovation policies are coordinated with the shift to sustainable development pathways, then the economic benefits of technological change could come at the cost of increasing climate risks (Chapter 16, Gossart 2015) Chapter 16, 16:1; Alarcón and Vos 2015). The environmental impacts of social and economic activities, including emissions of GHGs, are greatly influenced by the rate and direction of technological changes. Innovation and technological transformations present trade-offs that create externalities and rebound effects. This suggests that a sustainable future for people and nature requires rapid, radical and transformative societal change by integrating the technical, governance, financial and societal aspects (Chapter 16, 16.1; Pörtner et al. 2021).

One area that is pertinent to transitions and has received considerable attention in economic modelling involving climate change is innovation. In particular, some studies have shown how low-cost innovations and improvements in end-use technologies have significant potential for emissions reductions as well as sustainable development (Wilson et al. 2019). Currently information technologies are improving rapidly, and IoT, AI and Big Data can all contribute to other development needs. This is often the case in end-use sectors, as the benefits accrue directly to the individuals who use the new innovations. The achievement and widespread deployment of fully autonomous cars, for example, will bring about broader car- and ride-sharing with negative or low additional costs compared to more conventional approaches to car ownership, with their typically very low load factors. (Grubler et al. 2018) estimate that the low energy demand (LED) scenario which assumes information technology innovations and induced social changes, including a sharing economy, have considerable potential for harmonizing the multiple achievements of SDGs with low marginal abatement costs compared with other scenarios (IPCC 2018).

It is nonetheless important to highlight a caveat to the above logic on innovation. Whether a technological innovation is wholly sustainable or not becomes less clear when considering its effects on the wider economy. To illustrate, some models predict that CO_2 marginal abatement costs in the power sector will be 240 and 565 USD/tCO_2 for the 2 degree and below 2 degree goals respectively (IEA 2017).

In theory, if marginal abatement costs meet marginal climate damage, mitigation measures are economically optimal in the long run. Yet marginal damage from climate change is notoriously uncertain, and economic theories do not always reflect climate-related damage. On the other hand, marginal abatement mitigation costs impose additional costs in the short term. These added costs can cause productivity in capital to decline through increases in the prices of energy and products in which the energies are embodied. These increased costs can restrict the ability to invest in and achieve the sustainable development priorities. However, precisely the opposite can occur when innovation reduces additional costs or achieves negative costs. If technological innovation leads to the accumulation of capital and productivity increases due to the substitution of energy, material and labour, these are likely to deliver sustainable development and climate mitigation benefits.

17.2.2 Institutions, Governance, and Political Economy

This subsection focuses on institutions, governance and the political economy. Institutional and governance arrangements can influence which actors possess authority, as well as how motivated they are to cooperate in transition processes that are directed at finding solutions to climate change and other sustainability challenges. Often cooperation is enabled when policy frameworks or institutions align climate change with the political and economic interests of national governments, cities or businesses, and when institutional and governance arguments that support that alignment expand the scale of the transitions. However, there may also be political and economic interests and structures that can lock in unsustainable development patterns, frustrate this alignment and slow down transitions (Haas 2021; Mattioli et al. 2020; Newell and Mulvaney 2013; Power 2016).

An extensive literature has examined how the international climate agreements and architecture influence collaboration across countries regarding climate and sustainable development to support a transition (Bradley 2005). For example, international institutions offer opportunities for governments and other actors to share new perspectives on integrated solutions (Cole 2015). For some observers, however, decades of difficulties in crafting a comprehensive climate-change agreement and the resulting fragmented climate-policy landscape have been inimical to the collaboration needed for a transition (Chapter 1 and 13; Nasiritousi and Bäckstrand 2019; van Asselt 2014). Yet others see the potential for more incremental cooperation across countries, even without a single, integrated forms of climate governance (Keohane and Victor 2016).

A related argument suggests that fragmentation at the global level provides opportunities for cooperation at the national level (Kanie and Biermann 2017). For example, in contrast to the relatively top-down Kyoto Protocol, the bottom-up pledge and review architecture of the Paris Agreement has prompted national governments to integrate climate change with other sustainable development priorities (Nachmany and Setzer 2018; Townshend et al. 2013). Concrete examples included incorporating the SDGs into the NDCs as an international response to climate change (The Energy and Resources Institute 2017) or bringing climate into sustainable development strategies and so-called voluntary national reviews (VNRs) as part of the SDG and 2030 Agenda process (Elder and King 2018; Elder and Bartalini 2019).

Another branch of institutional research is concerned with the interactions between multiple levels of governance. In this multi-level governance perspective, cities and other subnational governments often lead transitions by devising innovative solutions to challenged to climate and local energy, transport, the environment, resilience and other forms of sustainability (Bellinson and Chu 2019; Doll and Puppim De Oliveira 2017; Geels 2011; Koehn 2008; Rabe 2007; van der Heijden et al. 2019). A complementary perspective suggests that national governments can help scale up transitions by allocating resources and can provide the technical support that can spread innovative solutions (Bowman et al. 2017; Corfee-Morlot et al. 2009; Gordon 2015). Such support has become increasingly important during the pandemic, as national government transfer funds for investments in climate-friendly infrastructure, transport systems and energy systems. This line of thinking is supported by calls to strengthen vertical and horizontal integration within and across government agencies and stakeholders in ways that can enhance policy coherence (Amanuma et al. 2018; OECD 2018, 2019). The incoherence or misalignment between national and local fiscal institutions and policies can restrict the ability of local governments to secure resources for climate-friendly investments. Such investments are particularly likely to flow, as more local governments have adopted net zero targets, climate emergency declarations and action plans that can stimulate innovations (Davidson et al. 2020). Others have seen greater potential for collaboration and innovation, with more multi-centred or polycentric forms of governance that lead to the formulation and dissemination of transformative solutions to climate and other environmental challenges (Ostrom 2008). Though much of the above governance research has focused on western countries, there are some applications in other regions and countries such as China (Gu et al. 2020).

Yet another set of channels facilitating integration between climate and other concerns are networks of like-minded actors working across administrative borders and physical boundaries. For instance, city networks such as the Global Covenant of Mayors for Climate and Energy (Covenant of Mayors 2019), the World Mayors Council on Climate Change (ICLEI 2019; C40 Cities 2019) and UN- UNDRR (2019) have agreed to share decision-making tools and good practices, and to sponsor ambition-raising campaigns that help align climate and sustainable development concerns within and across cities (Betsill and Bulkeley 2006) (see Chapter 8 and Section 17.3.3.5). This can be particularly important for less capable “following” and “laggard” cities needing greater financing and other forms of support to move a transition forward (Fuhr et al. 2018).

Furthermore, sub-national governments may often work together with civil-society groups to create new networked forms of governance (Biermann et al. 2012). Other forms of multi-stakeholder partnerships focusing on issues with strong climate synergies, such as forms of air pollution known as short-lived climate pollutants (Climate and Clean Air Coalition (CCAC)) or transport (Sustainable Low Carbon Transport Partnership (SLoCaT)), take their cue from global scientific communities or civic-minded advocacy groups that transmit knowledge across boundaries (Keck and Sikkink 1999). There is also scope for suggesting that the international climate regime serves a Global Framework for Climate Action (GFCA) in helping orchestrate the multilateral climate regime and non-state and subnational initiatives (Chan and Pauw 2014), though questions remain about its actual impacts on mitigation (Michaelowa and Michaelowa 2017).

Policymaking institutions and networks are themselves policies. A significant literature has looked at integrated policy frameworks and efforts across sectors, including climate adaptation and mitigation, as drivers of transitions (Landauer et al. 2015; Favretto et al. 2018; Obersteiner et al. 2016; Steen and Weaver 2017; Thornton and Comberti 2017). Policy coherence between climate and other development objectives is often considered essential to sustainable development (Sovacool 2018). A similar discussion about synergies and conflicts has been raised on the relationship between resilience and sustainability (Marchese et al. 2018). To help achieve coherence, there have been some efforts to develop suitable tools and decision-making frameworks (Scobie 2016).

A related line of reasoning has suggested that sustainable development often requires not one but a mix of policy instruments to bring about the multiple policy effects needed for social and technological change (Edmondson et al. 2019; Rogge and Johnstone 2017). Following these calls, some governments have aimed to address climate change and sustainability jointly with coherent and integrated approaches to achieving these agendas (Chimhowu et al. 2019), although for some countries (SIDS) this has proven more challenging (Scobie 2016).

Though the above work tends to downplay politics and business, others suggest that political economy should feature prominently in transitions. Some branches of political-economy research underline how resource-intensive and fossil-fuel industries leverage their resources and positions to undermine transitions (Chapter 1; Geels 2014; Jones, C.A. and Levy 2009; Moe 2014; Newell and Paterson 2010; Zhao et al. 2013). These vested interests can lock in status quo policies in countries where political systems offer interest groups more opportunities to veto or overturn climate- or eco-friendly proposals (Madden 2014). Companies with a strong interest in earning profits and building competitiveness from conventional fossil fuel-based energy systems have particularly strong incentives to capture politicians and agencies (Meckling and Nahm 2018). Such strategies can be particularly powerful when combined with concerns over job losses and dislocation, preventing transitions from gaining traction (Haas 2021; Mattioli et al. 2020; Newell and Mulvaney 2013; Power 2016).

This suggests that politics can be an impediment to change: other studies argue instead that politics can be harnessed to drive transitions forward. For example, some observers contend that building coalitions around green industrial policies and sequencing reforms to reward industries in such coalitions can align otherwise divergent interests and inject momentum into transitions (Meckling et al. 2015). Others see the effects of political economy varying over time depending upon external market conditions. To illustrate, renewable feed-in tariffs in Europe persisted for over two decades and were crucial in wind and solar power technologies making the breakthrough. But once competition from China led to the demise of European technology providers, and once European populations started to oppose surcharges on their electricity bills, feed-in tariffs were abolished by politicians in the purely national interest (Michaelowa and Michaelowa 2017).

17.2.3 Psychology, Individual Beliefs and Social Change

This subsection draws on value- and action-oriented research that employs inter- or transdisciplinary methods such as transactional psychology, transformative science and similarly focused disciplines (Wamsler et al. 2021). These approaches frequently encourage researchers to participate in transitions that induce changes in the researcher's own beliefs while triggering wider shifts in social norms (including human stewardship for the natural environment) (Adger et al. 2013; Hulme 2009; Ives et al. 2019; O'Brien 2018). This research also emphasizes how changes in individual beliefs could lead to climate actions that contribute to more sustainable, equitable and just societies (see e.g. "the mind- & paradigm shifts" (Göpel et al. 2016; Meadows 2008). They further suggest the potential for virtuous cycles of individual-level and wider social changes that ultimately benefit the climate (Banks 2007; Day et al. 2014; Lockhart 2011; Montuori and Donnelly 2018; Power 2016).

The starting point for this virtuous circle are inner transitions. Inner transitions occur within individuals, organizations and even larger jurisdictions that alter beliefs and actions involving climate change (Woiwode et al. 2021). An inner transition within an individual (see e.g., Parodi and Tamm 2018) typically involves a person gaining a deepening sense of peace and a willingness to help others, as well as protecting the climate and the planet (see e.g., Banks 2007; Power 2016). Inner transition can imply that individuals become sympathetic to concerns that include climate issues and values connected to nature. For instance, they may include a desire to become a steward of nature (Buijs et al. 2018), "live according to the principles of integrated sustainability" (Schweizer-Ries 2018), "achieve the good life" (see Section 1.6.2 in Chapter 1; Asara et al. 2015; Escobar 2015; Kallis 2017; Latouche 2018; Chapter 5) or protect the well-being of other living creatures (Section 1.6.3.1 in Chapter 1 and Chapter 5).

Examples have also been seen in relation to a similar set of inner transitions to individuals, organizations and societies, which involves embracing post-development, de-growth, or non-material values that challenge carbon-intensive lifestyles and development models (Kothari 2019; Neuteleers and Engelen 2015; Paech 2017; Sklair 2016). These shifts in values can occur when humans reconnect with nature, deepen their consciousness and take responsibility for protecting the planet and its climate (Cross et al. 2019; Martinez-Juarez et al. 2015; Speldewinde et al. 2015). Changes in both values and beliefs may also emerge through consciousness-raising processes where people cooperate in ways that would protect the climate (see Section 1.6.4 in Chapter 1; Banks 2007; Hedlund-de Witt et al. 2014; Woiwode and Woiwode 2019).

Many of the above-mentioned beliefs and values that support climate actions have spread through expanding interests in conservationist world views, indigenous cultures (see e.g., Lockhart 2011) and branches of neuroscience and psychology that suggest different notions of the self (Hüther 2018; Lewis 2016; Seligman and Csikszentmihalyi 2014). These beliefs and values can also be spread through meditation, yoga or other social practices that encourage lower carbon lifestyles (Woiwode and Woiwode 2019). Another channel for spreading climate concerns is sustainability culture, which is premised on connecting people and communities, and has also benefited from the internet and digital technologies that support these connections (see e.g., Bradbury 2015; Scharmer 2018). The spread of this culture, in turn, has led to the creation of social fields that allow changes to happen ((see e.g., Gillard et al. 2016) or has promoted low-carbon thinking and related behavioural changes (O'Brien 2018; Veciana and Ottmar 2018). Studies of social contagions may also offer insights into the mechanisms that lead to the adoption of new values and related climate actions (see e.g., Iacopini et al. 2019). It is nonetheless worth highlighting that communication networks and other mechanisms promoting the spread of interpersonal communication that can spread pro-climate views may also lead to the proliferation of climate scepticism and denial (Leombruni 2015). At the same time, some studies suggest that such scepticism can be countered by the generation of more credible information on climate change (Samantray and Pin 2019).

One of the more direct channels through which transitions spread are climate change education and action-oriented research (Fazey et al. 2018; Ives et al. 2019; Scharmer 2018; Schäpke et al. 2018; Schneidewind et al. 2016). For instance, research using "social experiments" or "real world labs" has helped give rise to shifts in mindsets on energy, food, transport and other systems that can benefit the climate (Bernstein and Hoffmann 2018; Berkhout et al. 2010; Bulkeley et al. 2015; Hoffmann 2010). In much the same way, the acquisition of transformational knowledge and transformative learning (Lange 2018; O'Neil and Boyce 2018; Pomeroy and Oliver 2018; Walsh et al. 2020; Williams 2013) contributes to thinking and acting that open climate-friendly development pathways (Berkhout et al. 2010; Lo and Castán Broto 2019; Roberts et al. 2018; Turnheim and Nykvist 2019; Section 1.7.2 in Chapter 1). First-person and action research can also facilitate similar changes that bring about climate actions (see e.g. Bradbury et al. 2019; Dick 2007; Hutchison and Walton 2015; Streck 2007).

17.2.4 System Level Explanations

Systems explanations help explain the dynamics of transitions toward sustainable development while explicitly uncovering links between the human and natural worlds, the socio-cultural embeddedness of technology, and the inertia behind high-carbon development pathways. This line of thinking often envisages transitions emerging from complex systems in which many different elements interact at small scales and spontaneously self-organize to produce behaviour that is unexpected, unmanaged and fundamentally different from the sum of the system's constituent parts.

Social-ecological systems theory describes the processes of exchange and interaction between human and ecological systems, investigating in particular non-linear feedback occurring across different scales (Folke 2006; Holling 2001). This approach has informed subsequent theoretical and empirical developments, including the 'planetary boundaries' approach (Rockström et al. 2009), conceptualizations of vulnerability and adaptive capacity (Hinkel 2011; Pelling 2010) and more recent explorations of urban resilience (Romero-Lankao et al. 2016) and regenerative sustainability (Clayton and Radcliffe 2018; Robinson and Cole 2015). Employing a systems lens to address the 'root causes' of unsustainable development pathways (such as dysfunctional social or economic arrangements) rather than the 'symptoms' (dwelling quality, vehicle efficiency, etc.) can trigger the non-linear change needed for a transformation to take place (Pelling et al. 2015). Exploring synergies between climate-change adaptation, mitigation and other sustainability priorities (such as biodiversity and social equity, for instance) (Beg 2002; Burch et al. 2014; Shaw et al. 2014) may help to yield these transformative outcomes, though data regarding the specific nature of these synergies is still emerging.

Socio-technical transition theory, on the other hand, explores the ways in which technologies such as low-carbon vehicles or regenerative buildings are bound up in a web of social practices, physical infrastructure, market rules, regulations, norms and habits (see, for example, Loorbach et al. 2017). Radical social and technical innovations can emerge that ultimately challenge destabilized or increasingly ineffective and undesirable incumbents, but path dependencies often stymie these transition processes, suggesting an important role for governance actors (Burch 2017; Frantzeskaki et al. 2012; Holscher et al. 2019).

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This also reveals the large-scale macro-economic, political and cultural trends (or contexts) that may reinforce or call into question the usefulness of current systems of production and consumption. One branch of this theory, transition management (Kern and Smith 2008; Loorbach 2010), explores ways of guiding a socio-technical system from one path to another. In particular, it highlights interactions between actors, technologies and institutions, and the complex governance mechanisms that facilitate them (Smith et al. 2005). The challenge, in part, becomes linking radical short-term innovations with longer-term visions of sustainability (Loorbach and Rotmans 2010) and creating opportunities for collaborative course-correction in light of new information or unexpected outcomes (Burch 2017).

17.2.5 Conclusions

This section has surveyed several explanations for interventions that can give rise to transitions. The review suggests that there are several differences between these various perspectives. Whether individuals, organisations, markets or sociotechnical systems drive or undermine transitions is a key distinction. These differences have implications for the evidence these claims draw on in support of their arguments. For instance, some of the explanations tend to employ qualitative evidence to explain changes in attitudes at the individual or community levels as paving the way for broader changes to cultures and belief systems. Others assess how institutional arrangements can be reformed in order to align climate with the sustainable development agenda to enable a transition.

While there are indeed significant differences between explanations, there are also important parallels. Such parallels begin with a shared emphasis on synergies and trade-offs between climate and sustainable development. Most explanations tend to underline the importance of synergies in aligning the climate with broader sustainability agendas. Most importantly, many of the explanations are complementary with the systems-level discussion in that they offer a broad framework, while economic, psychological and governance theories offer more specific insights. Moving a transition forward will often require drawing upon insights from multiple schools of thought. Though is unlikely that a one-size-fits-all set of factors will drive a transition, there is a growing body of empirical evidence shedding light on the factors that can strengthen synergies between climate and the broader sustainable development agenda.

17.3. Assessment of the results of studies where decarbonisation transitions are framed within the context of sustainable development

17.3.1 Introduction

This section assesses studies based on the links between sustainable development and climate change mitigation in order to facilitate robust conclusions on synergies and trade-offs between different policy objectives across methodologies, scenarios and sectors. Conclusions are drawn based on national and sub-national, sectoral and cross-sectoral, short- and long-term transition studies presented in this and other sections of the report as a basis for establishing an overall picture of how sustainable development and climate change policies can be linked as a basis for accelerated transitions

This section focuses initially on issues related to short- and long-term transitions to meet climate change and sustainable development goals in the context of the UNFCCC and the UN 2030 Agenda for Sustainable Development. Global-modelling results and economy-wide studies are then assessed, followed by a discussion of specific challenges in relation to renewable energy penetration and phasing out fossil fuels, stranded assets and just transitions. Key synergies and trade-offs between meeting the UN 2030 sustainable development goals (SDGs) and mitigation are then illustrated by means of cross-sectoral examples. Finally, an overview of the assessment of SDG synergies and trade-offs based on all sectoral chapters in this report for a range of key mitigation options is then presented.

17.3.2 Short-term and long-term transitions

It is increasingly being recognised that sustainable-development policy goals and meeting short- and long-terms climate policy goals are closely linked (IPCC 2018). It is also being realised that, under the Paris Agreement, climate change policies should be integrated into sustainable development agendas, while the UN 2030 Agenda as well includes SDG 13 on climate actions. In this way, both UN agreements provide joint opportunities for systematic transitions in support of both climate change and sustainable development. Achievement of the Paris Agreement's goals will require a rapid and deep worldwide transition in all GHG emissions sectors, including land-use, energy, industry, buildings, transport and cities, as well as in consumption and behaviour (United Nations Environment Programme 2019). Meeting the goals of such a transformation requires that the long-term targets and pathways to fulfil the stabilization scenarios play an important role in guiding the direction and pathways of short-term transitions. There is therefore a need for long- and short-term policies and investment decisions to be closely coordinated.

In the context of the Paris Agreement, countries have submitted their initial plans for the decarbonization of their economies to the UNFCCC in the form of their so-called national determined contributions (NDCs). The ambitions of the NDCs are closely related to the ongoing UNFCCC negotiations over the financial measures and forms of compensation. Although the Paris Agreement emphasizes the links between climate policies and sustainable development, the UN's 2030 Agenda and the SDGs are not very well represented at present in the NDCs, according to Fuso Nerini et al. (2019). Very few of the NDCs include any reference to the SDGs, which Fuso Nerini et al. (2019) highlight as a barrier to the successful implementation of the Paris Agreement, which induces them to call for a more holistic policy approach. Campagnolo and Davide (2019) have assessed the impacts of the submitted NDCs on poverty eradication and inequalities of income based on empirical research and a global CGE model. One conclusion is that the NDCs of less developed countries would tend to reduce poverty alleviation, but this can be offset if international financial support is provided for the mitigation actions.

The alignment of climate-policy targets in the NDCs with sustainable development has been assessed by means of integrated assessment models (IAMs), macroeconomic and sectoral modelling. Iyer et al. (2018) based on IAM-based studies, the implications of framing NDCs being placed more narrowly on mitigation targets rather than on a framing in which the impacts on sustainable development were explicitly taken into consideration. It was thus concluded that some SDGs would be directly supported as a side benefit of the climate policy targets included in the NDCs, while other SDGs needed a special policy design going beyond narrow climate policy objectives. Iyer et al. (2018) also assessed the regional distribution of efforts in terms of domestic mitigation costs and SDG impacts and concluded that the geographical distribution of mitigation costs and SDG benefits were not similar, so a special effort would be needed to match climate policies and policies to meet the SDGs. Accordingly, a national decision-making perspective suggests that SDGs should be integrated into national climate policies.

The NDCs submitted to the Paris Agreement have demonstrated a lack of progress in meeting the long-term temperature goals. In the context of the UN's 2030 Agenda, the UN Sustainable Development Report 2019 (Sachs et al. 2019) also concluded that there is a particular lack of progress in achieving SDG 13 (Climate action), SDG 14 (Life below water) and SDG 15 (Life on land). Given the close link between the SDGs and climate-change policies, the current obstacles in meeting the former could also be a barrier to realizing transitions to low-carbon societies. Conversely, opportunities to leverage the SDGs could in many cases involve climate actions, since policies enabling climate adaptation and mitigation could also support food and energy security and water conservation if they were well designed (see the detailed discussion in the section on synergies and trade-offs between climate policies and meeting the SDGs in section 17.3.3.7, Chapter 3 and IPCC 2018).These findings point to a specific need to align economic and social development perspectives, climate change and natural systems. While all countries share the totality of the SDGs, development priorities differ across countries and over time. These priorities are strongly linked to local contexts and depend on which dimension of the improvement in the well-being of people is considered to be the most urgent. Eradicating poverty and reducing inequality are key development priorities for many low- and middle-income countries. (Section 4.3.2.1 in Chapter 4).

A key barrier to the development of national plans and policies to meet the UN 2030 SDG goals is the lack of finance. Sachs et al. (2019) conclude that meeting the SDGs to achieve social transformations worldwide would require 2-3% of global GDP and that it would be a huge challenge to ensure that finance is targeted to the world's poorest countries and people. The UN Secretary General has called for the allocation of finance to meet the UN's 2030 Agenda with a strong emphasis on the private sector, but to date no governance frameworks or associated financial modalities have been established in the UN or the UNFCCC context for the formal alignment of sustainable development and transitions to take place in accordance with the low global temperature-stabilization targets in the Paris Agreement. Accelerating investments particularly in low-income countries will be required to meet both the Paris goals and the SDGs (Section 15.6.7 in Chapter 15). The mismatch between capital and investment needs, home bias considerations and differences in risk perceptions between rich and poor represent major challenges for private finance. Green bond markets and markets for sustainable financal products have increased significantly, and the landscape has continued to evolve since AR5 (Executive Summary in Chapter 15). Special efforts and activities are particularly required for raising finance in developing countries.

Based on the Paris Agreement, the UNFCCC has invited countries to communicate their mid-century and long-term low greenhouse-gas emission-development strategies by 2020 (UNFCCC 2019). National long-term low-emission development strategies and their global stocktake in the UNFCCC context provide a platform for informing the long-term strategic thinking on transitions towards low-carbon societies. One specific value of these plans is that they reflect how specific transition pathways, policies and measures can work in different parts of the world in a very context-specific way, that is, by taking context-specific issues and stakeholder perspectives into consideration. Many nations have submitted national long-term strategies to the UNFCCC, including sustainable development perspectives (See Section 4.2.4, 'Mid-century low-emission strategies at the national level' in Chapter 4 for a review of the plans and scientific assessments).

17.3.2.1 Model assessments on the sustainable development pathways for decarbonization

This section assesses the model evaluations of the sustainable development pathways for decarbonization, including the co-benefits and trade-offs involving explorations of alternative future development pathways as a basis for clarifying societal objectives and understanding the restrictions. Shifting development pathways to increased sustainability involves a number of complex issues, which are difficult to integrate into models. For a more detailed discussion about this, see Section 4.4.1 in Chapter 4 and the Cross-Chapter Box 5 in Chapter 4.

Development pathways that focus narrowly on climate mitigation or economic growth will not lead to the SDGs and long-term climate-stabilization objectives being achieved. The best chances of doing this lie in development pathways that can maximize the synergies between climate mitigation and sustainable development more broadly (Section 1.3.2 in Chapter 1). Areas of focal modelling include green investments, technological change, employment generation and the performance of policy instruments, such as green taxes, subsidies, emission permits, investments and finance. Short- and long-term macroeconomic models have been used to assess the impacts of such policy instruments. Jaumotte et al. (2021) analyse the economic impacts on net zero emissions by 2050 with a focus on short-term economic policies and the integration of climate policies such as CO_2 taxes with green reform policies. This may imply the co-creation of benefits between climate policy objectives, and macroeconomic policy goals such as employment creation.

There is an emerging modelling literature focusing on the synergies and trade-offs between low-carbon development pathways and various aspects of sustainable development. The early literature, including that on IAMs, and macroeconomic and sectoral models mainly focused on the co-benefits of mitigation policies in terms of reduced air pollution, energy security and to some extent employment generation security (IPCC 2014, 2018c; WGIII AR6 Chapter 6). Some models have been developed further with assessments of a broader range of the joint benefits of mitigation, health, water, land-use and food security (Clarke et al. 2014; IPCC 2014, 2018; Kolstad et al. 2014). According to WGIII AR6 Chapter 1, there is a need to incorporate issues and enablers further, including a wide range of non-climate risks, varying forms of innovation, possibilities for behavioural and social change, feasible policies and equity issues (Executive Summary in Chapter 1).

IAMs and macroeconomic models typically calculate mitigation costs based on the assumption that markets internalise externalities like GHG emissions through carbon prices (Barker et al. 2016; IEA 2017, 2019). Yet, there are legitimate questions to be asked about whether carbon-pricing will be efficient if markets are inefficient (World Bank 2019). However, market inefficiencies are difficult to integrate into the models. How GHG emissions taxes would actually work is thus quite uncertain based on the modelling studies (Barker et al. 2016; Fontana and Sawyer 2016; Meyer et al. 2018). Despite these limitations, the use of GHG emission taxes as an effective instrument based on modelling results in practice has implications for public policies and private-sector investments.

Despite the shortcomings of conventional economic thought and models, already pointed out, improved models have demonstrated new perspectives on how mitigation costs can be assessed in macroeconomic models. For instance, while a conventional perspective might suggest that climate-change mitigation costs can limit investments in sustainability because they reduce the productivity of capital by increasing energy prices and the products in which energies are embodied, another perspective is that innovation can imply increases in efficiency and that the substitution of energy, material and labour can lead to the accumulation of capital and productivity gains. This appears to occur with innovations in end-use energy applications generating emissions reductions and delivering on other sustainable development benefits (Wilson et al. 2019). Similarly, IAM models have been applied to model the potential for low energy demand scenarios associated with demand-side innovations in the service sector. Grubler et al. (2018) have developed a climate-friendly, low-energy demand (LED) scenario which assumes information technology innovations such as the internet of things (IoT) and induced social changes such as the sharing economy. Nonetheless there are still very important limits on the degree to which highly aggregated IAM models and macroeconomic models can integrate ethics, equity and several other key policy-relevant aspects of sustainable development (Easterlin et al. 2010; Koch 2020). A key limitation in this context is that, while all countries share the totality of the SDGs, development priorities differ across countries and over time. Moreover, these priorities are strongly linked to local contexts, and this can only be reflected directly in national models (Section 4.3.2 in Chapter 4).

An example of a project that assesses the economy-wide impacts of linking sustainable development with deep decarbonization is the deep decarbonization project or DDPP (Bataille et al. 2016), which is undertaking a comparative assessment of studies of sixteen countries representing more than 74% of global energy-related emissions for the pathway to two-degree stabilization scenarios. The DDDP's methodology is to combine scenario analysis in different national contexts using macroeconomic models and sectoral models and to facilitate a consistent cross-country analysis using a set of common assumptions.

The key conclusions of the DDPP team on the economy-wide impacts are that country studies like South Africa's demonstrate that it is possible to improve income distribution, alleviate poverty and reduce unemployment while simultaneously transitioning to a low-carbon economy (Altieri et al. 2016). The DDPP in Japan explores whether energy security can be enhanced through increases in renewable energy (Oshiro et al. 2016). The reduction of uncontrolled fossil-fuel emissions has significant public-health benefits according to the Chinese and Indian DDPPs, as fossil-fuel combustion is the major source of air pollution.

For example, in the Chinese DDDP, deep decarbonization scenarios have resulted in reductions of 42–79% in primary air pollutants (e.g., SO_2, NO_x, particulate matter (PM2.5), volatile organic compounds (VOCs), and NH3), thus meeting air-quality standards in major cities. The deep decarbonization scenarios include the large and fast energy-efficient improvements required to improve energy access and affordability. The DDPP studies are thus an example of an approach in which national deep-carbonization scenarios are linked to the development goals of income generation, energy access and affordability, employment, health and environmental policy.

Sustainable development scenarios have also been developed by the Low-Carbon Society's (LCS) assessments (Kainuma et al. 2012), in which multiple sustainable development and climate change mitigation goals were assessed jointly. The scenario analysis was conducted for Asian countries such as South Korea, Japan, India, China and Nepal with a soft linked IAM using economy-wide and sectoral models and linked to very active stakeholder engagement in order to reflect national policy perspectives and priorities. Some of the models are economy-wide global IAMs, while others are national partial equilibrium models.

The LCS scenarios also include a specific attempt to include ongoing dialogues with policy-makers and stakeholders in order to reflect governance and enabling factors and to enable the modelling processes to reflect political realism as far as possible. Diverse stakeholders who acted as validators of the scientific process were included, stakeholder preferences were revealed, and recipients and users of the LCS outputs were included in ongoing dialogues on outputs and in interpreting the results. The aim of the stakeholder interactions was thus to fill the gap between typical laboratory-style integrated modelling assessments and down-scaled but unaligned practical assessments performed at disaggregated geographical and sector-specific scales.

Energy scenarios for sustainable development were included in The World Energy Outlook of the IEA (IEA 2019, 2020) in terms of a Sustainable Development Scenario (SDS), which assessed not only SDG 13 (climate change) but also SDG 7 (energy access) and SDG 3.9 (air pollution). This scenario takes as its starting point the policy goal of meeting these SDGs and then assesses the costs of meeting an emissions reduction target of 70% of CO_2 from the energy system by 2030. The scenario concludes that retrofitting coal-fired power plants with pollution controls is the cheapest option for dealing with local pollution in the short term, but that this is not consistent with meeting the long-term emissions goals of the Paris Agreement. The SDS scenario combines the goal of reducing the amount of CO_2 in the energy system by 70%, with large decreases in energy-related emissions of NO_X, SO_2 and PM2.5, leading to a fall of 40–60% by 2030, and to 2.5 million fewer premature deaths from air pollution in 2030 than in the Stated Policies Scenario (STEPS), which represent a continuation of current trends in the energy system (IEA 2020).

The costs of energy-system transitions have been assessed by several energy-system studies. The economic costs of meeting the different goals depend on the stringency of the mitigation target, as well as economic (fuel prices etc.) and technological developments (technology availability, capital costs etc.). In addition, changes in infrastructure and behavioural patterns and lifestyles matter. Model-based assessments vary, depending on these assumptions and differences in modelling approaches (Krey et al. 2019; Section 6.7.7 in Chapter 6). Country characteristics determine the social, economic and technical priorities for low-emission pathways. Domestic policy circumstances impact on pathways and costs, e.g. when affordability and energy-security concerns are emphasized (Oshiro et al. 2016).

Mitigation policies can have important distributive effects between and within countries, and may affect impact on the poorest through their effects on energy and food prices (Section 3.6.4 in Chapter 3; Hasegawa et al. 2018; Fujimori et al. 2019), while higher levels of warming are projected to generate higher inequality between countries as well as within them (Chapter 16). Mitigation thus can reduce economic inequalities and poverty by avoiding such impacts (Section 3.6.4 in Chapter 3).

Improved air quality and the associated health effects are the co-benefit category dominating model-based assessments of co-benefits, but a few studies have also covered other aspects, such as the health effects of dietary change and biodiversity impacts (Section 3.6.3 in Chapter 3 and Section 17.3 of this chapter). Mitigation has implications for global economic inequalities through different channels and can compound or lessen inequalities, avoid impacts and create co-benefits that reduce inequalities (Section 3.6.4 in Chapter 3). There are, however, several challenges involved in balancing the dilemmas associated with meeting the SDGs, such as, for example, energy access, equity and sustainability. Fossil fuel-dependent developing countries cannot transit to low-carbon economics without considering the wider impacts on development by doing so (Section 3.7.3 in Chapter 3).

Climate change has negative impacts on agricultural productivity in general, including unequal geographical distribution (Chapter 3). On top of that, there is also a risk that climate-change mitigation aimed at achieving stringent climate goals could negatively affect food access and food security (Akimoto et al. 2012; Fujimori et al. 2019; Hasegawa et al. 2018). If not managed properly, the risk of hunger due to climate policies such as large-scale bioenergy production increases remarkably if the 2 °C and 1.5 °C targets are implemented (Section 3.7.1 in Chapter 3). Taking the highest median values from different IAMs for given classes of scenarios, up to 14.9 $GtCO_2\ yr^{-1}$ carbon dioxide removal (CDR) from BECCS is required in 2100, and 2.4 $GtCO_2\ yr^{-1}$ for afforestation. Across the different scenarios, median changes in global forest area throughout the 21st century reach the required 7.2 Mkm^2 increases between 2010 and 2100, and agricultural land used for second-generation bioenergy crop production may require up to 6.6 Mkm^2 in 2100, increasing the competition for land and potentially affecting sustainable development (AR6 scenarios database).

Reducing climate change can reduce the share of the global population exposed to increased stress from reductions in water resources (Arnell and Lloyd-Hughes 2014) and therefore to water scarcity as defined by a cumulative abstraction-to-demand ratio (Hanasaki et al. 2013). Byers et al. (2018), show that 8–14% of the population will be exposed to severe reductions in water supply if average temperatures increase between 1.5 and 2.0 °C (also see Section 3.7.2 in Chapter 3). Hayashi et al. (2018) assess the water availability for different emission pathways, including the 2°C and 1.5°C targets, in light of the various factors governing availability. There are very different impacts among nations. In Afghanistan, Pakistan and South Africa, water stress is estimated to increase by 2050 mainly due to increases in irrigation water associated with the rising demand for food, and climate change will already increase water stress within the next decades. Other factors, such as changes in the demand for municipal water, water for electricity generation, other industrial water and water for livestock due to climate change mitigation, are of limited importance.

Vandyck et al. (2018) estimate that the 2°C pathway would reduce air pollution and avoid 0.7–1.5 million premature deaths in 2050 compared to current levels. It is generally agreed that in both developed and developing countries there are additional benefits of climate change mitigation in terms of improved air quality (Section 3.7.4 in Chapter 3). Markandya et al. (2018) assessed the health co-benefits of air pollution reductions and the mitigation costs of the Paris Agreement using global scenarios for up to 2050. They concluded that the health co-benefits substantially outweighed the policy costs of achieving the NDC targets and either 2°C or 1.5°C stabilization. The ratio of health co-benefits to the mitigation costs ranged from 1.4 to 2.45, depending on the scenario. The extra effort of trying to pursue the 1.5°C target instead of the 2°C target would generate a substantial net benefit in some areas.

In India, the co-health benefits were valued at USD3.28–8.4 trillion and those in China at USD0.27–2.31 trillion. Gi et al. (2019) also show that developing countries such as India have a huge potential to produce co-benefits. In addition, this implies that while the cost advantages of simultaneously achieving reductions of CO_2 emissions and of PM2.5 are clear, the advantages for integrated measures could be limited, as the costs greatly depend on the CO_2 emissions reduction target.

Grubler et al. (2018) models a pathway leading to global temperature change of less than 1.5°C without CCS, taking end-use changes into account, including innovations in information technologies and changes to consumer behaviour apart from passive consumption. The pathway estimates global final-energy demand of 245 EJ/yr in 2050, which is much lower than in existing studies (also see Section 5.3.3 in Chapter 5). It also shows the possibilities of creating synergies between multiple SDGs, including hunger, health, energy access and land-use. Integrated technological and social innovations will increase the opportunity to achieve sustainable development. Millward-Hopkins et al. (2020) estimates global final energy at 149 EJ/yr in 2050 as required to provide decent material living standards, which is much lower than the 1.5 °C scenario ranges (330–480 EJ/yr in 2050) of IAMs (IPCC 2018) and the 390 EJ/yr in the IEA SDS (IEA 2019), and also lower than Grubler et al. (2018). The conclusion is that, although providing material living standards does not guarantee that every person will live a good life, there are large potentials in achieving low energy demand with sustainable development.

An overview of the co-benefits and trade-offs of several SDGs based on modelling results is provided in Figure 3.39 (Section 3.7 in Chapter 3). Selected mitigation co-benefits and trade-offs are provided in relation to meeting the 1.5 degree temperature goal based on a subset of models and scenarios, despite many IAMs so far not having comprehensive coverage of the sustainable development goals (Rao et al. 2017; van Soest et al. 2019). There are several co-benefits of mitigation policies, including increased forest cover (SDG 15) and reduced mortality from ambient PM2.5 pollution (SDG 3) compared to reference scenarios. However, mitigation policies can also cause higher food prices and thus increase the share of the global population at risk from hunger (SDG 2), while also relying on solid fuels (SDGs 7 & 3) as side effects. It is then concluded in Section 3.7 of Chapter 3, that these trade-offs can be balanced through targeted support measures and/or additional SD policies (Bertram et al. 2018; Cameron et al. 2016; Fujimori et al. 2019).

The World in 2050 Initiative (TWI) includes a comprehensive assessment of technologies, economies and societies embodied in the SDGs (IIASA 2018). The assessment addresses social dynamics, governance and sustainable development pathways within the areas of human capacity and demography, consumption and production, decarbonization and energy, food, the biosphere and water, smart cities and digitalization. The report concludes that the 17 SDGs are integrated and complementary and need to be addressed in unison. Studies using global IAMs that were presented in the GEO6 report (United Nations Environment Programme 2019, Chapter 22) concluded that transitions to low-carbon pathways will require a broad portfolio of measures, including a mixture of technological improvements, lifestyle changes and localized solutions. The many different challenges require dedicated measures to improve access to, for example, food, water and energy, while at the same time reducing the pressure on environmental resources and ecosystems. A key contribution may be a redistribution of access to resources, where both physical access and affordability play a role. The IAMs cover large countries and regions, and localized solutions are not properly addressed in the modelling results. This implies that, for example, trade-offs between energy access and affordability are not fully represented in aggregate modelling results.

There are also several country-level studies for deep emissions reductions (see Chapter 4 for an overview of the results). The studies find significant impacts of mitigation policies at the sectoral level, reflecting the fact that the sectoral scope does not allow for as much flexibility in mitigation measures the despite macroeconomic impacts being assessed to be small (Executive Summary in Chapter 4). Another key lesson is that the detailed design of mitigation policies is critical for the distributional impacts (Executive Summary in Chapter 4). The potential mitigation measures, the potential economic growth, the political priorities and so forth are different among nations, and there may be several emissions reduction transition pathways to long-term goals among nations (Figure 4.2 in Chapter 4).

17.3.2.2 Renewable energy penetration and fossil-fuel phase-out

As pointed out in Chapter 6, the achievement of long-term temperature goals in line with the Paris Agreement requires the rapid penetration of renewable energy and a timely phasing out of fossil fuels, especially coal, from the global energy system. Limiting warming to 1.5°C with no or limited overshoot means that global CO_2 emissions must reach "net zero" in 2050/2060 (IPCC 2018). Net zero emissions imply that fossil fuel use is minimised and replaced by renewables and other low-carbon primary forms of energy, or that the residual emissions from fossil fuels are offset by carbon dioxide removal. The 1.5°C scenario requires a 2-3% annual improvement rate in carbon intensities till 2050. The historical record only shows a slight improvement in the carbon intensity rate of global energy supplies, far from what is required to limit likely global warming to 2°C, or limit warming to 1.5°C with no or limited overshoot.

The role of coal in the global energy system is changing fast. Given the global temperature goals of the Paris Agreement, the global coal sector needs a transition to near zero by 2050 – earlier in some regions (Bauer et al. 2018; IEA 2017; IPCC 2018). Other global trends, including air quality, water shortages, the improved cost efficiencies of renewables, the technical availability of energy storage and the economic rebalancing of emerging countries, are also driving global coal consumption t to a plateau followed by a reverse (Sator 2018; Spencer et al. 2018). The world should be prepared for a managed transition away from coal and should identify appropriate transition options for the future of coal, which can include both the penetration of renewable energy and improvements in energy efficiency (Shah et al. 2015).

Phasing out fossil fuels from energy systems is technically possible and is estimated to be relatively low in cost (Chapter 6). The cost of low-carbon alternatives, including onshore and offshore wind, solar PV and electric vehicles, has been reduced substantially in recent years and has become competitive with fossil fuels (Shen et al. 2020). However, studies show that replacing fossil fuels with renewables can have major synergies and trade-offs with a broader agenda of sustainable development (Swain and Karimu 2020), including land use and food security (McCollum et al. 2018), decent jobs and economic growth (Swain and Karimu 2020). Clarke et al. (2014:Table 6.7) provides detailed mapping of the sectoral co-benefits and adverse side-impacts of and links to transformation pathways. In Section 17.3.3.7 in this chapter, this is supplemented with a mapping of the synergies and trade-offs between the deployment of renewable energy and the SDGs.

The general conclusion is that the potential co-benefits of renewable energy end-use measures outweigh the adverse impacts in most sectors and in relation to the SDGs, though this is not the case for the AFOLU (Agriculture, Forestry and Other Land Uses) sectors. Some locally negative economic impacts can result in increased energy costs and competition over land areas and water resources. Some sectors may also experience increasing unemployment as a consequence of the transition process. Although the deployment of renewable energy will generate a new industry and associated jobs and benefits in some areas and economies, these impacts will often not directly replace or offset activities in areas that have been heavily dependent on the fossil-fuel industry.

The transition to low emission pathways will require policy efforts that also address the emissions that are locked into existing infrastructure like power plants, factories, cargo ships and other infrastructure already in use: for example, today coal-fired power plants account for 30% of all energy-related emissions (IEA 2019). Over the past twenty years, Asia has accounted for 90% of all coal-fired capacity built worldwide, and these plants have potentially long operational lifetimes ahead of them. In developing economies in Asia, existing coal-fired plants are just twelve years old on average. There are three options for bringing down emissions from the existing stock of plants: to retrofit them with carbon capture, utilisation and storage (CCUS) or biomass co-firing equipment; to repurpose them to focus on providing system adequacy and flexibility while reducing operations; and to retire them early. In the

IEA Sustainable Development Scenario, most of the 2080 GW of existing coal-fired capacity would be affected by one of these three options.

Even though the transition away from fossil fuels is desirable and technically feasible, it is still largely constrained by existing fossil fuel-based infrastructure and stranded investments. The "committed" emissions from existing fossil-fuel infrastructure may consume all the remaining carbon budget in the 1.5°C scenario, or two thirds of the carbon budget in the 2°C scenario (Tong et al. 2019). Kefford et al. (2018) assess the early retirement of fossil-fuel power plants in the US, EU, China and India based on the IEA 2°C scenario and conclude that a massive early retirement of coal-fired power plants is needed, and that two to three standard 500 MW generators will need to come offline every week for fifteen years. This high rate is the result of a very large deployment of coal-fired power plants from 2004 to 2012. The early phasing out of this infrastructure will result in a significant share of stranded assets (Ansari and Holz 2020) with an impact on workers, local communities, companies and governments (van der Ploeg and Rezai 2020). The challenge is thus to manage a transition which delivers the rapid phasing out of existing fossil fuel-based infrastructure while also developing a new energy system based on low-carbon alternatives within a very short window of opportunity.

Chapter 6 similarly concludes that the transition towards a high penetration of renewable systems faces various challenges in the technical, environmental and socio-economic fields. The integration of renewables into the grid requires not only sufficient flexibility in power grids and intensive coordination with other sources of generation, but also a fundamental change in long-term planning and grid operation (see Chapter 6 for more details on these issues).

Examples from various countries show that, compared with top-down decision-making, bottom-up policy-making involving local stakeholders could enable regions to benefit and reduce their resistance to transitions. Kainuma et al. (2012) conclude that social dialogue is a critical condition for engaging local workers and communities in managing the transitions with the necessary support from transition assistance. They also point out that macro-level policies, training programmes, participatory processes and specific programmes to support employment creation for workers in fossil fuel-dependent industries are needed.

Examples of challenges in transitions away from using coal are given in Box 17.1.

START BOX 17.1 HERE

Box 17.1 Case study: coal transitions

The coal transition will pose challenges not only to the power sector, but even more importantly to coal-mining. A less diversified local economy, low labour mobility and heavy dependence on coal revenues will make closing down coal production particularly challenging from a political economy perspective. Policy is needed to support and invest in impacted areas to smooth the transition, absorb the impact and incentivize new opportunities. A supportive policy for the transition could include both short-term support and long-term investment. Short-term compensation could be helpful for local workers, communities, companies and governments to manage the consequences of coal closures. Earlier involvement with local stakeholders using a structured approach is crucial and will make the transition policy more targeted and better administered. The long-term policy should target support to the local economy and workers to move beyond coal, including a strategic plan to transform the impacted area, investment in local infrastructure and education, and preference policies to incentivize emerging businesses. Most importantly, ex-ante policy implementation is far better than ex-post compensation. Even without the climate imperative, historical evidence shows that coal closures can happen surprisingly fast.

Coal has hitherto been the dominant energy source in China and has accounted for more than 70% of its total energy consumption for the past twenty years, falling to 64% in 2015 (The National BIM Report 2018). In the 13th Five Year Plan (2016-2020), for the first time China included the target of a national coal consumption cap of 4.1 billion tons for 2020, as well as a goal of reducing the primary energy share of coal to 58% by 2020 from the level of 64% in 2015 (The National People's Congress of the People's Republic of China 2016). The main driving forces of the coal transition in China are increasing domestic environmental concerns and the pressure to reduce greenhouse gas emissions. Coal combustion contributes about 90% of total SO2 emissions, 70% of NOx emissions and 54% of primary PM2.5 emissions in China (Yang and Teng 2018). The early phasing out of coal also delivers a co-benefit in terms of reductions of air pollutants that are consistent with China's goal to improve air quality (Zhang et al. 2019), as well as the reduction of methane (Teng et al. 2019) and black carbon (Zhang et al. 2019). The coal transition in China will change the future value of coal-related assets, and both coal power generators in China and coal producers outside China need to identify appropriate responses to avoid and manage the potentially substantial stranding of fossil-fuel assets. A rapid transition away from coal is critical for China to reach the peak in its emissions (Cui et al. 2019). Despite the deployment of CCS and extending the use of coal, retrofitting CCS plant may be more expensive than deploying renewables (IEA 2019).

Presently, coal-fired power plants play a key role in the German energy system, providing almost 46% of the electricity consumed in Germany. These coal power plants play a crucial role in balancing fluctuations in producing electricity form renewables (Parra et al. 2019). Political and economic considerations, at least regionally, are also of great importance in the coal sector due to the approximately 35,000 people employed within it (including coal-mining and the power stations themselves). For a long time, coal-fired power plants were able to protect their position in Germany, but against the background of decreasing public acceptance, economic problems resulting from the growing use of renewables and ambitious GHG reduction targets, the sector cannot resist the political pressures against them any longer. The governing parties have agreed to establish a commission called "Growth, structural change and employment" to develop a strategy for phasing out coal-fired power plants (E3G Annual Review 2018). This Commission consists of experts and stakeholders from industry, associations, unions, the scientific community, pressure groups and politicians. Its establishment shows that the phasing-out process deserves close attention and that management policies must be implemented to ensure a soft landing for the electricity sector.

END BOX 17.1 HERE

The transition towards a high-penetration renewable system also raises concerns over the availability of rare metals for batteries like lithium and cobalt. While metal reserves are unlikely to limit the growth rate or total amount of solar and wind energy, used battery technologies and the known reserves currently being exploited are not compatible with the transition scenario due to insufficient cobalt and lithium reserves (Månberger and Stenqvist 2018). Global lithium production rose by roughly 13 percent from 2016 to 2017 to 43,000 MT in 2018 (Golberg 2021). Africa has rich reserves of lithium and is expected to produce 15% of the world's supply soon (Rosenberg et al. 2019). Such reserves are found in Zimbabwe, Botswana, Mozambique, Namibia, South Africa (Steenkamp 2017) and the Democratic Republic of Congo (Roker 2018).

The demand for these resources as ingredients in rechargeable batteries is growing rapidly, with global demand for cobalt set to quadruple to over 190,000tn by 2026. The DRC is a mineral-rich country (Smith et al. 2019a) with rich reserves of fossil fuels (coal and oil) (Buzananakova 2015). The extraction of lithium and cobalt can be environmentally and socially damaging, though its use as a principal component in most rechargeable batteries for electric vehicles and electronic smart grids affords it high sustainability value. Chapter 10 includes a more detailed assessment of the issues with mining these rare metals, as well as the associated social problems, including exploitative working conditions and child labour, the latter a major issue that needs to be taken into consideration in transitions. Recycling batteries is also highlighted as a major supplementary policy if negative environmental side impacts are to be avoided (Rosendahl and Rubiano 2019). In the future, more attention should be paid to reducing vulnerability through subsidizing R&D in rare metals recycling, establishing systems to incentivize the collection of rare-metal waste and promoting technological progress using abundant metals as a replacement for rare metals (Rosendahl and Rubiano 2019).

Chapter 10 also provides a more detailed assessment of the issues involved in mining these rare metals, as well as the associated social problems, including exploitative working conditions and child labour, the latter a major issue that needs to be taken into consideration in transitions. Recycling batteries is also highlighted as a major supplementary policy if negative environmental side impacts are to be avoided (Rosendahl and Rubiano 2019).

17.3.2.3 Stranded assets, inequality and just transitions

As the momentum towards achieving carbon neutrality grows, the risk of certain assets becoming stranded is on the increase. International policies and the push for low-carbon technologies in the context of climate change are reducing the demand for and value of fossil-fuel products. Stranded assets become devalued before the end of their economic life or can no longer be monetised due to changes in policies and regulatory frameworks, technological change, security, or environmental disruption. In short, stranded assets are "assets that have suffered from unanticipated or premature write-down, devaluations or conversions to liabilities" (Caldecott et al. 2013).

Stranded assets are likely to "lose economic value ahead of their anticipated useful life" (Bos and Gupta 2019). They are often described as creative when they become stranded because of innovation, competition or economic growth (Gupta et al. 2020). Divestment refers to "the action or process of selling off subsidiary business interests or investments.'' This often occurs due to changing social norms and perceptions of climate change.

Indeed, pressure is mounting on fossil-fuel industries to remove their capital from heavy carbon industries. As the former Governor of the Bank of England, Mark Carney, remarked, a wholesale reassessment of prospects, especially if it were to occur suddenly, could potentially destabilise markets, sparking a pro-cyclical crystallisation of losses and a persistent tightening of financial conditions. In other words, an abrupt resolution to the tragedy of horizons itself poses a risk to financial stability (OECD 2015). The divestment narrative is also based on the view that a shift away from intensive carbon resources will be significant, as the "less value will be destroyed, […] the more can be re-invested in low carbon infrastructure'(OECD 2015). Social movements are critical to triggering rapid transformational change and moving away from dangerous levels of climate change (Mckibben 2012). Although divestment is hailed as a necessary action to decouple fossil fuel from growth and force carbon-intensive industries to go out of business, there is the sense that there is no shortage of investors who are willing to buy shares, so that such resources are not stranded, but simply relocated. Criticism has been levelled at the divestment movement for not having a significant impact on funding fossil fuels and not being sufficiently in tune with other wide-ranging complexities that go beyond the moral dimensions (Bergman 2018). Despite being labelled a 'moral entrepreneur', the divestment movement has the potential to disrupt current practices in the fossil-fuel industry, shape a 'disruptive innovation' and contribute to a strategy for decarbonising economies globally (Bergman 2018). Divestment is contributing to the political situation that is 'weakening the political and economic stronghold of the fossil fuel industry' (Grady-Benson and Sarathy 2016).

The risks attached to the stranding of fossil-fuel assets have increased with the recent and sustained plunge in oil prices because of the global health pandemic (COVID-19) and the concomitant economic downturn, forcing demand to plummet to unprecedentedly low levels. (Oil prices have recently increased). Many economies in transition and countries dependent on fossil fuels are going through turbulent times where asset and transition management will be critical (UNEP/SEI 2020). However, COVID-19 provides a foretaste of what a low-carbon transition could look like, especially if assets become stranded in an effort to respond to the call for action in 'building back better' and putting clean energy jobs and the just transition at the heart of the post-COVID-19 recovery (IEA 2020; United Nations General Assembly 2021). COVID-19 provides a useful proxy for issuing two alerts. First, it is a reminder of the urgency of addressing climate change, given that delaying the move away from stranded assets will further worsen climate change. Second, failure to recognize the threat from stranded assets will result in new assets becoming stranded (Rempel and Gupta 2021). Hence, the momentum towards a transformational push is resting on a new opportunity ushered in by COVID-19 to emphasize the urgency for a new departure towards rapid emissions reductions (Cronin et al. 2021).

The stranded assets narrative has focused overwhelmingly on consumption by companies: not much emphasis has been placed on the commercialisation- and investment-related aspects. In addition, other carbon-intensive activities can also run the risk of being stranded, such as cement, petrochemicals, steel and aviation (Baron and David 2015). This is why stranded assets are often referred to as having a cascading impact on several other sectors.

Transitions are broad-based and complex, involving governance structures, institutions and climate vulnerabilities, and there is need to include historical responsibility, resource intensity and capacity differentials, thus relegating the debate across simplistic binary lines of developed versus developing countries (Carney 2016). Hence, transition processes will have to respond to several preconditions and structural inequalities related to climate finance, energy poverty, vulnerabilities and the broader macro-economic implications associated with managing the debt burden, fiscal deficits and uneven terms of development in developing countries. In addition to structural inequalities, the COVID-19 pandemic has severely disrupted energy and food systems to and reduced the speed at which developing countries can procure new low-carbon technologies and decouple economic growth from fossil fuels (Winkler 2020). For instance, global supply-chain transition costs might be lower when compared to in-country supply chains, as became evident when COVID-19 created further disruption to renewable energy projects (Cronin et al. 2021). Moreover, developing countries can experience difficulties in phasing out old technologies, especially if the latter has a cost disadvantage, has not benefitted from an established track record and its performance is uncertain (Bos and Gupta 2019). There is the risk of lock-in effects related to grandfathering when emitters comply with less stringent standards.

Despite their efforts in deploying renewable energies, many developing countries are still contending with problems related to the immaturity of the current technologies and the challenges of battery storage. In short, the transition to a low carbon development must consider the challenges of renewable energy penetration and existing energy-related vulnerabilities and inequalities. There are power asymmetries between first-comers and latecomers, especially in cases where mature technologies can be located in countries with less stringent laws and standards. Carbon leakage has implications for just transitions, as carbon-intensive industries can move their dirty industries to developing countries as a way of outsourcing the production of carbon (Bos and Gupta 2019; UNU-INRA 2020, Denton et al, 2021). When the challenge of climate mitigation is transferred to developing countries in the form of carbon leakage, the risks of carbon lock-in for developing countries are heightened (Bos and Gupta 2019).

Overcoming the carbon lock-in is not simply a matter of the right policies or switching to low-carbon technologies. Indeed, it would mean a radical change in the existing power relations between fossil-fuel industries and their governments and social structural behaviour (Seto et al. 2016). Some actions to fix the climate change problem can themselves create injustices, thereby challenging sustainable development (Cronin et al. 2021). Not paying sufficient attention to perceptions of injustice related to the rights to development, energy and resource sovereignty can further create resistance to climate action (Cronin et al. 2021).

The shrinking carbon budget has raised questions over whether to meet our commitment to 2 degrees Celsius if fossil-fuel resources were to be mined or left stranded, as McGlade and Ekins argue: '… [a] large portion of the reserve base and an even more significant proportion of the resource base should not be produced if the temperature rise is to remain below 2 degrees C' (McGlade and Ekins 2015). This logic means that developing countries that rely on fossil-fuel extraction will need to replace their hydrocarbon revenues with other income-generating activities. Stranded assets remind most oil-producing governments that fossil-fuel assets do not have a durable value and are vulnerable to politico-economic forces and fluctuations. The goal of staying within the 1.5°C temperature goal, in line with the Paris Agreement, is already part of the policy vision and planning of large fossil fuel-consuming economies. For early fossil-fuel producers, however, the reality that their resources may not yield the desired returns is often perceived as bad news, particularly in the context of the increasing depreciation of fossil-fuel products.

Stranded assets raise fundamental questions related to issues of equity and just transitions:

- Who decides which resources should be stranded?
- Who shoulders the burden of the transition and losses incurred from moving away from heavy industries with associated compensation?
- How should the advantages of short-term fossil-fuel exploitation be shared based on the principle of distributive justice?

The transition to a low-carbon development is wired in issues of justice and equity: how do you align carbon reductions to meet the needs of humanity? Distributive justice calls for a fairer sharing of the benefits and burdens of the transition process, while procedural justice is essentially about ensuring that the demands of vulnerable groups are not ignored in the pull to the transition. The impacts of climate change and the mitigation burdens are experienced differently by different social actors, with indigenous communities facing multiple threats and being subjected to unequal power dynamics (Sovacool 2021).

Nonetheless, the production of fossil fuels is central to many economies with numerous development implications related to rents associated with export revenues, energy security and poverty alleviation (Lazarus and van Asselt 2018). The central question is who decides which types of carbon should be burnable or non-burnable. Hence, social equality is at the heart of the transition process, but it falls short of a response on how to chart a new road map towards carbon neutrality, especially given that fossil-fuel producers and investors tend to belong to large, powerful companies and wield a great deal of influence and power, especially when their entrenched interests are at stake (Lazarus and van Asselt 2018). The question of whether developing countries should be compensated for foregoing their resources in light of their current development needs has not yielded many results and had only limited success in mobilising international finance, as demonstrated by the case of Yasuni-ITT in Ecuador (Sovacool and Scarpaci 2016). According to Sovacool et al. (2021), affected communities and their views may be discounted and excluded from planning, which can neglect important matters such as rights, recognition and representation (Sovacool 2021).

Fossil fuel-dependent countries are doubly exposed to the vulnerability related to climate-change impacts and are being targeted in the global effort to address the problem (Peszko et al. 2020). Countries that are heavily reliant on oil, coal and gas are also those most at risk from a low-carbon transition that may curtail the activities of their fossil-fuel industries and render the value chains and economies associated with the exploitation of fossil fuels unviable (Peszko et al. 2020).

Developing countries in Latin America and Africa that are reliant on revenue streams from fossil fuels may not see these returns converted into much needed infrastructure and other social and economic amenities that can reduce poverty. However, given the falling prices of renewables, developing countries do not have to face the burden of retrofitting their infrastructure to align with new low-carbon industries, since they can leapfrog technologies and shape a sustainable trajectory that is more resilient and fit for the future.

However, the transition towards a carbon-neutral world is complex and non-linear, and it will likely result in some disruptions, with manifest equality implications, given the scale of the transformation envisaged. There are parallel movements that can be observed. On the one hand, divestment initiatives are underway to move away from carbon-intensive investments. On the other hand, hydrocarbon-rich countries in some parts of the developing world are identifying new opportunities to reduce the fiscal loss associated with the loss of fossil-fuel revenues. Indeed, with global investment in energy expected to shrink by 20% this year, this has created fiscal challenges for countries that are heavily reliant on fossil-fuel products as their main source of revenue.

Other disruptions are linked to redundant contracts and postponed or cancelled explorations, as many oil companies are diversifying their production in the wake of the pandemic and are cutting back on planned hydrocarbon investments (Denton et al, 2021). These failed concessions and disruptions have implications for the just transition, especially in developing countries without the financial ability to pull out of fossil fuels and to diversify with the same urgency as the industrialized nations (Peszko et al. 2020). For instance, in South Africa, which is seeking to divest away from coal and decarbonize its energy sector, if the transition is not properly managed, this could lead to a loss in revenue of R1.8 trillion (USD125 billion), thus compromising the government's ability to support social spending (Huxham et al. 2019). Emerging oil producers like Uganda are having to postpone the start of production. Eni and Total, two of the largest international oil and gas majors in Africa, have already signalled they are making 25% cuts to their investment in exploration and production projects in 2020, representing a €4bn reduction in foreign direct investment for Total and a USD2bn reduction for Eni (Le Bec 2020).

A poorly managed transition will reproduce inequalities, thus contradicting the very essence of a just, sustainable, inclusive transition. Revenues from oil and gas have been ploughed into social safety nets and are supporting free senior high-school education in countries such as Ghana, thus enabling the realisation of SDG 4 on quality education (UNU-INRA 2020). The move from fossil fuels towards a low-carbon economy has economic implications for lower income countries that are dependent on hydrocarbon resources, are endowed with significant untapped oil and gas reserves, and may not have the transitional tools to move towards low-carbon technologies or economies (Peszko et al. 2020).

The energy transition landscape is changing rapidly, and we are witnessing multiple transitions. This creates room to manage the transition in ways that will prioritise the need for workers in vulnerable sectors (land, energy) to secure their jobs and to maintain a secure and healthy lifestyle, especially as the risks multiply for those who are exposed to heavy industrial jobs and all the associated outcomes. The shift to carbon neutrality is being driven by convergent factors related to energy security and the benefits of climate mitigation, including the health impacts of air pollution and consumer demand (Svobodova et al. 2020).

Climate change is high on the global agenda, as is energy's role in decarbonizing the economy, giving rise to a number of equality issues. Oswald et al. (2020) have shown that economic inequality translates into inequality in energy consumption, as well as emissions. This is largely because people with different levels of purchasing power make use of different goods and services, which are sustained by different energy quantities and carriers (Oswald et al. 2020; Poblete-Cazenave et al. 2021)

A study by Bai et al. (2020) shows that an increase in income inequality in China hinders the carbon abatement effect of innovations in renewable energy technologies, possibly even leading to an increase in carbon emissions, while a decrease in inequality of incomes is conducive to giving play to the role of this carbon abatement effect, thereby indicating that there is an important correlation between the goals of "sustainable social development" and "sustainable ecological development".

India is home to one sixth of world's population but accounts for only 6.8% of global energy use and consumes only 5.25% of electricity produced globally. During the period 1990–1991 to 2014–2015, overall energy intensity in India declined from 0.007 Mtoe per billion INR of GDP to 0.004 Mtoe per billion INR of GDP, an annual average decline of 2%. The industrial sector is making the highest contribution CO_2 mitigation by reducing its energy intensity (Roy et al. 2021).

Household carbon emissions are mainly affected by incomes and other key demographic factors. Understanding the contribution of these factors can inform climate responsibilities and potential demand-side climate-mitigation strategies. A study by Feng et al. (2021) on inequalities in household carbon the in USA shows that the per-capita carbon footprint (CF) of the highest income group (>200 thousand USD per year) with 32.3 tons is about 2.6 times the per-capita CF of the lowest income group (<15 thousand USD) with 12.3 tons. Most contributors of high carbon footprints across income groups in the US are heating, cooling and private transport, which reflects US settlement structures and lifestyles, heavily reliant as they are on cars and living in large houses.

Studies by Jaccard et al. (2021) on energy in Europe shown a top-to-bottom decile ratio (90:10) of 7.2 for expenditure, 3.1 for net energy and 2.6 for carbon. Given such inequalities, these two targets can only be met through the use of carbon capture and storage (CCS), large efficiency improvements and an extremely low minimum final energy use of 28 GJ per adult equivalent. Assuming a more realistic minimum energy use of about 55 GJ ae^{-1} and no CCS deployment, the 1.5◦C target can only be achieved at near full equality. The authors conclude that achieving both stated goals is an immense and widely underestimated challenge, the successful management of which requires far greater room for manoeuvre in monetary and fiscal terms than is reflected in the current European political discourse.

The 'Just Transition' concept has evolved over the years (Sweeney and Treat 2018) and is still undergoing further evolution. It emphasizes the key principles of respect and dignity for vulnerable groups, the creation of decent jobs, social protection, employment rights, fairness in energy access and use, and social dialogue and democratic consultation with relevant stakeholders, whilst coping with the effects of asset-stranding or the transition to green and clean economies. The concept has come under increased scrutiny, with its protagonists emphasizing the need to focus on the equality of the transition, not simply on its speed (Forsyth 2014). The emphasis on justice is also gaining in momentum, with a growing recognition that the sustainability transition is about justice in the transition and not simply about economics (Newell and Mulvaney 2013; Swilling, M. Annecke 2010; Williams and Doyon 2020). Scholars are increasingly of the view that a transition involving low-carbon development should not replace old forms of injustice with new ones (Setyowati 2021).

The economic implications of the transition will be felt by developing countries with high degrees of dependence on hydrocarbon products as a revenue stream, as they are exposed to reduced fiscal incomes, given the low demand for oil and low oil prices and the associated economic fallout of the pandemic. This link with stranded assets is important, but it may be overlooked, as countries whose assets are becoming stranded may not have the relevant resources, knowledge, autonomy or agency to design a fresh orientation or decide on the transition. In addition, some developing countries are dependent not only on fossil-fuel revenues, but also on foreign exchange earnings from exports. This dependence comes into sharp focus when one considers that 30% of the Malaysian government's revenues are linked to petroleum products, and that Mozambique, by exploiting its newly discovered natural-gas reserves, can earn seven times the country's current GDP over a period of 25 years (Cronin et al. 2021). Thus, any attempt to accelerate the transition to low-carbon development must take into account foreign exchange, domestic revenue and employment generation, which are precisely what ensure the attractiveness of fossil-fuel industries (Addison and Roe 2018).

Energy use and its deployment are sovereign matters. State responsibilities over the control and use of natural resources concern both current and future generations (Carney 2016). Climate-change impacts will disable the food, water and energy systems of the most vulnerable. Therefore, the resources required to enable a just transition are predicated on good leadership and governance institutions that will support quality and justice-based transitions. Beyond energy systems, changes to land systems can benefit from sustainable land management in ways that will reduce the pressure on land for food and at the same time support carbon storage. With land coming under increased pressure, land and forest management are critical for carbon sequestration, as well as other ecosystem benefits. Extractive processes have impacts on land, and often there are few if any redistributive benefits for communities in regions where extraction takes place. In addition, extraction of strategic minerals such as cobalt, copper and lithium have been linked to violence, human rights abuses and conflict (Cronin et al. 2021).

However, in the race to achieve carbon neutrality by 2050, some of the other priorities of the transition, like climate-change adaptation and its inherent vulnerabilities, might become muted, given the urgency to mitigate at all costs. Consequently, the transition imperative reduces the scope for local priority-setting and ignores the additional risks faced by countries with the least capacity to adapt. Equally, the 'just transition' is often seen through the prism of job losses and the attendant retooling and reskilling imperatives necessary to re-dynamize local businesses, especially those that may fail as a result of mine closures. It is equally important to consider current disparities in knowledge and capacity which could maintain the existing inequalities in the global regional distribution of costs and benefits. One striking example is the manufacturing of PV in India when compared to manufacturing PV in China. In China, manufacturing costs are lower than in India, as are import tariffs (Behuria 2020). Similarly, a solar industry might have greater development prospects in one region than another given existing regional disparities in human capital, infrastructure, finance and technological development (Cronin et al. 2021).

Low-carbon transitions and equality implications will depend on local contexts, regional priorities, the points of departure of different countries in the transition and the speed at which they will want to travel. Hence, timing and scope are important elements that are associated more with a quality transition than a race to the bottom. To date the debate has had some obvious blind spots, not least considerations of power, politics and political economy (Denton et al, 2021). Certainly, the transition will create winners and losers, as well as stakeholders that can frame their economic interests so as to determine the orientation, pace, timing and scope of the transition.

The determination of a just transition is complex and not simply dependent on the allocation of perceived risks or solutions, but rather on how risks and solutions are defined (Forsyth 2014). Acting urgently to achieve environmental solutions or meet transition imperatives has certain risks given the need to go beyond commonplace definitions of the just transition by emphasizing the distributive or procedural aspects. The framing of policies to align with fast and low-cost mitigation without paying sufficient attention to social and economic resilience creates its own potential risks and can enhance social vulnerability rather than address it. The need to distribute climate-change solutions must not delegitimise appropriate economic growth strategies, nor indeed create the additional risks of policy imposition. Perceptions of justice with regard to environmental problems and solutions matter equally. Hence, the types of transition pathway that are chosen may have equality implications. Mitigation at all costs, if done "cheaply and crudely", can create additional problems for social justice and inclusive development (Forsyth 2014).

The assumption that the benefits of mitigation are enough to offset trade-offs with other policy objectives can be questioned. If one accepts the argument that not all adaptation addresses vulnerability concerns (Kjellén 2006), and that some adaptation strategies can heighten vulnerabilities if there are flaws in their design and implementation, then the same logic applies, namely that not all mitigation is necessarily beneficial. Hence the emphasis on the transition resulting from mitigation should be placed not only on speed or cost effectiveness, but also on legitimacy of the actions, and whether the transition is well designed or not. In short, justice is not always a shorthand for acting ethically, but rather a point of reasoning on what is considered legitimate. Planning for the transition often discounts human rights and social inclusivity that can occur as the result of a rapid transition. The emphasis should be placed on the management of the transition rather than the speed – for instance, if in the rush to build new hydropower energy sources implies that populations are displaced, then this constitutes a human rights violation (Castro et al. 2016; Piggot et al. 2019).

Ambitious climate goals can increase the urgency of mitigation and accelerate the speed at which carbon neutrality is achieved. However, if the transition is done with speed, then this will leave diversification efforts stymied, particularly in developing countries that are highly dependent on fossil-fuel revenue streams (UNEP/SEI 2020). Transition decisions and policies may also have far-reaching gendered implications, as the closure of mines is often linked to several ancillary businesses impacts where men are laid off and women may have to take on multiple jobs to compensate for the reduction in the household's income (Piggot et al. 2019; UNU-INRA 2020).

A just transition holds out the prospects for alternative high-quality jobs, public-health improvements and an opportunity to focus on well-being and prosperity, with spill-over benefits to urban areas and economic systems. Nonetheless, countries that transition from fossil fuels experience different challenges, different levels of dependence and have different capacities to transition. There will be countries with lower capacity and higher dependence, and vice versa (UNEP/SEI 2020).

Deciding on matters of justice is essential to the transition, and there are several inherent questions to consider when thinking through the allocation of costs and benefits, as is the case with distributive justice. How matters are defined and who defines matters such as the timing of phasing out, prioritising which energy sources need to be phased out and who might be affected are all political economy questions (Piggot et al. 2019).

Similarly, when considering issues of procedural justice, there are matters related to interests, participation and power dynamics that are essential to the process, but that might also subvert the process, depending on whose rights, whose participation and whose power are being put in jeopardy.(Forsyth 2014; Piggot et al. 2019). Hence, both distribution and procedure matter, as do inter-generational and intra-generational equity in planning transitions. Six critical variables can shape or inhibit the transition process. These are dependence, timing, capacity, agency, scope and inclusion (Denton et al, 2021).

Dependence, or the extent to which a country may depend on revenue streams from fossil fuels, will determine their ability to manage the transition from fossil fuels. Countries who rely on the proceeds from hydrocarbon resources as economic rents to support fiscal income and spending on public service-related needs such as education, health and infrastructure, export earnings and foreign exchange reserves will have greater difficulties in foregoing their fossil-fuel resources.

Timing: the transition pathway has to be aligned with a timetable which is anchored in national development priorities. For example, South Africa's Integrated Resource Planning indicates that the transition away from coal, if not aligned with national development priorities, will reproduce new forms of inequality. In addition, if the transition is imposed and its timing is not organic, then this might also produce social inequalities.

Capacity: Transitions need to reflect spaces and planning. If knowledge about the transition pathway is not adequately mastered or in place, this can disable the process or steer it in the wrong direction. Capacity also relates to several attributes, including technical, governance, institutional, technologies, economic resources to manage the transition. Poorer countries will have difficulties in managing all these resources, as well as absorbing the costs associated with the transition (UNEP/SEI 2020).

Agency: transitions are inherently about the sovereign right to determine one's orientation towards low-carbon development. However, given the urgency to stick to the Paris Agreement and the new conditionalities related to post-COVID stimulus packages, the absence of agency to deal with the transition might jeopardize its flow, orientation and pace (Newell and Mulvaney 2013).

Scope: the extent to which the transition is rolled out and its potential impacts. If transition policies are ambitious in making commensurate diversification investments, this may enable job creation, but it may also affect employees who are insufficiently prepared to undertake new jobs and skills.

Inclusion. Who is considered in the transition process and how their interests and risks are assessed are important aspects of transition pathways. Stakeholders with strong vested interests may resist the transition, especially as it moves towards diversification activities and policies.

17.3.3 Cross-sectoral transitions

Transitions will involve multiple sectoral- and cross-sectoral policies. Section 17.3.3 presents a range of studies and conclusions on the relationship between climate-change mitigation goals and meeting the SDGs in order to identify major synergies and trade-offs. The interactions are manifold and complex (Section 4.3.1.2 in Section 4; Nilsson et al. 2016; Pradhan et al. 2017). Here we draw on conclusions from sectoral chapters and add additional studies as a basis for drawing more general conclusions about agriculture, food and land-use, the water-energy-food nexus, industry, cities, infrastructure and transportation, cross-sectoral digitalization, and mitigation and adaptation relations.

17.3.3.1 Agriculture, Forestry and Other Land Uses (AFOLU)

Sustainable development and mitigation policies are closely linked in the agriculture, food and land-use sectors. We assess synergies and trade-offs between meeting the SDGs and reducing GHG emissions within the sectors based on modelling studies and case studies illustrating how trade-offs between SDG 2 (zero hunger, biomass for energy) and SDG 15 (life on land) can be addressed by cross-sectoral mitigation options.

Chapter 7 emphasizes the high expectations on land to deliver mitigation, yet the pressures on land have grown with population, dietary changes, the impacts of climate change and the conversion of uncultivated land to agriculture and other land uses. Agriculture, Forestry and Other Land Uses (AFOLU) are expected to play a vital role in the portfolio of mitigation options across all sectors. The AFOLU sector is also the only one in which it is currently feasible to achieve carbon dioxide removal (CDR) from the atmosphere, including A/R, improved forest management and soil carbon sequestration (see Chapters 7 and 12). The AFOLU sector has a significant mitigation potential, with many scenarios showing a shift to net negative CO_2 emissions during the 21st century. Total cumulative AFOLU CO_2 sequestration varies widely across scenarios, with as much as 415 $GtCO_2$ being sequestered between 2010 and 2100 in the most stringent mitigation scenarios. The largest share of net GHG emissions reductions from AFOLU in both the 1.5°C and 2°C scenarios is from forestry-related measures, such as afforestation, reforestation and reduced deforestation. Afforestation, reforestation and forest management result in substantial carbon dioxide removal in many scenarios. CO_2 and CH_4 show larger and more rapid declines than N_2O, an indication of the difficulties of reducing N_2O emissions in agriculture (Chapter 3).

The Global Assessment on Biodiversity and Ecosystem Services Report (IPBES 2019, Chapter 5) assessed the relationship between meeting the goals of the Paris Agreement and SDGs 2 (zero hunger), 7 (affordable and clean energy) and 15 (life on land). It concluded that a large expansion of the amount of land used for bioenergy production would not be compatible with these SDGs. However, combining bioenergy options with other mitigation options, like more efficient land management and the restoration of nature, could contribute to welfare improvements and to accessing food and water. Demand-side climate-mitigation measures, like energy-efficiency improvements, reduced meat consumption and reduced food waste, were considered to be the most economically attractive and efficient options in order to support low GHG emissions, food security and biodiversity objectives. Implementing such options, however, can involve challenges in terms of lifestyle changes (IPBES 2019).

The potential joint contribution of food and land-use systems to sustainable development and climate change has also been addressed in policy programmes by the UN, local governments and the private sector. These programmes address options for pursuing sustainable development and climate change jointly, such as agroforestry, agricultural intensification, better agriculture practices and avoided deforestation. Griggs and Stafford-Smith (2013) assess production- and consumption-based methods of achieving joint sustainability and climate-change mitigation in food systems, concluding that efficiency improvements in agricultural production systems can provide large benefits. Given the expectations of high levels of population growth and the strong increase in the demand for meat and dairy products, there is also a need for the careful management of dietary changes, as well for those areas which could be used most effectively for livestock and plant production.

Loss of biodiversity has been highlighted in several studies as a major trade-off of the low stabilization scenarios (Prudhomme et al. 2020). A wide range of mitigation and adaptation responses – for example, preserving natural ecosystems such as peatland, coastal lands and forests, reducing the competition for land, fire management, soil management and most risk management options – have the potential to make positive contributions to sustainable development, ecosystems services and other social goals

(McElwee et al. 2020). Smith et al. (2019a) also stressed that agricultural practices (e.g. improving yields, agroforestry), forest conservation (e.g. afforestation, reforestation), soil carbon sequestration (e.g. biochar addition to soils) and the removal of carbon dioxide (e.g. BECCS) could contribute to climate-change mitigation (Smith et al. 2019a). However, there are also options that could improve biodiversity if they were implemented jointly with climate-change mitigation in AFOLOU. In their study, (Leclère et al. 2020) show that increasing conservation management, restoring degraded land and generalized landscape-level conservation planning could be positive for biodiversity. In general, the ambitious conservation efforts and transformations of food systems are central to an effective post-2020 biodiversity strategy.

The IPCC Special Report on Climate Change and Land (IPCC 2019) emphasizes the need for governance in order to avoid conflict between sustainable development and land-use management. It states: "Measuring progress towards goals is important in decision-making and adaptive governance to create common understanding and advance policy effectiveness". The report concludes that measurable indicators are very useful in linking land-use policies, the NDCs and the SDGs.

One example of an area where special governance efforts have been called for is the protection of forestry, ecosystem services and local livelihoods in a context of the large-scale deployment of high-value crops like palm oil, short-term, high income-generating activities and sustainable development. Serious challenges are already being seen within these areas according to (IPBES 2019).

Palm-oil is one example of a product with potentially major trade-offs between meeting the SDGs and climate-change mitigation in the agriculture, forest and other land uses (AFOLU) sector. Currently the area under oil palms is showing a tremendous increase, mostly in forest conversions to oil-palm plantations (Austin et al. 2019; Gaveau et al. 2016; Schoneveld et al. 2019). The conversion of peat swamp forest and mineral forest to oil palms will yield different amounts of CO_2. A study by Novita et al. (2020) shows that the carbon stock of primary peat-swamp forest was 1,770 Mg C/ha compared to a carbon stock of oil palm of 759 Mg C/ha. The study conducted by Guillaume et al. shows that the carbon stock in mineral soils was 284 Mg C/ha compared to that in rain forest, which was 110.76 Mg C/ha (Guillaume et al. 2018).

Restoring peatlands is one of the most promising strategies for achieving nature-based CDR (Girardin et al. 2021; Seddon et al. 2021). A study by Novita et al. (2021) shows that significantly different CO_2 emissions for different land-use categories are influenced more by the water table depth and latitude position for those locations relative to other observed parameters, such as bulk density, air temperature and rainfall.

Given that the frequent peat-land fires in Indonesia were caused by land clearances in the replanting season, multi-stakeholder collaboration between oil-palm plantations, local communities and local governments over practices such zero burning when clearing land might be one of the most effective ways to reduce the deforestation impact of oil palm (Jupesta et al. 2020). Behavioural changes as a mitigation option have been suggested as a major factor in aligning sustainable development, climate change and land management. In the absence of the policy intervention, the expansion of oil-palm plantations has provided limited benefits to indigenous and Afro-descended communities. Even when oil-palm expansion improves rural livelihoods, the benefits are unevenly distributed across the rural population (Andrianto et al. 2019; Castellanos-Navarrete et al. 2021). In any case, while oil-palm production can improve smallholders' livelihoods in certain circumstances, this sector offers limited opportunities for agricultural labourers, especially woman (Castellanos-Navarrete et al. 2019).

Economy-wide mitigation costs can be effectively limited by lifestyle, technology and policy choices, as well as benefit from synergies with the SDGs. Synergies come from the consumption side *by* managing demand. For example, reducing food waste leads to resources being saved because water, land-use, energy consumption and greenhouse gas emissions are all reduced (Chapter 3).

IPCC 6th AR Chapter 12 emphasized that diets high in plant protein and low in meat, in particular red meat, are associated with lower GHG emissions. Emerging food-chain technologies such as microbial, plant, or insect-based protein promise substantial reductions in direct GHG emissions from food production. The full mitigation potential of such technologies can only be realised in low-GHG energy systems.

Springmann et al. (2018) conclude that reductions in food waste could be a very important option for reducing agricultural GHG emissions, the demand for agricultural land and water, and nitrogen and phosphorous applications. In addition to the possibility to reduce food waste, their study analysed several other options for reducing the environmental effects of the food system, including dietary changes in the direction of healthier, more plant-based diets and improvements in technologies and management. It was concluded that, relative to a baseline scenario for 2050, dietary changes in the direction of healthier diets could reduce GHG emissions by 29% and 5–9% respectively in a dietary-guideline scenario, and by 56% and 6–22% respectively in a more plant-based diet scenario. Demand-side, service-oriented solutions vary between and within countries and regions, according to living conditions and context. Avoiding food waste reduces GHG emissions substantially. Dietary shifts to plant-based nutrition leads to healthier lives and reduce GHG emissions (Chapter 5.3).

A similar study also found a positive impact form zero food waste. The 'no food waste' scenario could decrease global average food calorie availability by 120 kcal person^{-1} d^{-1} and protein availability by 4.6 g protein person−1 d^{-1} relative to their baseline levels, thus reducing required crop and livestock production by 490 and 190 Mt respectively. This lower level of production reduces agricultural land use by 57 Mha and thus mitigates the associated side effects on the environment. The lower levels of production also reduce the requirements for fertilizers and water by 10 Mt and 110 km^3 respectively, and GHG emissions are reduced by 410 $MtCO_2e$ yr^{-1} relative to the 2030 baseline. Reducing food waste can contribute to lessening the demand for food, feed and other resources such as water and nitrogen, reducing the pressure on land and the environment while ending hunger (Hasegawa et al. 2019).

In 2007, Britain launched a nationwide initiative to reduce household food waste, which achieved a 21 percent reduction within five years (FAO 2019). The basis of this initiative was the "Love Food, Hate Waste" radio, TV, print and online media campaign run by a non-profit organization, the Waste and Resources Action Programme (WRAP). The campaign raised awareness among consumers about how much food they waste, how it affects their household budgets and what they can do about it. This initiative collaborated with food manufacturers and retailers to stimulate innovation, such as re-sealable packaging, shared meal-planning and food-storage tips. The total implementation costs during the five-year period were estimated at GBP 26 million, from which it was households that derived the most benefit, estimated to be worth GBP 6.5 billion. Local authorities also realized a substantial GBP 86 million worth of savings in food-waste disposal costs. As for the private sector, the benefits took the form of increased product shelf lives and reduced product loss. While households started to consume more efficiently and companies may have experienced a decline in food sales, the latter also stated that the non-financial benefits, such as strengthened consumer relationships, had offset the costs.

The Asia Pacific Economic Cooperation (APEC) group of countries has also created several types of public–private partnership to tackle food waste and reduce losses. Most of these partnerships are focused on food-waste recycling in both developed and developing countries (Rogelj et al. 2018). APEC members stated that knowledge-sharing and improved policy and project management were the most important advantages of public–private partnerships.

The inextricably intertwined factors in decision-making are influenced by the characteristics of the person, in interaction with the characteristics of more sustainable practices and products, which interact with a particular context that includes the immediate environment (e.g., household, farm), the indirect environment (e.g., community) and macro-environmental factors (e.g., the political, financial and economic contexts) (Hoek et al. 2021). Hence, to influence people to make decisions in favour of sustainable food production or consumption, a wider perspective is needed on decision-making processes and behavioural change, in which individuals are not targeted in isolation, but in interaction with this wider systemic environment.

In conclusion, the AFOLU sector offers many low-cost mitigation options, which, however, can also create trade-offs between land-use for food, energy, forest and biodiversity. Some options can help to mitigate such trade-offs, like agricultural practices (e.g., improved yields, agroforestry), forest conservation (e.g. afforestation, reforestation), soil carbon sequestration (e.g. biochar addition to soils) and the removal of carbon dioxide (e.g. BECCS), which could contribute to climate change mitigation. Lifestyle changes, including dietary changes and reduced food waste, are tightly embedded in modes of behaviour that are influenced by the immediate environment (e.g., household, farm), the indirect environment (e.g., community) and macro-environmental factors (e.g., political, financial and economic contexts). Achieving zero-food waste could reduce the demands for land (SDG 15), water use (SDG 6) and chemical fertilizers (SDG 9), leading to GHG emissions reductions (SDG 13) by encouraging sustainable consumption and production practices (SDG 12).

17.3.3.2 Water-Energy-Food-Nexus

This section addresses the links between water, energy and food in the context of sustainable development and the associated synergies and trade-offs, with links to related chapters. The focus outline includes scoping and the relationship with the SDGs, general climate-change impacts on global water resources, energy-system impacts and the relationship to renewables, enabling strategies, trade-offs and cross-sectoral implications (see also Chapter 12), nexus-management tools and strategies, and a box with examples from India and South Africa.

The continually increasing pressures on natural resources, such as land and water, due to the rising demands from increases in population and living standards, which also require more energy, emphasises the need to integrate sustainable planning and exploitation (Bleischwitz et al. 2018).

The water-energy-food nexus is at the epicentre of these challenges, which are of global relevance and are the focus of policies and planning at all levels and sectors of the global society. The nexus between water, energy and food (WEFN) (Zhang et al. 2018b) is tight and complex, and needs careful attention and deciphering across spatio-temporal scales, sectors and interests to balance proper management and trade-offs and to pursue sustainable development (Biggs et al. 2015; Dai et al. 2018; Hamiche et al. 2016). The WEFN touches upon the majority of the UN's SDGs, such as 2, 6-7 and 11-15 (Bleischwitz et al. 2018), and deals with basic commodities, thus guaranteeing the basic livelihoods of the global population.

The task of gaining an improved understanding of WEFN processes across disciplines such as the natural sciences, economics, the social sciences and politics has been further exacerbated by climate change, population growth and resource depletion. In light of the system of interlinkages involved, the WEFN concept essentially also covers land (Ringler et al. 2013) and climate (Brouwer et al. 2018; Sušnik et al. 2018) and can be further assessed in light of the relevant economic, ecological, social and SDG aspects (Fan et al. 2019a). Fan et al. (2019b) specifically, SDGs 2 (food), 6 (water), (7) energy, 11 (cities) and 12 (production and consumption) are considered essential to the WEFN (Bleischwitz et al. 2018). The nexus approach was introduced in the early 2010s, when it was argued that advantages could be gained by adopting a nexus approach with regard to cross-sectoral and human–nature dependencies and by taking externalities into account (Hoffmann 2011). Hence, within the nexus, obvious trade-offs exist with competing interests, such as water availability versus food production.

Climate change is projected to impact on the distribution, magnitude and variability of global water resources. A yearly increase in precipitation of 7% globally is expected by 2100 in a high-emissions scenario (RCP 8.5), although with significant inter-model, inter-regional and inter-temporal differences (Giorgi et al. 2019). Similarly, extreme events related to the water balance, such as droughts and extreme precipitation, are projected to shift in the future (RCP4.5) towards 2100: for example, the number of consecutive dry days is projected to increase in the Mediterranean region, southern Africa, Australia and the Amazon (Chen et al. 2014). In impact terms, an increase of 20-30% in global water-use is expected by 2050 due to the industrial and domestic demand for water. Already four billion people experience severe water scarcity for at least one month per year (WWAP-UNESCO 2019).

Globally, climate change has been shown to cause increases of 4%, 8% and 10% in the share of population being exposed to water scarcities under the 1.5°C, 2°C and 3°C scenarios for global warming respectively (RCP8.5) (Koutroulis et al. 2019). At the same time, climate change is projected to cause a general increase in extreme events and climate variability, placing a substantial burden on society and the economy (Hall et al. 2014). Other than the human influence on the global hydro-climate, human activities have been shown to surpass even the impact of climate change in low to moderate emission scenarios of the water balance (Haddeland et al. 2014). Similar conclusions have been found by (Destouni et al. 2013; Koutroulis et al. 2019).

An obvious consequence of the impact of climate change on future hydro-climatic patterns is the fact that the energy system is projected to experience vast impacts through climate change (Fricko et al. 2016; Van Vliet et al. 2016a; van Vliet et al. 2016; Chapter 6). In the short run, where fossil-fuel sources make up a significant share of the global energy grid, climate impacts related to water availability and water temperatures will affect thermoelectric power generation, which relies mainly on water cooling (Larsen and Drews 2019; Pan et al. 2018); water is also used for pollution and dust control, cleaning etc. (Larsen et al. 2019). Currently, 98% of electricity generation relies on thermoelectric power (81%) and hydropower (17%) (van Vliet et al. 2016).

Of these thermoelectric sources, the vast majority employ substantial amounts of water for cooling purposes, although there is a trend currently towards implementing more hybrid or drier forms of cooling (Larsen et al. 2019).

The renewable energy conversion technologies that are currently dominant globally and are projected to remain so are less vulnerable to water deficiencies than fossil-based technologies, since no cooling is used. These renewable energy conversion sources include, e.g., wind, solar PV and wave energy. The implementation of such sources will, in the longer run, have the potential to reduce water usage by the energy sector substantially (Lohrmann et al. 2019). Also, an increasing share of renewables within desalination, as well as improved irrigation efficiencies, have been shown to potentially improve the inter-sectorial WEFN water balance (Lohrmann et al. 2019). Also, an increasing share of renewables on connection with desalination, as well as improved irrigation efficiencies, have been shown to potentially improve the inter-sectorial WEFN water balance (Caldera and Breyer 2020). Some less dominant renewable-energy technologies do use water for cooling, such as geothermal energy and solar CSP, if wet cooling is employed. Despite the general detachment from water resources, wind and solar PV, for example, are highly dependent on climate-change patterns, including variability depending on future energy-storage capacities and on-/off-grid solutions (Schlott et al. 2018). Furthermore, regardless of whether or not they are based on renewables, climate change will affect energy usage across sectors, such as heating and cooling in the building stock. The energy systems in question need to be able to handle variations and extremes in demand (Larsen et al. 2020).

For the 2080s compared to 1971-2000, an increase of 2.4% to 6.3% in the global gross hydropower potential, from the hydrological side alone, is seen across all scenarios (van Vliet et al. 2016 and Chapter 6). Alongside the global increase in hydropower potential, the global mean water-discharge cooling capacity, which also relates to water temperatures, experiences a decrease of 4.5% to 15% across the scenarios. In very general and global terms, when combined, these changes support the shift towards sources of renewable energy, including hydropower, in the energy mix. When it comes to ensuring stability in the management of the electricity grid, hydro-climatological extremes have the potential to pose vast difficulties in certain regions and/or seasons depending on the nature of the energy mix (Van Vliet et al. 2016b). Van Vliet et al. (2016a) showed significant reductions in both thermoelectric and hydropower electricity capacities, exemplified by the 2003 European drought, which resulted in reductions of 4.7% and 6.6% respectively.

The energy sector is vulnerable to production losses caused mainly by heatwaves and droughts, whereas coastal and fluvial floods are also responsible for a large relative share of the energy sector's vulnerability, as assessed by (Forzieri et al. 2018) for Europe in 2100. In total, heatwaves and droughts will be responsible for 94% of the damage costs to the European energy system compared to 40% today. Similarly, (Craig et al. 2018) show that, despite potentially minor spatiotemporally aggregated differences for various energy-system components, such as demand, thermoelectric power, wind etc., the aggregated impact of climate change across these components will cause a significant impact on the energy system, as currently exemplified by the USA. In terms of investments and management, it is important to unravel these cross-component relations in light of the projected nature of the future climate.

In the ongoing transition towards renewable sources of energy (see also Chapters 3, 4 and 6), the impact of the hydro-climate on energy production continues to be highly relevant (Jones and Warner 2016). As the shares of thermoelectric energy production in the energy grid go down along with the introduction of thermoelectric cooling technologies using smaller amounts of water, new energy sources and technologies are being introduced, and existing sources scaled up. Of these, hydropower, wind and solar energy are the key energy sources currently and will be in the near future, making up 2.5% and 1.8% of the total global primary energy supply in 2017 respectively (IEA 2019). Wind and solar energy are directly independent of water in themselves, but are dependent on atmospheric conditions related to processes that also drive the water balance and circulation. Hydropower, on the other hand, is directly influenced by and dependent on the supply of water, while at the same time being an essential counter-component to seasonality and climatological variation, as well as to current and future demand curves and diurnal variations, as against wind and solar energy (De Barbosa et al. 2017).

Furthermore, policy instruments in power-system management, here exemplified by hydropower in a climate-change scenario, have been shown to enhance energy production during droughts (Gjorgiev and Sansavini 2018). The significant influence of variation in the planning of renewable energy for the 21st century has also been highlighted by (Bloomfield et al. 2016). At the same time, the integration of renewables must account for lower thermoelectric efficiencies and capacities due to increases in temperature (van Vliet et al. 2016), power-plant closures during extreme weather events due to a lack of cooling capacity (Forzieri et al. 2018) and further efficiency reductions and penalties following the implementation of CCS technologies in the effort to reach the GHG mitigation targets (Byers et al. 2015). However, more recent studies find more promising amounts of water being used for energy conversion (IEAGHG 2020; Magneschi et al. 2017).

The extraction, distribution and wastewater processes of anthropogenic water-management systems similarly use vast amounts of energy, making the proper management of water essential to reduce energy usage and GHG emissions (Nair et al. 2014 and Chapter 11). One study reports that the water sector accounts for 5% of total US GHG emissions (Rothausen and Conway 2011). Within the WEFN, there is an obvious trade-off between water availability and food production, competing demands that pose a risk to the supply of the basic commodities of food, energy and water in line with the SDGs (Bleischwitz et al. 2018; Gao et al. 2019), all of which has the potential for inter-sectorial or inter-regional conflicts (Froese and Schilling 2019). Currently, 24% of the global population live in regions with constant water-scarce food production, and 19% experience occasional water scarcities (Kummu et al. 2014). To counterbalance the demand for food and comestibles in regions that experience constant or intermittent supplies, transportation is needed, which in itself requires suitable infrastructure, energy supplies, a well-functioning trading environment and support policies. Of the 2.6 billion people who experience constant or occasional water scarcities in food production, 55% rely on international trade, 21% on domestic trade and the remainder on water stocks (Kummu et al. 2014).

The relations between the influence of hydro-climatic variability, socio-economic conditions and patterns of water scarcity have been addressed by (Veldkamp et al. 2015). A key finding of this study was the ability of the hydro-climate and the socio-economy to interact, enforcing or attenuating each other, though with the former acting as the key immediate driver, and the influence of the latter emerging after six to ten years.

The trade-offs between competing demands have been investigated on a continental scale in the US Great Plains, highlighting the influence of irrigation in mitigating reductions in crop yields (Zhang et al. 2018b). Despite crop-yield reductions of 50% in dry years compared to wet years, a key conclusion was that the irrigation should be counterbalanced against general water and energy savings within the context of trade-offs. In East Asia, the WEFN has been quantified, highlighting obvious trade-offs between economic growth, environmental issues and food security (White et al. 2018). This same study also highlights the concept of a virtual WEFN that includes water embodied within products that are traded and shipped. (Liu et al. 2019) find an urgent need for proper assessment methods, including of trade within the WEFN, due to the significant resource allocations.

Within the WEFN, the implementation of policies to achieve low stabilisation targets is strongly linked to sustainable development within the water sector with regard to water management and water conservation, indicating that additional coherence in policies affecting the water, energy and food sectors (among others) will be critical in achieving the SDGs see also Chapter 7). Subsidized fertilizers, energy and crops can drive unsustainable levels of water usage and pollution in agriculture. More than half the world's population, roughly 4.3 billion people in 2016, live in areas where the demand for water resources outstrips sustainable supplies for at least part of the year. Irrigated agriculture is already using around 70% of the available freshwater, and the large seasonal variations in water supply and the needs of different crops can create conflicts between water needs across sectors at different time scales (Wada et al. 2016). However, as there is little potential for increasing irrigation or expanding cropland (Steffen et al. 2015), gaps in food production gaps must be closed by increasing productivity and cropping densities on currently harvested land by increasing either rain-fed yields or water-use efficiency (Alexandratos and Bruinsma 2012).

It has been argued that applying an integrated approach to water-energy-climate-food resource management and policy-making is highly beneficial in properly addressing the co-benefits and trade-offs (Brouwer et al. 2018; Howells et al. 2013), accommodating the SDGs (Rasul 2016) and in general assessing enabling strategies to improve resource efficiency (Dai et al. 2018). For an integrated approach to analysing the WEFN, a number of modelling approaches, tools and frameworks have been proposed (Brouwer et al. 2018; de Strasser et al. 2016; Gao et al. 2019; Larsen et al. 2019; Smajgl et al. 2016), often involving multi-objective calibration. Such tools enable decision-makers to evaluate the optimal water-allocation and energy-saving solutions for the specific geography in question. As an example, (Scott 2011) found the higher transportability of electricity, compared to water, pivotal in water-energy adaptation solutions in the USA, while arguing for the additional coordination of water and energy policies as a key instrument in balancing the trade-offs.

Common to all these integrated efforts is the challenge involved in making comparisons across studies due to the combined complexities of assumptions, model codes, regions, variables, forcings etc. To accommodate these challenges, (Larsen et al. 2019) suggest employing shared criteria and forcing data to enable cross-model comparisons and uncertainty estimates, as also highlighted by (Brouwer et al. 2018). Other limitations in current WEFN research are partial system descriptions, the failure to address uncertainties, system boundaries, and evaluation methods and metrics (Zhang et al. 2018b). The lack of proper access to WEFN data and data quality has been highlighted by (D'Odorico et al. 2018; Larsen et al. 2019). Furthermore, gaps have been identified between theory and end-user applications in the lack of any focus on food nutritional values as opposed to calories alone, in the understanding of water availability in relation to management practices, in integrating new energy technologies and in the resulting environmental issues (D'Odorico et al. 2018).

Therefore, looking ahead, future fields of WEFN research should provide greater insights into all these aspects. Holistic frameworks have been put forward to facilitate methods of WEFN management by focusing on, for example, the geographical complexities with regard to transboundary challenges within hydrological catchments (de Strasser et al. 2016), aligning policy incentives (Rasul 2016) and making synergies and trade-offs in relation to WEFN SDG targets (Fader et al. 2018) etc. The roles of all levels of government in optimal WEFN management are also highlighted in (Kurian 2017), especially with regard to shaping the behaviour of individuals. Furthermore, (Kurian 2017) highlights the challenges involved in science and policy communicating with one another and in the provision of optimal instruments and guidelines. Engaging non-experts and end-users in scientific processes is seen as essential to capturing previous failures and successes and to ensure that understanding the challenges is updated to help shape the research questions.

Coordination of water use across different sectors and deltas is an important factor in sustainable water management. Examples of instruments and policies that support this from India and Sub-Saharan Africa in relation to the groundwater crisis are given below. India is the world's largest user of groundwater for irrigation, which covers more than half of the country's total irrigated agricultural area, is responsible for 70% of food production and supports more than 50% of the population (700 million people) (see also Chapter 7). However, excessive extraction of groundwater is depleting aquifers across the country, and falls in the water table have become pervasive. Improved water-use efficiency in irrigated agriculture is being considered, both globally and in India, as a way of meeting future food requirements with increasingly scarce water resources (Fishman et al. 2015).

The entirety of Sub-Saharan Africa has an undeveloped potential for groundwater exploitation, despite the general perception of a global groundwater crisis, this being due to the absence of services to support groundwater development (Cobbing 2020). It is estimated that most Sub-Saharan countries in Africa utilize less than 5% of their national sustainable yields (Cobbing and Hiller 2019). The initial tool for driving sustainable groundwater exploitation is a change in the narrative of a lack of resources in order to stimulate increased agricultural production and increased fulfilment of the SDGs (Cobbing 2020). Quantitative measures of actual groundwater vulnerability based on multiple indicators have been calculated by, for example, (van Rooyen et al. 2020), showing that 20.4% of South Africa's current water resources are highly vulnerable and are projected to worsen fifty years into the future.

Despite the positive perspectives regarding Sub-Saharan groundwater resources, the 2015-2017 water crisis in South Africa, including in Cape Town, clearly predicts vulnerability to climate variability (Carvalho Resende et al. 2019), which is predicted to increase. Serving as inspiration for the future mitigation of water depletion, (Olivier and Xu 2019) suggest certain governance tools to improve the diversification of water sources and the management of existing supplies.

17.3.3.3 Industry

Industrial transformation is a core component in achieving sustainable development. Across all industrial sectors, the development and deployment of innovative technologies, business models and policy approaches at scale will be essential in accelerating progress both with meeting the economic and social development goals and with achieving low emissions. In this section, we assess the synergies and trade-offs between mitigation options and the SDGs, with a specific focus on asking whether economic growth and employment creation can work jointly with climate actions and other SDGs in least developed and developing countries. Examples of synergies and trade-offs are provided based on the conclusions of Chapter 9 on the building sector and Chapter 11 on industry. The potential for greening industry is discussed in relation to eco-industrial parks, with examples from Ethiopia, China, South Africa and Ghana.

Chapter 11 concludes that achieving net zero emissions from the industrial sector are possible. This will require the provision of electricity free from greenhouse gas (GHG) emissions, including from other energy carriers, increased electrification, low carbon feedstocks, and a combination of energy efficiency, reduced demand for materials, a more circular economy, electrification and carbon capture, use and storage (CCUS).

The potential co-benefits of mitigation options in industry has been mapped out in Chapter 11 in relation to five categories of mitigation options: material efficiency and reductions in the demand for materials, the circular economy and industrial waste, carbon capture utilization and storage, energy efficiency, and electrification and fuel switching (Figure 11.15 in Chapter 11). In particular, the first two categories of options are assessed as having several co-benefits for the SDGs, including SDGs 3, 5, 7, 8, 9 11, 12, and 15. Some studies also point out the potential trade-offs in respect of employment and the costs of cleaner production. The other options primarily impact on climate actions, decent work and employment, and industry as such.

Okereke et al. (2019) offer important generic conclusions on green industrialisation and the transition based on a study of socio-technical transition in Ethiopia. The importance of drivers for changes in terms of clear policy goals and government support for green growth and climate policies, as well as support from a strong culture of innovation, is emphasized. The study also identifies key barriers in relation to stakeholder interactions, the availability of resources and the ongoing tensions between ambitions for high economic growth and climate change. Green innovation in industry critically depends on regulations. Gramkow and Anger-Kraavi (2018) have assessed the role of fiscal policies in greening Brazilian industry based on an econometric analysis of 24 manufacturing sectors. They conclude that instruments like low-cost finance for innovation and support to sustainable practices effectively promote green innovation.

Luken (2019) have assessed the drivers, barriers and enablers for green industry in Sub-Saharan Africa, concluding that major barriers exist related to material and input costs, as well as product requirements in foreign markets, and that as a result there are trade-offs between economic and environmental performance. Studies of ten countries are reviewed, and although they suffer from limited information, they conclude similarly that further progress is being hindered by poor access to finance and weak government regulation. (Greenberg and Rogerson 2014) They similarly conclude that the greening of industry in South Africa is lagging behind due to economic barriers and weak governance, despite its high priority in government planning and among international partners.

Ghana has launched a "One District One Factory" (1D1F) initiative, aimed at establishing at least one factory or enterprise in each of Ghana's 216 districts as a means of creating economic growth poles to accelerate the development of these areas and create jobs for the country's increasingly youthful population. The policy aims to transform the structure of the economy from one dependent on the production and export of raw materials to a value-added industrialized economy driven primarily by the private sector (Yaw 2018). As has been pointed out by (Mensah et al. 2021), in its initial design the programme did not take environmental quality into consideration. Although it was successful in creating economic growth, exports and employment, the environmental impacts have been negative. It has therefore been recommended that environmental regulations be imposed on foreign investments. Similar conclusions have been drawn by (Solarin et al. 2017).

Chapter 11 concludes that eco-industrial parks, in which businesses cooperate with each other in order to avoid environmental pressure and support sustainable development, have delivered several benefits in relation to overall reductions in both virgin materials and final wastes, implying significant reductions in industrial GHG emissions. Due to these advantages, eco-industrial parks have been actively promoted, especially in East Asian countries such as China, Japan and South Korea, where national indicators and governance exist (Geng et al. 2019; Geng and Hengxin 2009).

Zeng et al. (2020) have assessed the role of eco-industrial parks in China's green transformation for 33 development zones in relation to contributions to GDP, industrial value added, exports, water and energy consumption, CO_2 levels and sulphur emissions. They concluded that industrial parks have played a very important role in China's industrialisation, and that this structure has supported the decoupling of economic growth and energy and water consumption from the environmental impacts. However, improved environmental performance would require better access to finance and a higher priority by management.

Eco-industrial parks have been promoted in Ethiopia by the government and UNIDO, based on the expectation that they could help to boost the economy (UNIDO 2018, Oqubay et al 2021). One of the success stories is an industrial park in Hawassa, a nation-level textile and garment industrial park with a "zero emissions commitment" based on renewable energy and energy-efficient technologies. However, the concept of the industrial park, including feasible policies and institutional arrangements, is new to Ethiopia's regulatory processes, and this has created problems for management, knowledge and governance, hindering their fast implementation.

A number of business associations have developed strategies for sustainable development and climate change, including cooperate social responsibility (CSR). International initiatives have included the promotion of CSR initiatives by international investors in low-income countries to support a broad range of development priorities, including social working conditions, eliminating child labour and climate change (Lamb et al. 2017). Leventon et al. (2015) evaluated the role of mining industries in Zambia in supporting climate-compatible development and concluded that, although the industry has played a positive role in avoiding migration and pressure on forest resources, there is a lack of coordination between government and industry initiatives.

It can be concluded that most of the mitigation options in industry considered in this section could have synergies with the SDGs, but also that some of the renewable-energy options could indicate some trade-offs in relation to land use, with implications for food- and water security and costs. Carbon capture and storage could play an enabling role in the provision of reliable, sustainable and modern energy and could support decarbonisation, but it can also be costly (IEAGHG 2020; Mikunda et al. 2021). The provision of water for CCS can include both synergies and trade-offs with the SDGs due to recent progress in water-management technologies (Giannaris et al. 2020; IEAGHG 2020; Mikunda et al. 2021)

17.3.3.4 Cities, Infrastructure and Transportation

With 80% of the global population expected to be urban by 2050, cities will shape development paths for the foreseeable future (United Nation 2018). The challenge for many policymakers is to construct development paths that make cities clean, prosperous and liveable while mitigating climate change and building resilience to heatwaves, flooding and other climate risks. The IPCC 1.5 report sees achieving these objectives as feasible: cities could potentially realize significant climate and sustainable-development benefits from shifting development paths (Wiktorowicz et al. 2018). The section assesses the synergies and trade-offs between meeting the SDGs and climate-change mitigation, as well as providing a general overview of mitigation options in cities and of enabling factors, including city networks and plans for jointly addressing the SDGs and climate-change mitigation.

Chapter 8 concludes that urban areas potentially offer several joint benefits between mitigation and the SDGs, and that since AR5, evidence of the co-benefits of urban mitigation continues to grow. In developing countries, a co-benefits approach that frames climate objectives alongside other development benefits arise increasingly being seen as an important concept justifying and driving climate-change actions in developing countries (Sethi and Puppum De Oliveria 2018; Seto et al. 2016).

Evidence of the co-benefits of urban mitigation measures on human health has increased significantly since the IPCC AR5, especially through the use of health-impact assessments in cities like Geneva, where energy savings and cleaner energy-supply structures based on measures for urban planning, heating and transport have reduced CO_2, NOx and PM10 emissions and increased the opportunities for physical activity for the prevention of cardiovascular diseases (Diallo et al. 2016).

There is increasing evidence that climate-mitigation measures can lower health risks that are related to energy poverty, especially in vulnerable groups, such as the elderly (Monforti-Ferrario et al. 2019). Moreover, the use of urban forestry and green infrastructure as both a climate mitigation and an adaptation measure can reduce heat stress (Kim and Coseo 2019; Privitera and La Rosa 2017) while removing air pollutants to improve air quality (Scholz et al. 2018; De la Sota et al. 2019) and enhancing well-being, including contributions to local development and possible reductions of inequalities (Lwasa et al. 2015). Other studies evidence the potential to reduce premature mortality by up to 7,000 in 53 towns and cities and to create 93,000 net new jobs and lower global climate costs, as well as reduce personal energy costs based on road maps for renewable energy transformations (Jacobson et al. 2018).

The co-benefits of energy-saving measures described by 146 signatories to a city climate network due to improved air quality have been quantified as 6,596 avoided premature deaths (with a 95% confidence interval of 4,356 to 8,572 avoided premature deaths) and 68,476 years of life saved (with a 95% confidence interval of 45,403 and 89,358 years of life saved) (Monforti-Ferrario et al. 2019). Better air quality further reinforces the health co-benefits of climate-mitigation measures based on walking and bicycling, since the evidence suggests that increased physical activity in urban outdoor settings with low levels of black carbon improves lung function (Laeremans et al. 2018). Chapter 9 shows that mitigation actions in buildings have multiple co-benefits resulting in substantial social and economic value beyond their direct impacts on reducing energy consumption and GHG emissions, thus contributing to the achievement of almost all the United Nation's SDGs. Most studies agree that the value of these multiple benefits is greater than the value of the energy savings, while their quantification and inclusion in decision-making processes will strengthen the adoption of ambitious reduction targets and improve coordination across policy areas.

There are several examples of cities that have developed plans for meeting both the SDGs and mitigation, which demonstrates the feasibility of meeting these objectives jointly. Quito, Ecuador, a city with large carbon footprints (Global Opportunity Explorer 2019) and climate vulnerabilities, has adopted low-carbon plans that aim to achieve the climate goals while introducing net zero energy buildings and reducing water stress (Ordoñez et al. 2019; Marcotullio et al. 2018). Several cities in China, Indonesia and Japan have invested in green city initiatives by means of green infrastructural investments, which is claimed to be a form of smart investment. Through this type of investment, economic growth and greenhouse gas (GHG) emissions reductions can be achieved in cities (Jupesta et al. 2016). Multi-level governance arrangements, public-private cooperation and robust urban-data platforms are among the factors enabling the pursuit of these objectives within countries (Corfee-Morlot et al. 2009; Gordon 2015; Creutzig et al. 2019; Yarime 2017).

In addition to the mostly domestic enablers listed previously, some cities have also benefited from working with international networks. The Global Covenant of Mayors for Climate and Energy (Covenant of Mayors 2019), the World Mayors Council on Climate Change, ECLEI, C40, and UNDRR (ECLEI 2019; C40 Cities 2019; UN- UNDRR 2019) have provided targeted support, disseminated information and tools, and sponsored campaigns (Race to Zero) to motivate cities to embrace climate and sustainability objectives. Despite this support, it should be stressed that most cities are in the early stages of climate planning (Climate-Adapt 2019; Eisenack and Reckien 2013; Reckien et al. 2018). Furthermore, in some cases city policymakers may fail to highlight the synergies and trade-offs between climate and sustainable development or rebrand GHG-intensive practices as 'sustainable' in relevant plans (Tozer 2018).

With regard to city networks, Chapter 8, Section 8.5 concluded that the importance of urban-scale policies for sustainability has increasingly been recognized by international organizations and national and regional governments. For example, in 2015, more than 150 national leaders adopted the UN's 2030 Sustainable Development Agenda, including stand-alone SDG 11, "make cities and human settlements inclusive, safe, resilient and sustainable" (United Nations 2015 p. 14). The following year, 170 countries agreed to the UN New Urban Agenda (NUA), a central part of which is recognizing the importance of national urban policies (NUPs) as a key to achieving national economic, social and environmental goals (United Nations 2015a, 2017). Similarly, the Sendai Framework for Disaster Risk Reduction identifies the need to focus on unplanned and rapid urbanization to reduce exposure and vulnerability to the risks of disasters (United Nations 2015b).

For many cities, a key to reorienting development paths will be investing in sustainable, low-carbon infrastructure. Because infrastructure has a long lifetime and influences everything from lifestyle choices to consumption patterns, decisions over an estimated USD90 trillion of infrastructure investment (from now to 2030) will be critical in order to avoid becoming locked into unsustainable paths (WRI 2016). This is particularly true in developing countries, where demands for new buildings, roads, energy and waste-management systems are already surging. To some extent, policies that accelerate building renovation rates, including voluntary programmes (Van der Heijden 2018), can support transitions down more sustainable paths (Kuramochi et al. 2018). Factoring climate and sustainable development considerations into policy tools that facilitate quantitative emission performance standard (EPS) and the inclusion of climate and sustainable development benefits and risks in infrastructure assessments or risk-adjusted returns on investments in development banks could also prove useful (Rydge et al. 2015). Strong policy signals from the UNFCCC and from national climate policies and strategies (including NDCs) could facilitate uptake of the relevant policies and the use of these tools.

Infrastructural investments will also have wide-ranging implications for sustainable, low-carbon urban development, namely transport and mobility. To some extent, decision-making frameworks such as Avoid-Shift-Improve could help make these patterns low carbon and sustainable (Dalkmann and Brannigan 2007; Wittneben et al. 2009). Mixed land-use planning and compact cities can not only help avoid emissions or shift travellers into cleaner modes (Cervero 2009),), they can also improve air quality, reduce commuting times, enhance energy security and improve connectivity (Pathak and Shukla 2016; Zusman et al. 2011)

17.3.3.5 Mitigation-adaptation relations

The section will consider the links between mitigation and adaptation options in the context of sustainable development and the associated synergies and trade-offs. Cross-cutting conclusions will be drawn based on Chapter 3 and the sectoral chapters of AR6 WGIII and Chapter 18 of AR6 WGII. The focus will be on the following sectors: agriculture, food and land use; water-energy-food; industry and the circular economy; and urban areas.

IPCC, WG II, concludes that coherent and integrated policy-planning is needed in order to support integrated climate change adaptation and mitigation policies and that this is a key component of climate-resilient development pathways. Section 4.5.2 in Chapter 4 assesses development pathways and the specific links between mitigation and adaptation, concluding that there can be co-benefits, and trade-offs, where mitigation implies maladaptation. However, adaptation can also be a prerequisite for mitigation. It is therefore concluded that making development pathways more sustainable can build the capacity for both mitigation and adaptation.

Climate actions, including climate-change mitigation and adaptation, are highly scale-dependent, and solutions are very context-specific. Especially in developing countries, a strong link exists between sustainable development, vulnerability and climate risks, as limited economic, social and institutional resources often result in low adaptive capacities and high vulnerability. Similarly, the limitations in resources also constitute key elements weakening the capacity for climate-change mitigation (Jakob et al. 2014). The change to climate-resilient societies requires transformational or systemic changes, which also have important implications for the suite of available sustainable-development pathways (Kates et al. 2012; Lemos et al. 2013). Thornton and Comberti (2017) point to the need for social-ecological transformations to take place if synergies between mitigation and adaptation are to be captured, based on the argument that incremental adaptation will not be sufficient when climate-change impacts can be extreme or rapid and when deep decarbonization simultaneously involves social change (Chapter 18 in AR6 WG II).

As discussed in AR6 WG II, Section 18.4 in Chapter 18, there are synergies and trade-offs between adaptation and sustainable development, as well as between mitigation and sustainable development, which is supported by comprehensive assessments such as that by (Dovie 2019; Sharifi 2020). Links between mitigation and adaptation options are identified in Chapter 18 in AR6 WG II, such as expected changes in energy demand due to climate change interacting with energy-system development and mitigation options, changes to agricultural production practices to manage the risks of potential changes in weather patterns affecting land-based emissions and mitigation strategies, or mitigation strategies that place additional demands on resources and markets. This increases the pressures on and costs of adaptation or ecosystem restoration linked to carbon sequestration and the benefits in terms of the resilience of natural and managed ecosystems, but it also could restrict mitigation options and increase costs. Chapter 3 of AR6 WG III similarly concludes that the connectedness and coherence of actions to mitigate climate change could support the conservation and adaptation of ecosystems and meet the sustainable development goals more widely.

Options to reduce agricultural demand (e.g., dietary change, reducing food waste) can have co-benefits for adaptation through reductions in the demand for land and water (Smith et al. 2019b). For example, Grubler et al. (2018) show that stringent climate-mitigation pathways without reliance on BECCS can be achieved through efficiency improvements and reduced energy service and consumptions levels in high-income countries.

Agriculture, food and land-use is the sector where most climate policy options can simultaneously generate impacts on mitigation, adaptation and the SDGs (Locatelli et al. 2015; Kongsager et al. 2016). Bryan et al. (2013) identified a range of synergies and trade-offs across adaptation, mitigation and the SDGs in Kenya, given the diversity of its climatic and ecological conditions. Improved management of soil fertility and improved livestock-feeding practices could provide benefits to both climate-change mitigation and adaptation, as well as increase income generation from farming. However, other improvements to agricultural management in Kenya, for example, soil water conservation, could only provide benefits across all three domains in some specific sub-regions.

Conservation agriculture can yield mitigation co-benefits through improved fertiliser use or the efficient use of machinery and fossil fuels (Cui et al. 2019; Harvey et al. 2014; Pradhan et al. 2018). Climate-smart agriculture (CSA) ties mitigation to adaptation through its three pillars of increased productivity, mitigation and adaptation (Lipper et al. 2014), although managing trade-offs among the three pillars requires care (Kongsager et al. 2016; Thornton and Comberti 2017; Soussana et al. 2019). Sustainable intensification also complements CSA (Campbell et al. 2014). Enhanced sustainable adaption can lead to effective emission-reduction benefits, such as climate-smart agricultural technologies (Nefzaoui et al. 2012; Poudel 2014) and ecosystem-based adaptation. Berry, P et al. (2015); Geneletti and Zardo (2016); and Warmenbol and Smith (2018) have shown how increases in livelihoods can contribute to climate change mitigation in Europe.

Agroforestry can sustain or increase food production in some systems and increase farmers' resilience to climate change (Jones et al. 2013). Some sustainable agricultural practices have trade-offs, and their implementation can have negative effects on adaptation or other ecosystem services. Agricultural practices can aid both mitigation and adaptation on the ground, but yields may be lower, so there may be a trade-off between resilience to climate change and efficiency. Interconnections within the global agricultural system may also lead to deforestation elsewhere (Erb et al. 2016). Implementation of sustainable agriculture can increase or decrease yields, depending on context (Pretty et al. 2006) (Chapter 4).

Land-based mitigation and adaptation will not only help reduce greenhouse gas emissions in the AFOLU sector, but also help augment the sector's role as a carbon sink by increasing forest and tree cover through afforestation and agroforestry activities and other eco-system-based approaches. Some of these options, however, can also have negative impacts on GHG emissions in the form of indirect impacts on land use (for a more detailed discussion, see Chapter 7). If managed and regulated appropriately, the land use, land-use change and forestry (LULUCF) sector could play a key role in mitigation and be a key sector for emissions reductions beyond 2025 instead of contributing substantially to emissions reductions beyond 2025 (Keramidas et al. 2018). However, the large-scale deployment of intensive bioenergy plantations, including monocultures, replacing natural forests and subsistence farmlands are likely to have negative impacts on biodiversity and can threaten food and water security, as well as local livelihoods, partly by intensifying social conflicts, partly by reducing resilience (Díaz et al. 2019). Expansion on to abandoned or unused croplands and pastures nonetheless present significant global potential, and will avoid the sustainability risks of expanding agriculture into natural vegetation (Næss et al. 2021).

Based on a literature review, Berry et al. (2015) identified water-saving and irrigation techniques in agriculture as attractive adaptation options that have positive synergies with mitigation in increasing soil carbon, reducing energy consumption and reducing CH_4 emissions from intermittent rice-paddy irrigation. These measures could, however, reduce water flows in rivers and adversely affect wetlands and biodiversity. The study also concluded that afforestation could reduce peak water flows and increase carbon sequestration, but trade-offs could emerge in relation to the increased demand for water.

Fast-growing tree monocultures or biofuel crops may enhance carbon stocks but reduce downstream water availability and the availability of agricultural land (Harvey et al. 2014). Similarly, in some dry environments, agroforestry can increase competition with crops and pastureland, decreasing productivity and reducing the yields of catchment water (Schrobback et al. 2011; Chapter 7).

Hydro-power dams are among the low-cost mitigation options, provided the cost of constructing the plant is taken into account, but they could have serious trade-offs in relation to key sustainable-development aspects, since in respect of water and land availability dams can have negative effects on ecosystems and livelihoods, thereby implying increased vulnerabilities. Section 17.3.3.2 on the water-energy-food nexus includes examples of trade-offs between the benefits of producing electricity from hydro-power dams and the trade-offs with ecosystem services and using land for agriculture and livelihoods.

There are several potentially strong links between climate-change adaptation in industry and climate-change mitigation. Various supply chains can be affected by climate change, energy supply and water supply, and other resources can be disrupted by climate events. Adaptation measures can influence GHG emissions in their turn and thus mitigation because of the demand for basic materials, for example, as well as by influencing outdoor environments and labour productivity (Chapter 11.1.4).

Implementing adaptation options in industry can also imply increasing the demand for packaging materials such as plastics and for access to refrigeration. These are among the adaptation options that are dependent on temperature and storage possibilities, as well as being major sources of GHG emissions.

An increasing number of cities are becoming involved in voluntary actions and networks aimed at drawing up integrated plans for sustainable development and climate-change mitigation and adaptation, including cities in both high- and low-income countries around the world. Grafakos et al. (2019); Sanchez Rodriguez et al. (2018) concluded that cities are an obvious place for the development of plans that can capture several synergies between sustainable development and climate-resilient pathways. Kim and Grafakos (2019); and Landauer et al. (2019) similarly concluded that cities are an obvious platform for the development of integrated planning efforts because of the scale of policies and actions, which could potentially match the different policy domains. Kim and Grafakos (2019) assessed the level of integration of mitigation and adaptation in urban climate-change plans across 44 major Latin American cities, concluding that the integration of climate-change mitigation and adaption plans was very weak in about half the cities and that limited donor finance was a main barrier. The authors also mention barriers in relation to governance and the weakness or lack of legal frameworks. The integration of SDGs with adaptation could help increase the willingness of politicians to implement climate actions, as well as provide stronger arguments for investing the required resources (Sanchez Rodriguez et al. 2018).

The local integration of planning and policy implementation practices was also examined by Newell et al. (2018) in a study of eleven Canadian communities. It was concluded that, in order to put plans into practice, a deeper understanding needs to be established of the potential synergies and trade-offs between sustainable development and climate-change mitigation and adaptation. A model was applied to the evaluation of key impacts, including energy innovation, transportation, the greening of cities and city life. The impact assessment came to the conclusion that multiple benefits, costs and conflicting areas could be involved, and that bringing a broad range of stakeholders into policy implementation was therefore to be recommended.

There are several links between mitigation and adaptation options in the building sector, as pointed out in Chapter 9. Adaptation can increase energy consumption and associated GHG emissions (Kalvelage et al. 2013; Campagnolo and Davide 2019), for example, in relation to the demand for energy to meet indoor thermal comfort requirements in a future warmer climate (de Wilde and Coley 2012; Li and Yao 2012; Clarke et al. 2018). Mitigation alternatives using passive approaches may increase resilience to the impacts of climate change on thermal comfort and could reduce cooling needs (Wan et al. 2012; Andrić et al. 2019). However, climate change may reduce their effectiveness (Ürge-Vorsatz et al. 2014).

Mitigation and the co-benefits of adaptation in urban areas in relation to air quality, health, green jobs and equality issues are dealt with in Section 8.2 in Chapter 8, where it is concluded that most mitigation options will have positive impacts on adaptation, with the exception of compact cities, with trade-offs between mitigation and adaptation. This is because decreasing urban sprawl can increase the risks of flooding and heat stress. Detailed mapping between mitigation and adaptation in urban areas shows that there are many, very close interactions between the two policy domains and that coordinated governance across sectors is therefore called for.

Rebuilding and refurbishment after climate hazards can increase energy consumption and GHG emissions in the construction and building materials sectors, as it could making the existing building stock more climate-resilient (Hallegatte 2009; de Wilde and Coley 2012; Pyke et al. 2012) and thus also support implementation of the Sendai framework on disaster risk reduction (United Nations 2015b). Climate change in the form of extremely high temperatures, intense rainfall leading to flooding, more intense winds and/or storms and sea level rises (SLRs) can seriously impact transport infrastructure, including the operations and mobility of road, rail, shipping and aviation; Chapter 10 assesses the impacts on subsectors within transportation. At the same time, these sectors are major targets for GHG mitigation options, and many countries are currently examining what to do in terms of combined mitigation-adaptation efforts, using the need to mitigate climate change through transport-related GHG emissions reductions and pollutants as the basis for adaptation action (Thornbush et al. 2013; Wang and Chen 2019). For example, urban sprawl indirectly affects climate processes, increasing emissions and vulnerability, which worsens the ability to adapt (Congedo and Munafò 2014). Hence greater use of rail by passengers and freight will reduce the pressures on the roads, while having less urban sprawl will reduce the impacts on new infrastructure, often in more vulnerable areas (IPCC 2019; Newman et al. 2017).

Despite many links between mitigation and adaptation options, including synergies and trade-offs, Chapter 13 concludes that there are few frameworks for integrated policy implementation. One review of climate legislation in Europe found a lack of coordination between mitigation and adaptation, their implementation varying according to different national circumstances (Nachmany et al. 2015).

In developing and least developed countries, there are many examples of climate policies in the NDCs that have been drawn up in the context of sustainable development and that cover both mitigation and adaptation (Chapter 13; Beg 2002; and Duguma et al. 2014). However, there are many barriers to joint policy implementation. Despite the emphasis on both mitigation and adaptation policies, there is very limited literature on how to design and implement integrated policies (Di Gregorio et al. 2017; Shaw et al. 2014). For example, the links within the water, energy and food nexus require coordination among sectoral institutions and capacity-building in innovative frameworks linking science, practice and policy at multiple levels (Cook and Chu 2018; Nakano 2017; Shaw et al. 2014).

Another challenge is the shortage of financial, technical and human resources for implementing joint adaptation and mitigation policies (Antwi-Agyei et al. 2018b; Chu 2018; David and Venkatachalam 2019; Kedia 2016; Satterthwaite 2017). Several studies have stressed that the lack of finance for integrating policy implementation between sustainable development and climate-change mitigation and adaptation may constitute barriers to the implementation of adaptation projects to protect least-developed countries with many vulnerabilities.

Locatelli et al. (2016) come to similar conclusions regarding finance based on interviews with multilateral development banks, green funds and government organizations in respect of the agricultural and forestry sectors. International climate finance has been totally dominated by mitigation projects.

Those who were interviewed were asked about their willingness to change this balance and to commit more resources to projects that address both climate-change mitigation and adaptation. More than two-thirds of those interviewed, however, raised concerns that integrated projects could be too complicated and that a greater alignment of financial models across different policy domains could entail greater financial risks. Another barrier mentioned in respect of finance was that mitigation projects were primarily aimed at GHG emissions reductions, while adaptation projects had more national benefits and were also more suitable for community development and promoting equality and fairness. In an assessment of 201 projects in the forestry and agricultural sectors in the tropics Kongsager et al. (2016), found that a majority of the projects contributed to both adaptation and mitigation or at least had the potential to do so, despite the separation between these two objectives by international and national institutions.

17.3.3.6 Cross-sectoral digitalization

In this section, the potential role of digitalization as a facilitator of a fast transition to sustainable development and low emission pathways is assessed based on sectoral examples. The contributions of digital technology could contribute to efficiency improvements, cross-sectoral coordination, including new IT services, and decreasing resource use, implying several synergies with the SDGs, as well as trade-offs, for example, in relation to reduced employment, increasing energy demand and the increasing demand for services, possibly increasing GHG emissions.

The COVID-19 pandemic caused radical temporary breaks with past energy use trends. How post-pandemic recovery will impact on the longer-term energy transition is unclear. Recovering from the pandemic with energy-efficient practices embedded in new patterns of travel, work, consumption and production reduces climate mitigation challenges (Kikstra et al. 2021). The potential of digital contact-tracing to slow the spread of a virus had been quietly explored for over a decade before the COVID-19 pandemic thrust the technology into the spotlight (Cebrian 2021). The COVID-19 crisis is among the most disruptive events in recent decades and has had consequences for consumer behaviour. During the lockdowns in most countries, consumers have turned to online shopping for food products, personal hygiene and disinfection (Cruz-Cárdenas et al. 2021), making society more digitally literate.

The cost of new services provided by digitalization can be high, and this could imply barriers for low-income countries in joining new global information sharing systems and markets. Altogether this implies that any assessment of the contribution of digitalization to support the SDGs and low-carbon pathways will only be able to provide very context-specific results. Digital technologies could potentially disrupt production processes in nearly every sector of the economy. However, as an emerging area experiencing the rapid penetration of many sectors, there could be a window of opportunity for integrating sustainable development and low emission pathways. IIASA (2020) concludes that the digital revolution is characterised by many innovative technologies, which can create both synergies and trade-offs with the SDGs (IIASA 2020).

Digital technologies could potentially disrupt production processes in nearly every sector of the economy. However, as an emerging area experiencing the rapid penetration of many sectors, there could be a window of opportunity for integrating sustainable development and low emission pathways. TWI2050 (2020) concludes that the digital revolution is characterised by many innovative technologies, which can create both synergies and trade-offs with the SDG's (IIASA 2020).

WBSD (2019) has assessed the potential of communication technologies (ICT) to contribute to the transition to a global low-carbon economy in the energy, transportation, building, industry, and other sectors. The potential is estimated to be around 15% CO_2-equivalent emissions reductions in 2020 compared with a business as usual scenario. A range of ICT solutions have been highlighted, including smart motors and industrial process-management in industry, traffic-flow management, efficient engines for transport, smart logistics and smart energy systems.

The TWI2050 2019 report (IIASA 2019) assessed both the positive and negative impacts of digitalization in the context of sustainable development. It found that efficiency improvements, reduced resource-consumption and new services can support the SDGs, but also that there were challenges, including in relation to equality, facing the least developed and developing countries because of their low level of access to technologies. The necessary preconditions for successful digital transformation include prosperity, social inclusion, environmental sustainability, protection of jobs and good governance of sustainability transitions. One negative impact of digitalisation could be the rebound effects, where easier access to services could increase demand and with it GHG emissions. Digitalization in the manufacturing sector could also provide a comparative advantage to developed countries due to the falling importance of labour costs, while the barriers to emerging economies seeking to enter global markets could accordingly be increased.

In respect of governance, Krishnan et al. (2020) point out that the creation of synergies between sustainable development and low-emission urbanization based on digitalization could face barriers in the form of inadequate knowledge of structures and value creation through ecosystems that would need to be addressed by means of smart digitalizing, requiring organizational measures to support transformation processes.

Urban areas are one of the main arenas for new digital solutions due to rapid urbanization rates and high concentrations of settlements, businesses and supply systems, which offer great potential for large-scale digital systems. The emergence of smart cities has supported the uptake of smart integrated energy, transportation, water and waste-management systems, while synergies have been created in terms of more flexible and efficient systems. In its 2018 Policy and Action document, the Japanese Business Federation (Keidanren) launched Society 5.0, which include plans for smart city development (Carraz and Yuko 2019; Narvaez Rojas et al. 2021). To achieve smart cities, Society 5.0 aimed to facilitate diverse lifestyles and business success, while the quality of life offered by these options will be enhanced. It also aims to offer high-standard medical and educational services. Autonomous vehicles will be available and integrated with smart grid systems in order to facilitate mobility and flexibility in energy supply with a high share of renewable energy. The energy system will include microgrids, renewable with demand-side controls aligned with local conditions.

Chapter 6 of this report on “Energy Systems” points out that there are many smart energy options with the potential to support sustainable development by facilitating the integration of high shares of fluctuating renewable energy in electricity systems, potentially storing energy in EV batteries or fuel cells, and applying load shifting by varying prices over time. It is concluded that very large efficiency gains are expected to emerge from digitalization in the energy sector (Figure 6.18 in Chapter 6).

Section 9.9.2 in Chapter 9 concludes that the improved energy efficiency and falling costs in the building sector that could result from digitalization could have rebound effects in increasing both energy consumption and comfort levels. Increasing GHG emissions could be the result, but if low-income consumers are given faster access to affordable energy, this could agree with the SDGs, making it desirable to integrate policies targeting mitigation.

Section 10.1.2 in Chapter 10 discusses how the sharing economy, which, for example, could be facilitated by ICT platforms, could influence both mitigation and the SDGs. On the one hand, sharing has the potential to save transport emissions, especially if EVs are supplied with decarbonised grid electricity. However, an increase in transport emissions could result from this if increasing demand and higher comfort levels are facilitated, for example, by making access to EVs relatively easy compared with mass transit. Another possible trade-off is that the supply of public transport services would be limited to the elderly and other user groups.

Green innovation in agriculture is another emerging area in which digitalization is making huge progress. From the perspective of water provision, weather data can be used to predict rain amounts so that farmers can better manage the application of farm chemicals to minimize polluting aquifers and surface water systems used for drinking water. Meanwhile, smart meters, onsite and remote sensors and satellite data connected to mobile devices allow real-time monitoring of crop-water and optimal irrigation requirements. On the supply side, remote tele-control systems and efficient irrigation technologies enable farmers to control and optimize the quantity and timing of water applications, while minimizing the energy-consumption trade-offs of pressurized irrigation in both rural and urban agricultural contexts (Germer et al. 2011; Ruiz-Garcia et al. 2009).

Technology-driven precision agriculture, which combines geomorphology, satellite imagery, global positioning and smart sensors, enables enormous increases in efficiency and productivity. Taken together, these technologies provide farmers with a decision-support system in real time for the whole farm. Arguably, the world could feed the projected rise in population without radical changes to current agricultural practices if food waste can be minimized or eliminated. Digital technologies will contribute to minimizing these losses through increased efficiencies in supply chains, better shipping and transit systems, and improved refrigeration.

In conclusion, in most cases digitalization options may have both positive synergistic impacts on mitigation and the SDGs and some negative trade-offs. Energy-sector options are assessed primarily as having synergies, while some digitalisation options in transport could increase the demand for emission-intensive modes of transport. Digital platforms for the sharing economy could have both positive and negative impacts depending on the goods and services that are actually exchanged (see Cross Chapter Box 6 in Chapter 7). Options related to agriculture and the energy-water-food nexus could help manage resources more efficiently across sectors, which could create synergies. Digitalization can also raise a number of ethical challenges according to (Clark et al. 2019). Wider public discussion of internet-based activities was accordingly recommended, including topics such as the negotiation of online consent and the use of data for which consent has not been obtained.

17.3.3.7 Cross-sectoral overview of synergies and trade-offs between climate change mitigation and the SDGs

Based on a qualitative assessment in the sectoral chapters 6, 7, 8, 9, 10, and 11, Figure 17.1 below provides an overview of the most likely links between sectoral mitigation options and SDGs in terms of synergies and trade-offs. The general overview provided in the figure is supplemented by specific sector by sector comments on how the synergies and trade-offs mapped depend on the scale of implementation and the overall development context of places where the mitigation options are implemented. For some mitigation options these scaling and context-specific issues imply that there can be both synergies and trade-offs in relation to specific SDGs. In addition to the information provided in Figure 17.1, supplementary material (Supplementary Material Table 17.1) includes the detailed background material provided by the sectoral chapters in terms of qualitative information for each of the synergies and trade-offs mapped.

The assessment of synergies and trade-offs presented in Figure 17.1 depends on the underlying literature assessed by the sectoral chapters. In cases where no information about the links between specific mitigation options and SDGs are indicated, this does not imply that there are no links, but rather that the links have not been assessed by the literature.

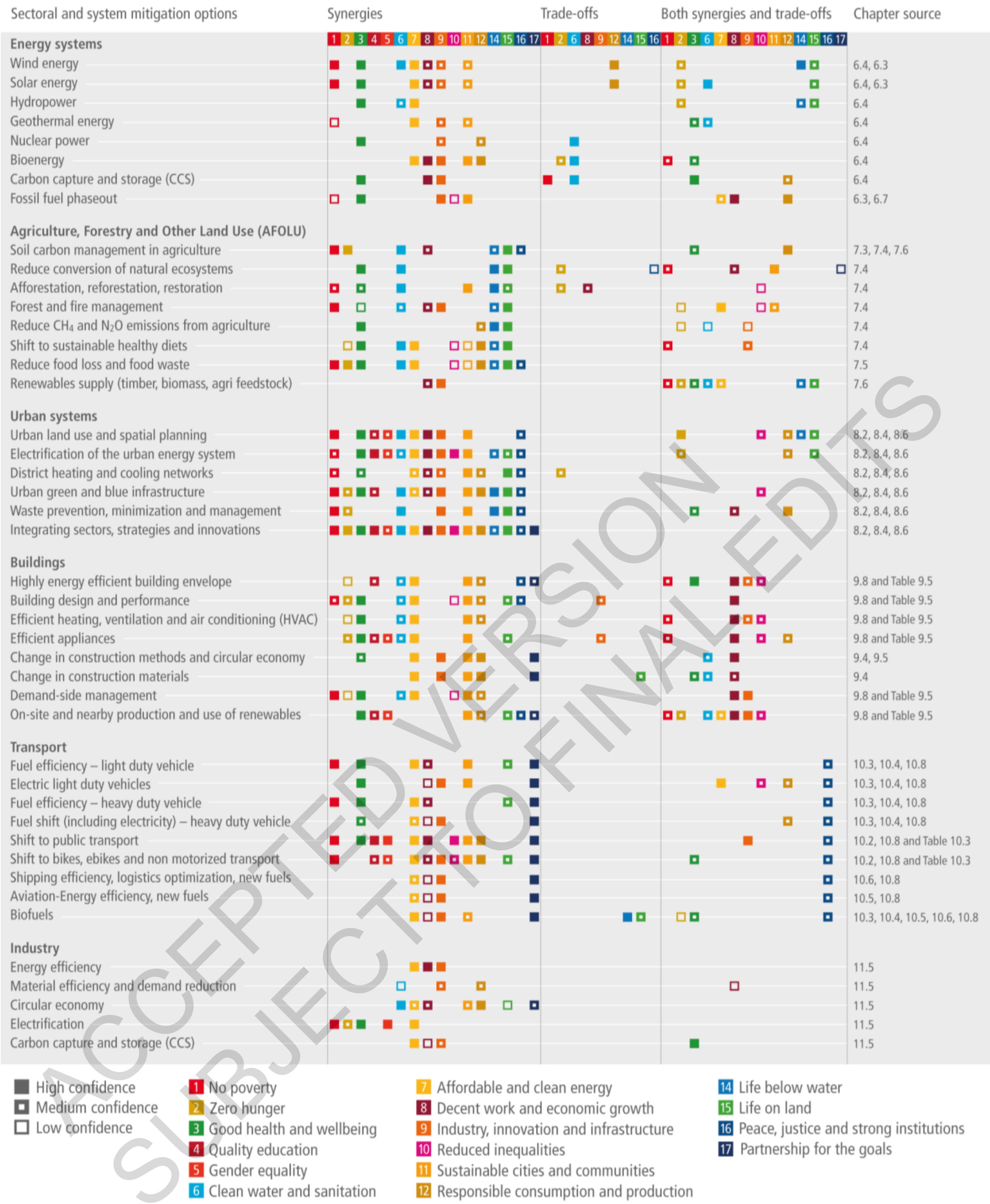

Figure 17.1 Trade-offs and synergies between sectoral mitigation options and the SDGs

Most of the energy sector options are assessed as having synergies with several SDGs, but there could be mixed synergies and trade-offs between SDG 2 ‘zero hunger’ for wind and solar energy, and for hydropower due to land-use conflicts and fishery damage. Offshore wind could also have both synergies and trade-offs with SDG 14 ‘life below water’ dependent on scale and implementation site, and it is emphasized that land-use should be coordinated with biodiversity concerns. Both wind and solar energy are assessed as having trade-offs with SDG 12 'responsible production and consumption' due to significant material consumption and disposal needs.

Geothermal energy is assessed as having synergies with SDG 1 'zero poverty' due to energy access and mixed synergies and trade-offs in relation to SDG 3 'good health and well-being' due to reduced air pollution, but with some risks in relation to water pollution, and in relation to SDG 'clean water and sanitation', if it is not well managed. Nuclear power is assessed as having synergies with SDG 3 'good health and well-being' due to reduced air pollution, but potential trade-offs in relation to SDG 6 'clean water and sanitation' due to high water consumption, and water consumption issues are also possible in relation to many of the other mitigation options in the energy sector. Synergies are identified in relation to SDG 12 'responsible production and consumption' for nuclear power due to low material consumption. CCUS has been assessed as having trade-offs in relation SDG 1 'end poverty' due to high costs and SDG 6 'clean water and sanitation' due to high water consumption. Synergies are related to SDG3 'improved health and well-being', and to SDG 9 'industry, innovation and infrastructure' due to the facilitation of decarbonisation of industrial processes. Both synergies and trade-offs could arrive in relation to SDG 12 'responsible production and consumption', since some rare chemicals and other inputs could in some cases be used with large-scale applications.

Bioenergy use as a fuel is assessed as one of the energy-sector mitigation options with most synergies and trade-offs with the SDGs. There could be synergies with SDG 1 'no poverty', with SDG 8 'decent work and economic growth' and SDG 9 'industry, innovation and infrastructure', This option, however, if combined with CCS, can be expensive and can compromise SDG1 'end poverty' due to the high costs involved.

Agriculture, forestry and other land-use mitigation options are very closely linked to the SDGs and offer both synergies and trade-offs, which in many cases are highly dependent on the scale of implementation. All the mitigation options included in Figure 17.1 are assessed as potentially having synergies with SDG 1 'end poverty', but trade-offs could also happen if large areas are used for biocrops and taken away from other activities, thus causing poverty, as well as in relation to food costs if healthier diets are made more expensive. In relation to SDG 2 'zero hunger', most of the mitigation options are assessed as being associated with both synergies and trade-offs. Trade-offs are particularly a risk with large-scale applications of afforestation projects, bioenergy crops and other land-hungry activities, which can crowd out food production.

SDG 'good health and well-being' can be supported by many mitigation options in the agriculture, forestry and food sectors, primarily due to the reduced environmental impacts, and the same is the case with SDG 14 'life below water' due to decreased nutrient loads, and SDG 15 'life on land' due to increased biodiversity, with the caveat however, that SDGs 14 and 15 could have both synergies and trade-offs dependent on land use. It is considered that there could be both synergies and trade-offs in relation to SDG 8 'decent work and economic growth' due to competition over land use related to the mitigation options reducing deforestation and reforestation and restoration, and the same is the case in relation to SDG 7 'affordable and clean energy' depending on the economic outcome of the mitigation options. Similarly the mitigation option of reduced CH_4 and N_2O emissions from agriculture are assessed as having mixed impacts on SDG 8 'decent work and economic growth', and SDG 9 'industry, innovation and infrastructure' depending on innovative food production. The mitigation options of reforestation and forest management are assessed as having mixed impacts on SDG 10 'reduced inequalities' depending on the involvement of local communities in projects. The assessment emphasises that the synergies and trade-offs of the mitigation options with the SDGs in this sector are very context- and scale-dependent, depending on how measures are carried out, for example, in relation to the enhanced production of renewables needed to replace fossil fuel-based products. If done on a massive scale and not adapted to local circumstances, there are adverse implications for food security, livelihoods and biodiversity.

All the urban mitigation options that have been assessed are considered to have synergies with the SDGs, and in a few cases both synergies and trade-offs are identified. In general, many links between mitigation options in the urban area and the SDGs have been identified in the literature. Urban land-use and spatial planning, for example, can support SDG1 'end poverty', and can also reduce vulnerability to climate change if integrated planning is undertaken, while access to food (SDG 2 'zero hunger'), and water (SDG 6) can also be achieved if supported by integrated planning. Electrification, district heating, and green and blue infrastructure in urban areas are expected to have synergies with all the SDGs addressed by the reviewed studies.

Mitigation options like waste prevention minimization and management are also assessed as having many synergies with the SDGs, but trade-offs could depend on the application of air-pollution control technologies, and on the character of informal waste-recycling activities. The impacts of the possible synergies and/or trade-offs with the SDGs will change according to the specific urban context. Synergies and/or trade-offs may be more significant in certain contexts than others. Regarding the SDGs, urban mitigation can support shifting pathways of urbanization towards sustainability. The feasibility of urban mitigation options is also malleable and can increase with more enablers. Strengthened institutional capacity that also supports the scale and coordination of the mitigation options can increase the synergies between urban mitigation options and the SDGs.

As for the urban mitigation options, the reviewed buildings sector studies reveal a lot of links between mitigation and the SDGs. Highly efficient building envelopes are expected to have synergies with the SDGs in all cases except those with potential trade-offs in relation to SDG 10 'reduced inequalities in relation to incomes'. Many SDG synergies are also identified for the building design and performance, heating, ventilation and air conditioning, and efficient appliances mitigation options. However, some trade-offs could appear in relation to SDG 8 'decent work and economic growth' due to macroeconomic impacts of reduced energy consumption, decreasing prices and stranded investments. Similar issues related to the economic impacts of reduced energy demand are also highlighted for all the other mitigation options, included for the building sector. In relation to construction materials and the circular economy, some trade-offs have been identified in relation to SDG 6 'clean water and sanitation' and SDG 15 'life on land' related to the use of biobased materials.

Consideration of the building sector highlights important context-specific issues related to synergies and trade-offs between mitigation options and SDGs such as the economic impacts (synergies and trade-offs) associated with reduced energy demand, resulting in lower energy prices, energy efficiency investments, the fostering of innovation and improvements in labour productivity. Furthermore, the distributional costs of some mitigation policies may hinder the implementation of these measures. In this case, appropriate access policies should be designed to shield poor households efficiently from the burden of carbon taxation. Under real-world conditions, improved cookstoves have shown smaller, and in many cases limited, long-term health and environmental impacts than expected, as the households use these stoves irregularly and inappropriately, and fail to maintain them, so that their usage declines over time. Specific distributional issues are highlighted in relation to various cookstove programs.

The mitigation options in the transportation sector are assessed as having synergies with SDG 1 'no poverty' and SDG 3 'good health and well-being' due to reduced environmental pollution, with exceptions in relation to pollution from biofuels and the risks of traffic accidents. Trade-offs are also mentioned in relation SDG 2 'zero hunger' where the production of biofuels takes land away from food production. Synergies are assessed in relation to SDG 7 'affordable and clean energy', SDG 8 'decent work and economic growth' and SDG 9 'industry, innovation and infrastructure'. It is emphasized that some mitigation options, like the increased penetration of electric vehicles, require innovative business models, and that digitalization and automatic vehicles will support the socio-economic structures that impede adoption of EV's and the urban structures that enable reduced car dependence. In conclusion, there is a need for investments in infrastructure that can support alternative fuels for LDVs. The large-scale electrification of LDVs requires the expansion of low-carbon power systems, while charging or battery-swapping infrastructure is needed for some segments.

The mitigation options in the industrial sector have been assessed primarily as having synergies with meeting the SDGs. Several options, including energy efficiency, material recycling and electrification, are assessed has being able to create increased employment and business opportunities related to SDG 8 'decent work and economic growth', but material efficiency improvements could reduce tax revenues. Electrification is assessed as having many synergies with SDGs, such as supporting SDG 1 'end poverty', SDG 2 'zero hunger', and SDG 3 'good health and well-being'. CCS applied in industry is assessed as having synergies in terms of the control of non-CO_2 pollutants (such as sulphur dioxide), but increases in non-CO_2 pollutants (such as particulate matter, nitrogen oxide and ammonia). The conclusion is that 15-25% additional energy will be required by CCS technologies compared with conventional plants, implying that production costs could increase significantly. For the industrial sector in general, it is concluded that the balance between synergies and trade-offs between mitigation options and SDGs in industry depends on technology and the scale of the sharing of co-benefits across regions, as well as on the sharing of benefits in business models over whole value chains.

Thus a number of cross-sectoral conclusions on synergies and trade-offs between mitigation options and the SDGs appear from the overview provided in Figure 17.1. There are many synergies in all sectors between mitigation options and the SDGs, and in a few cases there are also significant trade-offs that it is very important to address, since they can compromise major SDGs including SDG1 'no poverty', SDG 2 'zero hunger', and in some cases SDG 14 and SDG 15 'life below water' and 'life on land'. In particular, mitigation options in relation to land-use, such as afforestation and reforestation and bioenergy crops, can in some cases imply trade-offs with access to food and local sharing of benefits, but synergies can also exist if proper land management and cross-sectoral policies take sustainable land-use into account. The impacts and trade-offs for this sector are highly scale- and context-dependent, so the final outcome of mitigation policies should be considered in detail.

The urban systems and transportation could potentially achieve many synergies between mitigation policies and the SDGs, but integrated planning and infrastructure management are critical to avoiding trade-offs. Similarly, the buildings sector and industry have identified many potential synergies between mitigation options and the SDGs, but that raises issues related to the costs of new technologies, and in relation to households and buildings important equity issues are emerging in relation to the ability of low-income groups to afford the introduction of new technologies. Altogether these cross-sectoral conclusions call for a need to support policies that aid coordination between different sectoral domains and that include context-specific assessments of the sharing of benefits and costs related to the implementation of mitigation options.

17.4 Key barriers and enablers of the transition: synthesizing results

This section provides a deep and broad synthesis of theory (section 17.2) and evidence (section 17.3) in order to identify the conditions that either enable or inhibit transitions to sustainable low-carbon futures. Following the literature on sustainability transitions (see Cross-chapter Box 12 on Transition Dynamics), the section finds that there is rarely any one single factor promoting or preventing such transitions. Rather, marked departures from business as usual typically involve several factors, including technological innovations, shifts in markets, concerted efforts by scientists and civil-society organizations to raise awareness of the costs of continued emissions, social movements, policies and governance arrangements, and changes in belief systems and values.

All of this comes together in a co-evolutionary process that has unfolded globally, internationally and locally over several decades (Hansen and Nygaard 2014; Rogge et al. 2017; Sorman et al. 2020), and that may be guided or facilitated by interventions that target leverage points in the underlying development path (Burch and Di Bella 2021; Leventon et al. 2021). While transitions necessarily follow context-specific trajectories, more general lessons can be drawn by comparing the empirical details with both system-level and narrower explanations of change.

Sections 17.2 and 17.3 show that transitions often face multiple barriers, including infrastructure lock-in, behavioural, cultural and institutional inertia (Markard et al. 2020), trade-offs between transitions and other social or political priorities (Chu 2016), cost and a reliable (and growing) supply of renewable energy technologies and constituent materials (García-Olivares et al. 2018). Transitions away from fossil fuels and toward renewable energy-based systems, for instance, will require significant land-use decisions to avoid negative trade-offs with biodiversity and food security (Capellán-Pérez et al. 2017). Previous sections underline a related need to move beyond focusing on "rational" assessments of the costs and benefits of policies and technologies to involve people at all levels in order to overcome these multiple barriers. For example, the case of coal-fired power in China (section 17.3) shows that a transition to a lower carbon system is unlikely to happen even if models find it technically feasible and cost-effective. Rather, achieving a transition requires breaking locked-in high-carbon technological trajectories, path dependencies and resistance to change from the industries and actors that are benefiting from the current system (Rogge et al. 2017). Lock-in effects may be weaker in sectors and policy areas where fewer technologies exist, potentially opening the door to innovations that embed the climate in broader sustainability objectives (e.g., technologies and innovations that support the integration of food, water and energy goals). Such effects may still happen when there are significant information asymmetries and high-cost barriers to action, as can occur when working across multiple climate and development-related sectors (Kemp and Never 2017).

However, the same conditions that may serve to impede a transition (i.e., organizational structure, behaviour, technological lock-in) can also be 'flipped' to enable it (Burch 2010; Lee et al. 2017), while the framing of policies that are relevant to the sustainable development agenda can also create a stronger basis and stronger policy support. The technological developments and broader cultural changes that may generate new social demands on infrastructure to contribute to sustainable development will involve a process of social learning and awareness building (Naber et al. 2017; Sengers et al. 2019). However, it is also important to note that strong shocks to these systems, including accelerated climate-change impacts, economic crises and political changes, may provide crucial openings for accelerated transitions to sustainable systems through fundamental institutional changes (Broto et al. 2014). The global COVID-19 pandemic is one such shock that has sparked widespread conversations about recovery that is fundamentally more sustainable, equitable and resilient (McNeely and Munasinghe 2021). Key enabling conditions appear to be individual and collective actions, including leadership and education; financial, material, social and technical drivers that foster innovation; robust national and regional innovation systems that enhance technological diffusion (Wieczorek 2018); supportive policy and governance dynamics at multiple levels that permit both agility and coherence (see e.g. Göpel et al. 2016); measures to recognize and address the challenges to equality inherent in the transition; and long-range, holistic planning that explicitly seeks synergies between climate change and sustainable development while avoiding trade-offs. The sections that follow seek to assess and integrate these key categories of the barriers to and enablers of an accelerated transition to sustainable development pathways.

17.4.1 Behavioural and lifestyle changes

Transitions toward more sustainable development pathways are both an individual and a collective challenge, requiring an examination of the role of values, attitudes, beliefs and structures that shape behaviour, and of the dynamics of social movements and education at the local community, regional and global levels. Labelling the carbon included in products, for example, could help the decision-making process and increase awareness and knowledge. Individual action suggests aggregated but uncoordinated actions taken by individuals, whereas collective sustainability actions involve coordination, a process of participation and governance that may ensure more efficient, equitable and effective outcomes. There is evidence that the behaviour of individuals and households are part of a more encompassing collective action (see also Chapter 5.4.1).

Indeed, individual actions are necessary but insufficient to deliver transformative mitigation, and it is suggested that this be coupled with collective actions to accelerate the transition to sustainable development (Dugast et al. 2019). Actors with conflicting interests will compete to frame mitigation technologies that either "build or erode" the legitimacy of the technology, contested framing sites that can occur between incumbent and emerging actors or between actors in new but competing spaces

(Rosenbloom et al. 2016). How narratives are built around desired development pathways and specific emerging technologies, as well as how local values are integrated into visions of the future, have relevance for how these experiments are managed and enabled to expand (Horcea-Milcu et al. 2020; Lam et al. 2020).

17.4.1.1 Social movements and education

Sustainable development and deep decarbonization will involve people and communities being connected locally through various means – including globally via the internet and digital technologies (Bradbury 2015; Scharmer 2018; Scharmer, C, Kaufer 2015) –in ways that form social fields that allow sustainability to unfold (see also Gillard et al. 2016) and that prompt other shifts in thinking and behaviour that are consistent with the 1.5°C goal (O'Brien 2018; Veciana and Ottmar 2018). Indeed, social movements serve to develop collective identities, foster collective learning and accelerate collective action ranging from energy justice (see Section 17.4.5) (Campos and Marín-González 2020) to restricting fossil-fuel extraction and supply (Piggot 2018). This does not apply only to adults: as seen in the "Fridays for Future" marches, the young are also involving themselves politically (Peterson et al. 2019). Many initiatives have started with these marches, including "science for future" and new forms of sustainability science (Shrivastava et al. 2020).

It was Theory-U (Scharmer 2018, building on the work of scholars like Schein, Lewin or Senge) that inspired a so-called "massive open online course" (MOOC) jointly initiated by the Bhutan Happiness Institute and German Technical Assistance (GIZ) in 2015, since when it has been developed further and adapted to transform business, society and self as one example of how social movements can go together with science and education. It brings together people from different professions, cultures and continents in shared discussions and practices of sustainability. It also included marginalised communities and is shifting towards more sustainable lifestyles in all sectors (Nikas et al. 2020), including climate action.

Moreover, approaches like the "Art of Hosting" (Sandfort and Quick 2015) and qualitative research methods like storytelling and first-person research, as well as second-person inquiries, for example (Scharmer, C, Kaufer 2015; Trullen and Torbert 2004; Varela 1999), have been employed to bridge differences in cultures and sciences, as well as to forge connections between those working on climate change and sustainable development. Likewise, experiential tools, simulations and role-playing games have been shown to increase knowledge of the causes and consequences of climate change, the sense of urgency around action and the desire to pursue further learning (Ahamer 2013; Eisenack and Reckien 2013; Hallinger et al. 2020; Rooney-Varga et al. 2020).

The results from these research communities reveal how experiential learning takes place and how it encourages bonding between people, society and nature. This can be achieved by going jointly and consciously into nature (Gioacchino 2019), by creating spaces for intensive dialogue sessions with colleagues (Goldman-Schuyler et al. 2017) and forming, for example, a very practical u.lab hub, which involves following the MIT-u.lab course with a local community and is accompanied scientifically (Pomeroy and Oliver 2018). Others have pointed to social networks such as the "transition initiative" (Hopkins 2010), eco-village networks (see e.g., Barani et al. 2018), civil-society movements (Seyfang and Smith 2007) and intentional communities (see e.g., Grinde et al. 2018; Veciana and Ottmar 2018) as ways of generating the shared understandings that are central to inner and outer transitions, as well as the broader development of social movements. In some cases, these networks build on principles like permaculture to encourage people to "observe and interact," "produce no waste" and "design from patterns to details", not only in agriculture and gardening, but also in sustainable businesses and technologies to reduce CO_2 emissions (see e.g., Ferguson and Lovell 2014; Lessem 2018).

A related line of inquiry involves education for sustainable development (ESD). This builds on the UNESCO programme, 'ESD for 2030', and involves core values like peace culture, valuing cultural diversity and living global citizenship. One of the core insights from research on ESC is lifelong education continuing outside the classroom, a lifelong learning process that involves sustained actions by all ages and social segments (see e.g., Hume and Barry 2015) and achieving collaboration (Munger and Riemer 2012). Some authors have pointed to good levels of communication either directly or through the internet as the key to facilitating this learning (Sandfort and Quick 2015). Others have noted that transformative learning – that is, deepening the learning process – is critical because it helps to induce both shared awareness and collective actions (see e.g., Brundiers et al. 2010; Singleton 2015; Wamsler and Brink 2018).

A final area of work points to the importance of moving toward the knowledge production that underpins awareness-raising (Pelling et al. 2015). The accumulation of applied knowledge is leading increasingly to the co-design of participatory research with local stakeholders who are investigating and transforming their own situations in line with climate action and sustainable development (see e.g., Abson et al. 2017; Fazey et al. 2018; Wiek et al. 2012).

17.4.1.2 Habits, values and awareness

Many of the cases that explore transitions to sustainable development point to engrained habits, values and awareness levels as the most persistent yet least visible barriers to a transition. For example, in the transport sector, individuals can quickly become accustomed to personal vehicles, making it difficult for them to transition to sustainable, low-carbon modes of public transport. Demand for high-carbon transportation may also be locked in, and habits reinforced, if low-cost housing (for instance) is not sufficiently served by more sustainable (i.e. mass transit, safe cycling and walking infrastructure) transportation options (Mattioli et al. 2020).

This is made all the more challenging because car-manufacturing "incumbents" utilize information campaigns directed at the public, pursue lobbying and consulting with policy-makers, and set technical standards that privilege the status quo and prevent the entry of more sustainable innovations (Smink et al. 2015; Turnheim and Nykvist 2019). Tools such as congestion pricing, however, have been shown to be effective in motivating the switch from single-occupancy vehicle use to public transit, thus improving air quality and reducing traffic delays in dense city centres (Baghestani et al. 2020).

Complicating the problem further is that even well-intentioned top-down programmes initiated by an external actor may in some cases ultimately hinder transformative change (Breukers et al. 2017). For instance, in Delhi, India, attempts to introduce ostensibly more sustainable bus rapid transit (BRT) systems failed in part due to an arguably top-down approach that had limited public support. It may nonetheless be difficult to win public support (Bachus and Vanswijgenhoven 2018), and even grassroots initiatives may themselves be contested and dynamic, making it difficult to generate the collective push to drive a bottom-up transition forward (Hakansson 2018).

However, dominant, top-down approaches and local, grassroots "alternative" approaches and values do overlap and interact. For example, in Manchester, UK, dominant and alternative discourses interact with each other to create sustainable transformations through re-scaling (decentralizing) energy generation, creating local engagement with sustainability, supporting green infrastructure to reduce costs, re-claiming local land, transforming industrial infrastructure and creating examples of sustainable living (Hodson et al. 2017).

Embedding local values in higher-level policy frameworks is also significant for forest communities in Nepal and Uganda. Even so, policy intermediaries are not confident that these values will be advanced due largely to an emphasis on carbon accounting and the distribution of benefits (Reckien et al. 2018). In this case, however, norm entrepreneurs were able to promote the importance of local values through the formation of grassroots associations, media campaigns and international support networks (Reckien et al. 2018).

17.4.2 Technological and social innovation

Individuals and organizations, like institutional entrepreneurs, can function to build transformative capacity through collective action (Brodnik and Brown 2018). The transition from a traditional water-management system to the Water Sensitive Urban Design (WSUD) model in Melbourne offers an illustration of how whole systems can be changed in an urban system.

Private-sector entrepreneurs also play an important role in fostering and accelerating transitions to sustainable development (Burch et al. 2016; Ehnert et al. 2018a; Dale et al. 2017). Sustainable entrepreneurs (SEs), for instance, are described as those who participate in the development of an innovation while simultaneously being rooted in the incumbent energy-intensive system. SE actors who have developed longer term relationships, both formal and informal, with the public authorities can have considerable influence on developing novel renewable-energy technologies (Gasbarro et al. 2017). Institutions and policies that nurture the activities of sustainable entrepreneurs, in particular small- and medium-sized enterprises (Burch et al. 2016), can facilitate and strengthen transitions toward more sustainable development pathways, as can more fundamental adjustments to underlying business models, rather than relying only on incremental adjustments in the efficiency with which resources are used (Burch and Di Bella 2021).

The creation and growth of sustainable energy and clean-tech clusters enable economic development and transformation on regional scales. Such clusters can put pressure on incumbent technologies and rules to accelerate energy transitions. Successful clusters are nurtured by multi-institutional and multi-stakeholder actors building institutional support networks, facilitating collaboration between sectors and actors, and promoting learning and social change. Notably, regional economic clusters generate a buzz, which can have a strong influence on public acceptance, support and enthusiasm for sociotechnical transitions (McCauley and Stephens 2012).

In Norway, many incumbent energy firms have already expanded their operations into the alternative energy sector as both producers and suppliers (who often follow the lead of producers). Producers are responding to perceptions of larger-scale changes in the energy landscape (e.g., the green shift), along with uncertainties in their own sectors, and innovation can spill across actors in multiple sectors (Koasidis et al. 2020). While these firms are expanding out of self-interest, the expansion provides more legitimacy to new forms of technology and enables transfers of knowledge and resources to be introduced within this developing niche (Steen and Weaver 2017). Many large, well-established firms are pursuing sustainability agendas and opting for transparency with regard to their greenhouse gas emissions (Guenther et al. 2016; Kolk et al. 2008), supply chain management (Formentini and Taticchi 2016) and sustainable technology or service development (Dangelico et al. 2016).

Experiments with the transition open up pathways that can lead to energy transitions on broader scales. Experiments can build capacity by developing networks and building bridges between diverse actors, leveraging capital from government funds, de-risking private- and public-sector investment, and acting as hubs for public education and engagement (Rosenbloom et al. 2018).

Material barriers and spatial dynamics (Coenen et al. 2012; Hansen and Coenen 2015) are other critical obstacles to innovation: often, infrastructure and built environments change more slowly than policies and institutions due to the inherently long lifespans of fixed assets (Turnheim and Nykvist 2019). The example of transport infrastructure in Ontario, Canada, illustrates the need to integrate climate change into these infrastructural decisions in the very short term to combat the risk of being left with unsustainable planning features long into the future, especially combustion engines, significant road networks and suburbanization (Birch 2016).

17.4.3 Financial systems and economic instruments

Market-oriented policies, such as carbon taxes and green finance, can promote low-carbon technology and encourage both private and public investment in enabling transitions. Policies that are currently being tested include loan guarantees for renewable energy investments in Mali, policy insurance to reduce credit defaults within the feed-in tariff regime in Germany, or pledged funding to fully finance or partner private firms in order to advance renewable energy projects (Roy et al. 2018a). However, there may be some limitations in using carbon-pricing alone (rather than in combination with flexible regulations and incentives) where market failures hinder low-carbon investments (Campiglio 2016; World Bank 2019) and high political costs are incurred (Van Der Ploeg 2011).

Many forms of transformational change to energy systems are not possible when financial systems still privilege investing in unsustainable, carbon-intensive sectors. One of the root causes of the failure of traditional financial systems is the undervaluation of natural capital and unsettled property right issues that are associated with it. The exclusion of proper rents for scarcities or for global and local externalities, including climate change, can undermine larger-scale changes to energy systems (Clark et al. 2018). But even smaller-scale low-carbon energy and infrastructure projects can fail to get off the ground if uncertainty and investment risk discourage project planning and bank-lending programmes (Bolton et al. 2016). The EU's previous actions regarding the "shareholder maximisation norm" and non-binding measures have created path dependencies, limiting its flexibility in creating sustainable financial legislation. However, the Sustainable Finance Initiative and the Single Market may prove to be "policy hotspots" in encouraging sustainable finance (Ahlström 2019).Taking advantage of these hotspots may be crucial in overcoming path dependencies and setting new ones in motion.

One possible positive turn in this regard is the acceleration in investing in the environment (impact and ESG) globally: for instance, there is evidence that some institutional investors are divesting from coal, potentially auguring well for the future (Richardson 2017). The encouragement of governance and policy reforms that could facilitate similar expansions of investment in sustainable firms and sectors (Clark et al. 2018; Owen et al. 2018) could contribute to the dynamic feedback that gives a transition lift and injects momentum into it. Also, the degrowth movement, with its focus on sustainability over profitability, has the potential to speed up transformations using alternative practices like fostering the exchange of non-monetary goods and services if large numbers of stakeholders want to invest in these areas (Chiengkul 2017).

17.4.4 Institutional capacities and multi-level governance

Capable institutions and multi-level governance often support the inter-agency coordination and stakeholder coalitions that drive sustainable transitions. Such institutions and governance arrangements are frequently required to formulate and implement the multi-sectoral policies that spur the adoption and scaling of innovative solutions to climate change and other sustainable development challenges. For example, such institutional and governance conditions have helped support the industrial policies that will be needed to spread renewables through the creation of domestic supply chains (Zenghelis 2020) or to pilot CDR methods (Quarton and Samsatli 2020).

However, government agencies with climate and other remits do not always work well together: the absence of coordination and consensus building mechanisms can further deepen inter-agency conflicts that stall a transition. These challenges appear not only within but also between levels of decision-making. Studies of developing megacities, for instance, have found the lack of mechanisms promoting vertical cross-level integration to be a sizable constraint on decarbonisation (Canitez 2019). Differences in perspectives across non-state actors can similarly frustrate transitions in areas such as green buildings (Song et al. 2020).

Here coordination complicates matters: coalition-building may require mutually reinforcing changes to institutions and policies. For example, decentralized renewable energy has made progress in Argentina, but consumer electricity subsidies give agencies and firms supporting conventional energy an advantage over those promoting renewable energy. Similarly, the lack of concrete guidance in green finance policies can deprive government agencies and other stakeholders of the information needed to balance ecological and financial goals (Wang and Zhi 2016). Many of these challenges can be particularly formidable in developing countries, where agencies lack sufficient financial and other capacities. A lack of government funds to cover ongoing maintenance costs along with resource shortages in rural locations can pose constraints on sustainable energy (Schaube et al. 2018).

Building inter-agency or multiple stakeholders is frequently challenging because of the mutually reinforcing interactions between institutions and ideas. The imperceptible embedding of long-standing development paradigms (such as ‘grow now, clean up later’) in agency rules and standard operating procedures can make changes to governance arrangements challenging. This is partly because these rules and procedures can also shape the interests of key decision-makers (e.g., the head of an environmental agency). For some, this suggests a need to look not just at changing prevailing ideas and interests, but also at broader institutional and governance arrangements (Kern 2011).

However, institutional and governance reforms can be more than a technical exercise. Political, economic and other power relations can lock in dominant institutional and economic structures, making the integration of climate and sustainable development agendas exceedingly difficult. For example, though there have been recent reforms, the initial lack of early progress in Australia's energy transition is partly attributable to institutions of political economy being oriented to providing steady supplies of affordable fossil fuels (Warren et al. 2016).

This suggests that it is important to look closely at the pre-existing political economic system as well as the institutional context and capacities in assessing the prospects for transitions to sustainability. Furthermore, this is how existing institutions interact with ideas that often strengthen lock-ins. To illustrate, studies have shown that the status-quo orientations of leaders (including decision-makers' disciplinary backgrounds, world views and perceptions of risk) (Willis 2018), as well as the organizational culture and management paradigms within which they operate, affect the speed and ambitions of climate policies (Rickards et al., 2014).

Some studies have focused on factors that can break institutional and ideational lock-ins (Arranz 2017), while others have found that intentional higher-level (or, in the language of socio-technical transitions, "landscape") pressures can be the destabilizing force needed to move transitions forward (Falcone and Sica 2015). Often the state or national government (as the sovereign that determines how resources are used and allocated) can play a key role in destabilizing incumbent energy regimes, a role that is significantly strengthened by public support (Arranz 2017; Avelino et al. 2016). However, this role is not limited to government insiders. In some contexts, regime outsiders have also played a pivotal role in destabilizing regimes by combining persuasive narratives that gain market influence (Arranz 2017). Carbon-intensive luxury goods and services for wealthy consumers, for instance, especially if applied at the "acceleration" phase of a transition, can help transform long-term social practices and behaviour and dissolve the "structural imperative for growth" (Wiedmann et al. 2020). In a similar fashion, environmental taxes can remove "locked-in" technology and place pressure on dominant regimes to become more sustainable (Bachus and Vanswijgenhoven 2018).

In many contexts, it is not multiple institutional and policy variables that come together to break unsustainable inertias. In South Korea, where the state was an initiator and enabler of change, the clean-energy transition took much longer than anticipated due to private-sector resistance. However, when policy-makers focused on incorporating adaptive learning and flexibility into their decision-making, public- and private-sector interests gradually converged and joined with top-down policy-making to drive the transition forward (Lee et al. 2019). Thus, a political strategy can help align the interests and institutions needed to break lock-ins.

This becomes clear in studies that show that political coalitions can affect the speed of transitions (Hess 2014). These same studies show that incumbent industry coalitions are now competing with 'green' coalitions in terms of campaign spending over environmentally-friendly ballot proposals (Hess 2014). Another way of shifting political-economic incentives is by offering a realistic exit strategy for incumbents, like interventions that provide long-term incentives for renewable energy firms (de Gooyert et al. 2016; Hamman 2019).

Overall, the previous subsection suggests that complementary policies and institutions that simultaneously integrate across multiple sectors and scales and also alter political economic structures that lock in carbon-intensive energy system are more likely to move a sustainable transition forward (Burch 2010). Yet, despite a trend in climate governance towards greater integration and inclusivity and certain other novel governance approaches, traditional approaches to governance and a tendency to incrementalism remain dominant (Holscher et al. 2019). Building the governance arrangements and capacities that prioritize climate change across all sectors and scales while destabilizing entrenched interests and putting pressure on existing norms, rules and practices is still needed in many contexts (Holscher et al. 2019).

At least three themes require further research in the scholarship on governance of transitions: 1) the role of coalitions in supporting and hindering acceleration; 2) the role of feedback, through which policies may shape actor preferences, which in turn create stronger policies; and 3) the role of broader contexts (political economies, institutions, cultural norms, and technical systems) in creating conditions for acceleration (Roberts et al. 2018). Importantly, these themes may serve as both barriers to and opportunities for transitions (ibid.).

17.4.5 Equity in a just transition

Energy justice, although increasingly being emphasized (Pellegrini-Masini et al. 2020), has been under-represented in the literature on sustainability and in debates on energy transitions, and it remains a contested term with multiple meanings (Green and Gambhir 2020). Energy justice includes affordability, sustainability, equality (accessibility for current and future households) and respect (ensuring that innovations do not impose further burdens on particular groups) (Fuso Nerini et al. 2019). Furthermore, it suggests that a just transition is a shared responsibility among countries that are making more rapid progress towards net negative emissions and those economies that are focused on pressing development priorities related to improved health, well-being and prosperity (van den Berg et al. 2020).

Looking at climate change from a justice perspective means placing the emphasis on a) the protection of vulnerable populations from the impacts of climate change; b) mitigating the effects of the transformations themselves, including easing the transition for those whose livelihoods currently rely on fossil fuel-based sectors; and c) envisaging an equitable decarbonized world. Neglecting issues of justice risks a backlash against climate action generally, particularly from those who stand to lose from such actions (Patterson et al. 2018), and it will also have implications for the pace, scale and quality of the transition. Explicit interventions to promote sustainability transitions that integrate local spaces into the whole development process are necessary but not sufficient in creating a just transition (Breukers et al. 2017; Ehnert et al. 2018b).

Renewable energy transitions in rural, impoverished locations can simultaneously reinforce and disrupt local power structures and inequalities. Policy interventions to help the most impoverished individuals in a community gain access to the new energy infrastructure are critical in ensuring that existing inequalities are not reinforced. Individuals who are empowered by energy development projects can influence the onward extension of sustainable energy to other communities (Ahlborg 2017). In Denmark in the 1970s, for example, grassroots windmill cooperatives opened a pathway to the creation of one of the world's largest wind-energy markets. The unique dynamics of grassroots-led changes mean that new technologies and low-carbon initiatives develop strong foundations by being designed, tested and improved in the early stages with reference to the socio-political contexts in which they will grow later (Ornetzeder and Rohracher 2013).

Intersectional theory can shine a light on the hidden costs of resource extraction, as well as renewable energy development (see, for instance, (Chatalova and Balmann 2017), which go beyond environmental or health risks to include the socio-cultural impacts on both communities adjacent to these sites and those who work in them (Daum 2018). Indeed, development decisions often do not properly integrate the burdens and risks placed on marginalized groups, like indigenous peoples, while risk assessments tend to reinforce existing power imbalances by failing to differentiate between how benefits and risks might impact on certain groups (Healy et al. 2019; Kojola 2019). In some cases, such as the deployment of small-scale solar power in Tanzania by a non-profit organization, an explicit gender lens on the impacts of energy poverty revealed the significant socio-economic benefits of improving access to renewable energy (Gray et al. 2019).

17.4.6 Holistic planning and the nexus approach

Poor sectoral coordination and institutional fragmentation have triggered a wide range of unsustainable uses of resources and threatened the long-term sustainability of food, water and energy security (Rasul 2016). Greater policy coherence among the three sectors is critical to moving to a sustainable and efficient use of resources (United Nations 2019), given that political ambition, values, the energy mix, infrastructure and innovation capacities collectively shape transition outcomes (Neofytou et al. 2020). Capacity- and coalition-building, particularly among sub-national and non-state actors (e.g. non-governmental organizations) is a particularly important enabler of greater coherence (Bernstein and Hoffmann 2018). The nexus approach, a systems-based methodology that focuses attention on the many ways in which natural resources are deeply interwoven and mutually interdependent, can strengthen coordination and help to avoid maladaptive pathways (Cremades et al. 2016).

A major shift is required in the decision-making process in the direction of taking a holistic view, developing institutional mechanisms to coordinate the actions of diverse actors and strengthening complementarities and synergies (Nikas et al. 2020; Rasul 2016). Currently, nexus approaches have moved from purely conceptual arguments to application and implementation. (Liu et al. 2018) suggest the need for a systematic procedure and provide perspectives on future directions. These include expanding nexus frameworks that take into account interaction linkages with the SDGs, incorporating overlooked drivers and regions, diversifying nexus toolboxes and making these strategies central to policy-making and governance in integrating and implementing the SDGs.

In respect of processes, (Seyfang and Haxeltine 2012) found a lack of realistic and achievable expectations among both members (internally) and the wider public (externally), which hampers the acceleration of transitions. This movement could concentrate strategically on developing and promoting short-term steps towards shared long-term visions, including clearly identifiable goals and end-points. Sustainability science must link research on problem structures with a solutions-oriented approach that seeks to understand, conceptualize and foster experiments in how socio-technical innovations for sustainability develop, are diffused and are scaled up (Miller et al. 2014).

Various strategies and processes have been explored that might facilitate the translation of barriers into enablers, thus accelerating transitions to sustainable development. Common themes include frequent monitoring and system evaluation to reveal the barriers in the first place, the collaborative co-creation and envisioning of pathways toward sustainable development, ambitious goal-setting, the strategic tackling of sources of path dependence or inertia, iterative evaluations of progress and risk management, adaptive management and building in opportunities for agile course-correction at multiple levels of governance (Burch et al. 2014; Halbe et al. 2015). Given the political infeasibility of stable, long-term climate policies, the better choice may be to embrace uncertainty in specific policies but entrench the low-carbon transition as the overarching goal. Framing climate policy too narrowly, rather than taking a more holistic, sustainable development-oriented approach, may tie success to single policies, rather than allowing for system-wide change.

Decarbonisation may be encouraged by embedding the transition in a broader socio-economic agenda, focusing on constructing social legitimacy to justify the transformation, encouraging municipalities with a material interest in the transition and reforming institutions to support the long-term transition goals (Rosenbloom et al. 2019). In jurisdictions where climate and energy policy have been integrated and harmonized, such as the UK, progress has been made in transitioning to sustainable energy (Warren et al. 2016).

Developing countries that are rich in fossil fuels now have an opportunity to reset their development trajectories by focusing on those opportunities that will offer resilient development in land-use change, low-carbon energy generation and not least more efficient resource-planning (UN- UNDRR 2019). Resource-rich developing countries can choose an alternative pathway by deciding to monetize carbon capital and diversifying away from the high-carbon aspects of risk. Countries rich in hydrocarbons can diversify their energy mix and maximize their renewable energy potential. For instance, Namibia, a net importer of electricity, is seeking to reduce its current dependence on hydrocarbons by promoting solar energy. The government has issued permits allowing independent power producers (IPPs) to sell directly to consumers, thus ending the monopoly hitherto enjoyed by the state utility company NamPower (Kruger et al. 2019).

Cities are important spaces where the momentum to achieve low-carbon transitions can be built (Burch 2010; Holscher et al. 2019; Shaw et al. 2014), especially where centralized energy structures and national governance and politics are posing deep-rooted challenges to change (Dowling et al. 2018; Meadowcroft 2011). Cities can enter networks and partnerships with other cities and multilevel actors, spaces that are important for capacity-building and accelerating change (Dale et al. 2020; Heikkinen et al. 2019; Westman et al. 2021).

Addressing the uncertainties and complexities associated with locally, regionally and nationally sustainable development pathways requires creative methods and participatory processes. These may include powerful visualizations that make the implications of climate change (and decarbonization) clear locally (Shaw et al. 2014; Sheppard et al. 2011), other visual aids or “progress wheels” that effectively communicate the relevant contexts (Glaas et al. 2019), storytelling and mapping, and both analogue and digital games (Mangnus et al. 2019).

17.5 Conclusions

This chapter has been concerned to assess the opportunities and challenges for acceleration *in the context of sustainable development*. As such, many of the claims reviewed involve not only increasing the speed of the transition but also ensuring that it is just, equitable and delivers a wider range of environmental and social benefits. A sustainability transition requires removing the underlying drivers of vulnerability and high emissions (quality and depth) while aligning the interests of different communities, regions, sectors, stakeholders and cultures (scale and breadth).

Interest in a sustainability transition has grown steadily over the history of the IPCC and of climate and related policy processes. That interest hit a high point in 2015 with the Paris Agreement and the 2030 Agenda for Sustainable Development and its 17 SDGs. It has continued to remain high as countries have issued NDCs on climate change, VNRs on the SDGs and, in some instances, integrated climate and SDG plans (or similarly themed integrated actions, e.g. circular economy plans). Interest has also gained momentum as local governments, businesses and other stakeholders have followed suit with climate change- or SDG-related plans.

Implementing many of the recent pledges, however, has proved challenging. Part of the challenge is a need to address everything from public policies and prevailing technologies to individual lifestyles and social norms to governance arrangements and institutions with associated political economy implications. These factors can lock in development pathways and prevent transitions from gathering the momentum needed for large-scale transformations of socioeconomic systems. Another consideration is that transition pathways are likely to vary across and within countries due to different development levels, starting points, differential vulnerabilities, capacities, agencies, geographies, power dynamics, political economies, ecosystems and other contextual factors.

Even with this diversity, prominent lines of economic, institutional, psychological and systems thinking have reflected on interventions that can enable transitions. Because these disciplines often focus on different levels of analysis and draw upon diverse analytical methods and empirical evidence, the recommended interventions also tend to vary. For instance, economic arguments often point to the need for targeted regulation or investments, institutional claims centre on multilevel governance reforms, and psychology encourages participation to change mind sets and social norms. Systems-level perspectives offer a useful frame for bringing together these views, but may not capture the richness and details of them treated separately. Greater inter- and transdisciplinary research is needed to integrate the more focused interventions and show how they work together in a system. Such research will be particularly important for working on the concern running through these studies: strengthening synergies between climate and the broader sustainable development agenda.

National and sub-national, sectoral and cross-sectoral, short- and long-term transition studies have assessed the links between sustainable development and mitigation policies and synergies and the trade-offs between the different policy domains. Some general conclusions can be drawn on synergies and trade-offs, despite the actual impacts of policy implementation depending on scale, context and the development starting point.

From a cross-sectoral perspective, it can be concluded that the AFOLU sector offers many low-cost mitigation options with synergetic SDG impacts, which, however, can also create trade-offs between land-use for food, energy, forest and biodiversity. Some options can help to mitigate such trade-offs, like agricultural practices, forest conservation and soil carbon sequestration. Lifestyle changes, including dietary changes and reduced food waste, could jointly support the SDGs and mitigation. Industry also offers several mitigation options with SDG synergies, for example, related to energy efficiency and the circular economy. Some of the renewable-energy options in industry could indicate some trade-offs in relation to land use, with implications for food- and water security and costs. Cities provide a promising basis for implementing mitigation with SDG synergies, particularly if urban planning, transportation, infrastructure and settlements are coordinated jointly. Similarly, studies of the building sector have identified many synergies between the SDGs and mitigation, but there are issues related to the costs of new technologies. Also, in relation to households and buildings, important equity issues emerge due to the ability of low-income groups to afford the introduction of new technologies. Altogether these cross-sectoral conclusions create a need for policies to address both synergies and trade-offs, as well as for coordination between different sectoral domains. Context-specific assessments of synergies and trade-offs are here important, as is sharing the benefits and costs associated with mitigation policies.

Several opportunities for creating SDG synergies and avoiding trade-offs have also been identified in relation to integrated adaptation and mitigation policies. The AFOLU sector has a large potential for integrating adaptation and mitigation policies related to agriculture, bioenergy crops, forestry and water use. As was concluded for mitigation options, integrated adaptation and mitigation policies also entail the risks of creating trade-offs in relation to food, water, energy access and biodiversity. There are several potentially strong links between climate-change adaptation in industry and climate-change adaptation more generally. Various supply chains can be affected by climate change, and mitigation options related to energy and water supply can be disrupted by climate events, implying that great benefits may come from integrating adaptation in industrial planning efforts. Adaptation options in industry can imply increasing the demand for packaging materials such as plastics and for access to refrigeration, which are also major sources of GHG emissions, which then would require further mitigation options. Mitigation and the co-benefits of adaptation in urban areas in relation to air quality, health, green jobs and equality issues can in most cases to be synergetic and can also support the SDGs. One exception are compact cities, with their trade-offs between mitigation and adaptation because decreasing urban sprawl can increase the risks of flooding and heat stress. Detailed mapping of mitigation and adaptation in urban areas shows that there are many, very close interactions between the two policy domains and that coordinated governance across sectors is therefore called for.

Meeting the ambitions of the Paris Agreement will require phasing out fossil fuels from energy systems, which is technically possible and is estimated to be relatively low in cost. However, studies also show that replacing fossil fuels with renewables can have major synergies and trade-offs with a broader agenda of sustainable development if a balance is established in relation to land use, food security and job creation (McCollum et al. 2018). Furthermore, the transition to low-emission pathways will require policy efforts that also address the emissions locked into existing infrastructure, like power plants, factories, cargo ships and other infrastructure already in use: for example, today coal-fired power plants account for 30% of all energy-related emissions. Thus, even though the transition away from fossil fuels is desirable and technically feasible, it is still largely constrained by existing fossil fuel-based infrastructure and the existence of stranded investments. The "committed" emissions from existing fossil-fuel infrastructure may consume all the remaining carbon budget in the 1.5°C scenario or two thirds of the carbon budget in the 2°C scenario.

Stranded hydrocarbon assets, including hydrocarbon resources and the infrastructure from which they are produced, and investments made in exploration and production activities, are likely to become unusable, lose value, or may end up as liabilities before the end of the anticipated economic lifetime. This phenomenon is rapidly becoming a global reality as social norms change and the pressure to reduce emissions mounts. Energy and other forms of structural inequities are likely to make the transition planning more challenging, especially given stranded assets.

Countries dependent on fossil fuel income will need to forego these revenues to keep well within the Paris agreement requirements and align with the rapidly growing divestment movement. Climate injustice, energy poverty, and COVID 19 have reduced the space and maneuverability for developing countries to innovate and use surplus funds to procure new and clean technologies. A rising debt burden already hamstrings many. Decisions on how to spend the remaining carbon budget and who has the right to decide on what to do with existing fossil fuels reflect the complexity of the transition and its non-linearity character. Given the asymmetrical dimension of energy production, distribution, and use, it is likely that stranded assets will have implications for oil-producing countries, especially for early producers who perceive that newfound oil and gas will open doors to new forms of prosperity.

While the transitional drivers are not in place in some developing countries, i.e., technology, infrastructure, knowledge, and finance, among others, investing in new forms of renewable energy for land, energy, or water sectors will see the emergence of a more diversified economy and one less vulnerable to carbon and other exogenous risks. The transition away from fossil fuels will come with hard choices. Still, these choices can enable a sustainable development world and reduce the many asymmetries and injustices inherent in the current system, not least the gaping energy disparities that divide the developed and the developing world.

Equality and justice are central dimensions of transitions in the context of sustainable development. Viewing climate change through the lens of justice requires a focus on the protection of vulnerable populations from the impacts of climate change, addressing the unequal distribution of the costs and consequences of the transitions themselves, including for those whose livelihoods are rooted in fossil fuel-based sectors, and developing more creative and participatory processes for envisioning an equitable decarbonized world. Neglecting issues of justice will have implications for the pace, scale and quality of the transition.

Ultimately, the evidence demonstrates that there is rarely any one single factor promoting or preventing transitions. A constellation of elements come into play, including technological innovations, shifts in markets, social and behavioural dynamics, and governance arrangements. Indeed, transitions require an examination of the role of values, attitudes, beliefs and the structures that shape behaviour, as well as the dynamics of social movements and education at multiple levels. Likewise, technological and social innovation both play an important role in enabling transitions, highlighting the importance of multi-institutional and multi-stakeholder actors building institutional support networks, facilitating collaboration between sectors and actors, and promoting learning and social change. Financial tools and economic instruments are crucial enablers, since many forms of transformational change to energy systems are not possible when financial systems still privilege investing in unsustainable, carbon-intensive sectors. These instruments are deployed within the context of the multi-level governance of climate change, which suggests the importance of complementary policies and institutions that simultaneously integrate across multiple sectors and scales to address the multiple sources of lock-in that are shaping the current carbon-intensive energy system. Systems-oriented approaches, which holistically address the intersections among climate, water and energy (for instance), have significant potential to reveal and help avoid trade-offs, foster experimentation, and deliver a range of co-benefits on the path towards sustainable development.

Frequently Asked Questions (FAQs)

FAQ 17.1 Will decarbonisation efforts slow or accelerate sustainable development transitions?

Sustainable development offers a comprehensive pathway to achieving ambitious climate change mitigation goals. Sustainable development requires the pursuit of synergies and the avoidance of trade-offs between the economic, social and environmental dimensions of development. It can thus provide pathways that accelerate progress towards ambitious climate change mitigation goals. Factoring in equality and distributional effects will be particularly important in the pursuit of sustainable policies and partnerships, and in accelerating the transition to sustainable development. Using climate change as a key conduit can only work if synergies across sectors are exploited and if policy implementation is supported by national and international partnerships.

The speed, quality, depth and scale of the transition will depend on the developmental starting point, that is, on explicit goals as well as the enabling environment consisting of individual behaviour, mindsets, beliefs and actions, social cohesion, governance, policies, institutions, social and technological innovations etc. The integration of both climate change mitigation and adaptation policies in sustainable development is also essential in the establishment of fair and robust transformation pathways.

FAQ 17.2 What role do considerations of justice and inclusivity play in the transition towards sustainable development?

Negative economic and social impacts in some regions could emerge as a consequence of ambitious climate change mitigation policies if these are not aligned with key sustainable development aspirations such as those represented by the SDGs on 'no poverty, energy-, water- and food access' etc., which could in turn slow down the transition process. Nonetheless, many climate change mitigation policies could generate incomes, new jobs and other benefits. Capturing these benefits could require specific policies and investments to be targeted directly towards including all parts of society in the new activities and industries created by the climate change mitigation policies, and that activities that are reduced in the context of transitions to a low carbon future, including industries and geographical areas, are seeing new opportunities. Poor understanding of how governance at multiple levels can meet these challenges to the transition may fail to make significant progress in relation to national policies and a global climate agreement. It may therefore either support or weaken the climate architecture, thus constituting a limiting factor.

FAQ 17.3 How critical are the roles of institutions in accelerating the transition and what can governance enable?

Institutions are critical in accelerating the transition towards sustainable development: they can help to shape climate change response strategies in terms of both adaptation and mitigation. Local institutions are the custodians of critical adaptation services, ranging from the mobilisation of resources, skills development and capacity-building to the dissemination of critical strategies. Transitions towards sustainable development are mediated by actors within particular institutions, the governance mechanisms they use as implementing tools and the political coalitions they form to enable action. Patterns of production and consumption have implications for a low-carbon development, and many of these patterns can act as barriers or opportunities towards sustainable development. Trade policies, international economic issues and international financial flows can positively support the speed and scale of the transition; alternatively, they can have negative impacts on policies that may inhibit the process. Nonetheless, contextual factors are a fundamental part of the change process, and institutions and their governance systems provide pathways that can influence contextual realities on the ground. For instance, politically vested interests may lead powerful lobby groups or coalition networks to influence the direction of the transition, or they could put pressure on a given political elite through the imposition of regulatory standards, taxation, incentives and policies that may speed or delay the transition process. Civil society institutions, such as NGOs or research centres, can act as effective governance 'watch dogs' in the transition process, particularly when they exercise a challenge function and question government actions in respect of transitions related to sustainable development.

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