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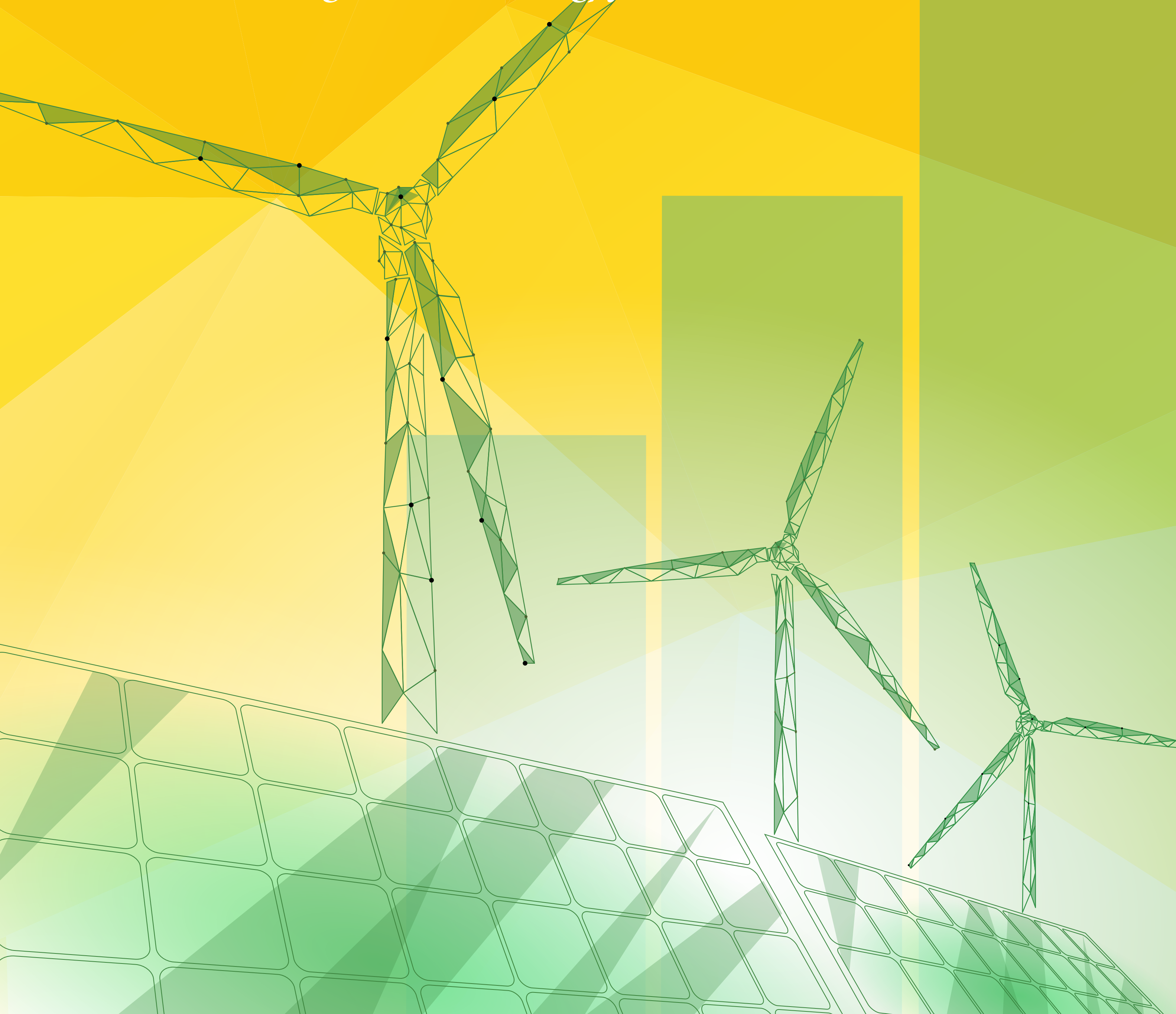
The Climate Technology Progress Report 2024

Unleashing Renewable Energy for Ambitious NDCs



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The Climate Technology Progress Report 2024

Unleashing Renewable Energy for Ambitious NDCs

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GLOSSARY

Climate technology Climate technologies are those that help us reduce greenhouse gas emissions and adapt to the adverse effects of climate change. (See definition of technology below).
Deployment The act of bringing technology into effective application, involving a set of actors and activities to initiate, facilitate and/or support its implementation (IPCC 2022a).
Diffusion The spread of a technology across different groups, users or markets over time (IPCC 2022a).
Enabling environment The set of resources and conditions within which the technology and the target beneficiaries operate. The resources and conditions that are generated by structures and institutions that are beyond the immediate control of the beneficiaries should support and improve the quality and efficacy of the transfer and diffusion of technologies (Nygaard and Hansen 2015).
Feasibility The potential for a mitigation or adaptation technology to be implemented. Factors influencing feasibility are context-dependent, temporally dynamic and may vary between different groups and actors. Feasibility depends on geophysical, environmental-ecological, technological, economic, sociocultural and institutional factors that enable or constrain the implementation of an option. The feasibility of options may change when different options are combined and increase when enabling conditions are strengthened (IPCC 2022b).
Governance Process of managing public and private interactions through collaboration, negotiation, and coordination between different actors, including the state, civil society, national and international organisations and the private sector. Governance is broader than government and does not rely solely on top-down authority. Instead, it emphasises participation, decentralization, cooperation, and the use of wider collective strategies for implementation.
Innovation Both the processes of research and development and the commercialization of the technology, including its social acceptance and adoption (IPCC 2000). Furthermore, innovation is seen as the process of generation, acceptance and implementation of new ideas, processes, products or services (Thompson 1965) as well as an outcome – any thought, behaviour or thing that is new (Barnett 1953).
Innovation system All important economic, social, political, organizational and other factors that influence the development, diffusion and use of innovations (IPCC 2000).
Institution Rules, norms and conventions that guide, constrain or enable human behaviours and practices. Institutions can be formally established, for instance through laws and regulations, or informally established, for instance by traditions or customs. Institutions may spur, hinder, strengthen, weaken or distort the emergence, adoption and implementation of climate action and climate governance (IPCC 2022b).
Regulatory Factors Regulation can be defined as: A rule or order issued by governmental executive authorities or regulatory agencies and having the force of law. Regulations implement policies and are mostly specific for groups of people, legal entities, or targeted activities. Regulation is also the act of designing and imposing rules or orders. Informational, transactional, administrative and political constraints may limit the regulator's capability for implementing preferred policies (IPCC AR6, 2022).
Responsible Innovation Responsible innovation refers to the process of designing and implementing innovations in a way that anticipates and evaluates potential impacts on society and the environment (Owen & Stilgoe 2013). It requires inclusive, transparent decision-making involving a broad range of stakeholders. The goal is to ensure that innovation aligns with societal needs and ethical standards, promoting sustainability and positive social outcomes while minimizing harm. This approach emphasizes responsibility throughout the innovation lifecycle.
Risk Management Plans, actions, strategies or policies to reduce the likelihood and/or magnitude of adverse potential consequences, based on assessed or perceived risks (IPCC AR6, 2022). In the case of digital technologies, risk management refers to addressing transparency, accountability, and facilitating collaboration among stakeholders to address risk. Risk management strategies should seek to align diverse groups, ensuring that the negative socio-economic and environmental impacts of digital innovations are adequately addressed.
System transitions System transitions involve a wide portfolio of mitigation and adaptation options that enable deep emissions reductions and transformative adaptation in all sectors. The systems include: energy; industry; cities, settlements and infrastructure; land, ocean, food and water; health and nutrition; and society, livelihood and economies (IPCC AR6).
Technology Technology is "a piece of equipment, technique, practical knowledge or skills for performing a particular activity" (IPCC 2000). It is common practice to distinguish between three different components of technology (Müller 2003): • Hardware: the tangible component, such as equipment and products • Software: Software: the processes associated with the production and use of the hardware • Orgware: the institutional framework, or organization, involved in the adoption and diffusion process of a technology These three components are all part of a specific technology, but the relative importance of each component may vary from one technology to another.
Technology transfer The exchange of knowledge, hardware and associated software, money and goods among stakeholders, which leads to the spread of technology for adaptation or mitigation. The term encompasses both the diffusion of technologies and technological cooperation across and within countries (IPCC 2022a).
Transformative change A system-wide change that requires the consideration of social and economic factors which, together with technology, can bring about rapid change at scale (IPCC 2018).
Transition The process of changing from one state or condition to another in a given period of time. Transition can occur in individuals, firms, cities, regions and nations, and can be based on incremental or transformative change (IPCC 2022a; IPCC 2022b).

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FOREWORD

Following the agreement reached at COP28, including the commitment to triple renewable energy capacity globally and double the global average annual rate of energy efficiency improvements by 2030, nations were encouraged to demonstrate greater ambition when updating their NDCs by 2025, ensuring alignment with the Paris Agreement and Sustainable Development Goals. The 2023 Global Stocktake has underscored the urgent need for accelerated action in this critical decade to keep the 1.5 °C goal within reach.

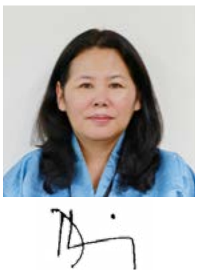
The 2025 NDC update presents an opportunity for countries to identify and prioritize climate technologies, address challenges through implementation of enablers and take a systems approach, while integrating scalable renewable energy technologies into their national strategies. This approach can accelerate emissions reductions and bolster climate resilience, while at the same time generating sustainable development impacts if implemented in a just and equitable manner.

A diverse portfolio of mitigation and adaptation options, supported by enabling policies such as streamlined regulations, subsidies, and public-private partnerships can facilitate faster deployment of these technologies. Understanding the aspects of technology development and transfer significantly influences how well we enhance and accelerate implementation of climate technologies.

The 2024 edition of the Climate Technology Progress Report, entitled "Unleashing Renewable Energy for Ambitious NDCs," focuses on renewable energy technologies, taking a systems approach in assessing what progress we are making on the adoption, what has enabled it, where are the gaps, and building on this understanding, how do we better enhance climate technology development and transfer? The Report strives to promote science-based and systemic approaches, bolstering transformative technology solutions, and focusing on high-impact, high-potential sectors and actions. It fills a space where it provides systematic and annual assessments of the current state and progress on technology development and transfer in various areas.

The report also provides scientifically credible and policy-relevant assessments of different aspects of technology development and transfer in key areas, including those related to feasibility, finance, innovation, and governance; delivers information relevant to the UNFCCC process and to the implementation of the Paris Agreement; and strengthens informed country action on technology transfer including the creation of enabling environments.

In the interim, the Technology Executive Committee (TEC) has invited Parties, international organizations, and international donors to consider the findings and key messages of the 2022 and 2023 CTPR reports. This year's report aims to build on this invitation by providing policymakers and COP29 negotiators with guidance on how we can enhance technology development and transfer of renewable energy technologies, in line with the newest commitments established at COP28.



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EXECUTIVE SUMMARY

CONTEXT

The twenty-eighth session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP 28) marked a shift towards ending the fossil fuel era, with countries pledging to accelerate the transition to renewable energy. The Global Stocktake highlighted the need for urgent action, revealing that we are not on track to meet the 1.5°C target. COP 28 set goals to triple renewable energy capacity and double energy efficiency by 2030, and Parties agreed to establish the Technology Implementation Programme (TIP) to bolster support for the implementation of technology priorities identified by developing countries. At the twenty-ninth session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP 29) in Baku, the TIP will be further discussed with a view to enhancing technology implementation as part of the Azerbaijan COP 29 Presidency's "means of implementation" package, which includes ongoing discussions on improving collaboration and cooperation between the Technology Mechanism and the Financial Mechanism.

The 2024 Climate Technology Progress Report (CTPR) provides an update on the progress made towards tripling renewable energy capacity by 2030 and on the enabling conditions to create this transition, through a technology transfer and systems approach lens, particularly in view of countries' preparations of updated nationally determined contributions (NDCs) to be submitted in 2025.

Further to this, it is expected that at COP 29, a pivotal decision on the New Collective Quantified Goal (NCQG) will be made. This new goal aims to channel more funds into urgent climate actions in developing countries. It will support the implementation of low-carbon, climate-resilient technologies across sectors. By increasing financial resources, the NCQG is intended to empower developing countries to enhance their climate ambitions, particularly as they prepare for the next round of NDCs in 2025. By establishing stronger links between technology and finance, as envisaged through the Global Stocktake, the NCQG and the TIP, the international community can ensure that both developed and developing countries are equipped with the information, tools, technologies and resources they need to meet their climate targets and maintain global momentum towards a sustainable, low-carbon and climate-resilient future.

For 2024, the Technology Executive Committee has invited Parties, international organizations and international donors to consider the findings and key messages of the 2022 and 2023 CTPRs. The 2024 CTPR aims to build on these previous efforts by providing policymakers, COP 29 negotiators and other stakeholders with comprehensive insights and recommendations about the status of renewable energy. These are based on a systems approach to expedite the development and transfer of renewable energy technologies.

TECHNOLOGY ADOPTION AND FEASIBILITY

With the integration of energy storage solutions, electricity systems powered predominantly by renewables are rapidly becoming not only viable, but also increasingly cost-competitive compared to fossil fuel-based systems. While challenges remain in fully transitioning all energy sectors to renewable sources, significant progress can be achieved by prioritizing grid modernization and storage technologies. Furthermore, accelerated efforts are needed to increase the use of renewables in transport and heating. This can be achieved through direct methods (such as solar thermal energy, geothermal energy and ambient heat) and, importantly, through electrification powered by renewable electricity generation. While bioenergy plays a key role, its sustainability must be carefully evaluated, with consideration of factors such as emissions and land-use change. Prioritization of wind- and solar-powered electrification often offers a more sustainable pathway.

There is a strong correlation between increased adoption rates and reduction of technology costs. Specifically, there are technology-inherent characteristics, such as smaller and more modular technology features and low design complexity (including solar photovoltaic modules and light-emitting diodes [LEDs]) that have hugely benefited from price reductions, primarily through "learning by doing", and economies of scale in mass manufacturing. Conversely, technologies with high design complexity (e.g. geothermal power and biomass power plants) are often "lumpy" and large-scale, requiring a high degree of technical, project management and financing capabilities. Thus, the high uncertainty, high cost of implementation, long product development cycles and high cost of coordination in large value chains act as challenges to learning by doing and inter-project spillovers.

A fully integrated energy system, incorporating grid modernization, advanced control mechanisms, and flexible generation and demand resources can significantly reduce the need for long-duration (seasonal) electricity storage. However, strategic deployment of storage remains crucial for grid stability and reliability, particularly as the penetration of variable renewable energy sources increases. While traditional biomass remains a significant source of renewable energy, particularly in regions with limited energy access, it is essential to promote sustainable biomass practices and explore alternatives. Electrification powered by wind and solar power, coupled with appropriate storage solutions, presents a promising pathway for providing clean, reliable and safe energy access in regions such as sub-Saharan Africa and parts of Asia. If flexible technologies and advanced control mechanisms are introduced and full sector coupling is achieved, the integrated energy system will not require seasonal electricity storage.

Electricity systems powered predominantly by renewables will be increasingly viable over the coming decades, but it will be challenging to supply the entire energy system with renewable energy. Large shares of variable solar photovoltaics and wind power can be incorporated in electricity grids through batteries and other forms of storage; transmission; flexible non-renewable generation; advanced controls; and greater demand-side responses. Due to their declining costs, renewable energy technologies (particularly solar and wind technologies coupled with storage) are increasingly the most economically viable solutions in many regions globally.

Several renewable energy technologies show high potential for energy system transitions, with significant synergies between mitigation, adaptation and sustainable development. Globally, solar and wind power are highly feasible, with few challenges to progress on implementation. However, at the regional level, data gaps may be limiting regional expansion. Co-benefits from renewable energy technologies with Sustainable Development Goals (SDGs) highlight that implementation of these technologies can be consistent with expansion of justice and equity, by understanding and prioritizing the local contexts and the needs of the most vulnerable groups. Several renewable energy technologies meet mitigation and adaptation goals with strong co-benefits with the SDGs, including electricity generation, energy storage and demand mitigation for buildings and transport, as well as measures that support the resilience and reliability of these systems. Enhancement of institutional capacity, along with supportive policies, regulations and standards, is needed to improve the overall feasibility of many of the lowest-scoring renewable energy technologies.

Inadequate access to clean, reliable and safe energy is a persistent challenge. It is therefore crucial to acknowledge that a significant portion of renewable energy, primarily traditional biomass, continues to be utilized in regions such as sub-Saharan Africa and parts of Asia.

INVESTMENT AND FINANCE

Holistic policy mixes that address the energy sector, the financial sector and the broader economy are needed to reduce the cost of capital and incentivize investment in renewable energy, including energy storage. Successful examples demonstrate that policy support for renewables coupled with storage can lead to lower levelized cost of electricity than fossil fuels, as seen in countries such as Egypt, Uruguay, Costa Rica, India and China. The persistently high cost of capital in many developing countries is a key investment barrier. Holistic policy mixes that address the energy sector, the financial sector and the economy more broadly are needed to reduce these costs.

Renewable energy technologies, especially solar and wind technologies, have seen rapid cost reductions. China, member countries of the Organisation for Economic Co-operation and Development, and some emerging markets lead in financial commitments and renewable energy investments. Nevertheless, despite technological maturity and ample potential, renewable energy investment is still very limited in many developing countries and is not growing in other emerging economies. The current investor landscape is dominated by large private investors, revealing opportunities for alternative ownership structures that can support communities in generating broad societal benefits and fostering just transitions.

The availability of finance not only drives capacity additions but also leads to significant cost reductions in climate technologies. Mobilization of climate finance continues to be crucial in enhancing progress on technology development and transfer, and in meeting conditional targets under the updated NDCs. With growth rates between 23 per cent and 30 per cent in recent years, the investment volume growth appears to have slowed recently, with only a 4 per cent increase in investments projected from 2023 to 2024. Thus, it is essential to explore innovative forms of finance for technology development and transfer, ranging from public to private funding, including concessional finance, blended finance and grant-based mechanisms.

Understanding market structure and the types of investors involved is key to creating progress on technology development and transfer, as the diversity of actors reflects the maturity of markets and helps shape policy interventions. To accurately assess the financial needs of technology development and transfer for tripling renewable energy capacity, it is essential to estimate the required investment volumes by region and improve data on the cost of capital, which serves as an early indicator for climate technology deployment. Enhanced data collection will foster greater transparency, a critical factor in effective financial planning and policymaking for technology development and transfer.

Applying a system transition lens offers an opportunity to create metrics that go beyond simply tracking financial flows. Financial metrics should capture the broader impacts of investments into technology development and transfer, such as aligning renewable energy initiatives with the SDGs and evaluating their social, economic and environmental benefits.

INNOVATION, DIGITALIZATION AND GOVERNANCE

Digital innovations, supported by responsible governance, can accelerate renewable energy diffusion, enhance mitigation efforts and create cross-sectoral benefits. However, strong governance mechanisms and circular economy strategies at the national level are needed to mitigate the increased demand for information and communications technology hardware and infrastructure, which could offset potential gains.

Digital technologies including artificial intelligence (AI) are increasingly important for mapping renewable energy potential, improving efficiency and enabling interconnections with other sectors, such as water and agriculture. However, they cannot replace the physical infrastructure and governance systems needed for energy transition. Upscaling of AI-based technologies, such as using machine learning for advanced solar mapping, requires fostering public-private partnerships, considering risks and challenges of using AI, promoting transparent and accessible data, and integrating AI tools into national energy strategies.

Robust governance frameworks are necessary to ensure the responsible use of AI in renewable energy projects, including setting national standards for data privacy and equitable access. Accessible AI-enabled platforms for all socioeconomic groups, including marginalized communities, are crucial and can be facilitated through subsidies and a global AI fund promoting digital literacy. Accelerating renewable energy adoption in line with global pledges to triple capacity requires robust institutional and governance frameworks that integrate both energy and digital strategies.

National policies should focus on building digital literacy and skills to generate evidence on energy and digitalization. The policies should promote country ownership, and mobilization of international funding for digital education and clean energy development in low and middle-income countries. National policies should mandate that new and expanding data centres be powered by renewable energy sources and use sustainable materials in their construction and operation. This will minimize the environmental impact of the growing digital sector and ensure its alignment with climate goals.

Context-specific understanding of digitalization's role in decarbonization pathways, especially at the regional level, remains inadequate and requires further study from various perspectives. Country-specific assessments are key to embedding responsible governance in digital innovation policies, strengthening the connection between digital and energy sectors. These policies should drive cross-sectoral governance and investments in climate technology solutions, fostering an enabling environment for achieving the goals of the Paris Agreement and the SDGs.

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1.

Introduction

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1.1 CONTEXT

During recent Conferences of the Parties to the United Nations Framework Convention on Climate Change (COPs), countries reaffirmed their strong commitment to working towards the goal of limiting global warming to 1.5°C, in line with the Paris Agreement. This was further underscored in the Emissions Gap Report 2024 (UNEP 2024), which states that countries must significantly increase their ambition and action in the next round of Nationally Determined Contributions, or the Paris Agreement's 1.5°C goal will be unattainable within a few years. The twenty-eighth session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP 28) signalled the beginning of the end of the fossil fuel era. Countries committed to accelerating the transition away from fossil fuels and embracing renewables such as wind and solar power. The Global Stocktake (GST), a process that allows countries and stakeholders to assess their collective progress towards the goals of the Paris Agreement on climate change, emphasized this direction, and COP 28 set global targets to triple renewable energy capacity and double the rate of energy efficiency improvements by 2030. It also emphasized the acceleration of low- and zero-emission technologies.

Further, the GST revealed that we are not on track to limit global warming to 1.5°C, and the opportunity for meaningful change is rapidly closing. This highlights the urgent, bold actions that governments and stakeholders must take in this critical decade to keep the 1.5°C goal within reach, thereby securing lives and livelihoods. The GST also established a new Technology Implementation Programme (TIP) to bolster support for the implementation of technology priorities identified by developing countries (United Nations Framework Convention on Climate Change [UNFCCC] 2023). At the twenty-ninth session of the Conference of the Parties to the UNFCCC (COP 29) in Baku, the TIP will be further discussed with a view to enhancing technology implementation as part of the Azerbaijan COP 29 Presidency's "means of implementation" package, which includes ongoing discussions on improving collaboration and cooperation between the Technology Mechanism and the Financial Mechanism.

Recent reports have also emphasized the urgent need to triple renewable energy capacity and double energy efficiency by 2030 to meet global climate goals. The COP 28 Presidency, along with the International Renewable Energy Agency (IRENA) and the Global Renewables Alliance, emphasized in their report (COP 28, IRENA and Global Renewables Alliance 2023) that to achieve these ambitious targets, a comprehensive mix of policies is essential. Beyond deployment and enabling policies, structural changes are necessary to ensure the transition to an energy-efficient economy and a renewables-based power system that is just,y fair and beneficial for all. IRENA (2024) highlights that accelerated deployment of renewable energy, coupled with energy efficiency measures, provides the most realistic means to reduce global emissions by 43 per cent by 2030, in line with the findings of the Intergovernmental Panel on Climate Change (IPCC). The report also notes that achieving the target of tripling renewable power capacity by 2030 is technically feasible and economically viable, but requires commitment, policy support and investment at scale, as well as significant acceleration of the deployment of renewable energy, energy storage and renewable fuels, and improvements in energy efficiency. The International Energy Agency (IEA) (2024) offers a comprehensive overview of global government plans for renewable energy capacity, examining whether recent trends in renewable deployment align with government targets and the objective of tripling renewable energy capacity by 2030.

An updated assessment of sectoral emission reduction potentials shows that the techno-economic emission reduction potential based on existing technologies and at costs below US$200 per ton of carbon dioxide equivalent (tCO2e) remains sufficient to bridge the emissions gap in 2030 and 2035 (UNEP-CCC and Common Futures 2024).

Building on to these as well as other major efforts, this 2024 edition of the Climate Technology Progress Report (CTPR) focuses on renewable energy technologies and continues to build on the systems approach set out in previous years' CTPRs (United Nations Environment Programme [UNEP] Copenhagen Climate Centre [CCC] and UNFCCC Technical Executive Committee [TEC] 2022; UNEP CCC, Climate Technology Centre and Network [CTCN] and UNFCCC TEC 2023) for assessing progress on technology development and transfer. System transitions, which are necessary to achieve the required transformational change to keep the 1.5°C target within reach, involve the process of shifting from one state or condition to another within a specific time frame. Collectively, and if appropriately guided, system transitions can enable faster and deeper adaptation and mitigation actions, while also advancing broader sustainable development.

While the global community acknowledges the pressing need to accelerate the shift to renewable energy, this transition is essential not only for mitigating climate change, but also for addressing energy poverty, and for fostering economic growth and resilience. The affordability of energy transitions hinges on lowered costs and enhanced capital availability. Many renewable energy technologies, such as wind and solar photovoltaic

(PV) technologies, require significant upfront investments, which are balanced over time by reduced operating and fuel costs. As the energy system becomes more capital-intensive, maintaining low financing costs will be crucial to accelerating energy transitions and ensuring they remain affordable.

In 2025, Parties to the Paris Agreement will submit their updated nationally determined contributions (NDCs). This will be a pivotal opportunity for countries to present ambitious strategies that harness the transformative power of renewable energy to meet both their climate and development objectives. A just energy transition necessitates changes and shifts in technologies, job markets and economic opportunities. Developing new skills, capacities and expertise domestically is crucial to support these transformational processes. Ensuring that sustainable energy is accessible, affordable and reliable for the broader public is also essential.

The time frame for the updated NDCs will last until 2035. The lead-up to this critical decade's midpoint will thus be an opportunity to enhance ambitions and accelerate implementation to achieve the goals of the Paris Agreement. The new round of NDCs can offer clear and guiding frameworks to mobilize both government and non-state actors, encouraging them to take rapid action to decarbonize their economies, reduce greenhouse gas emissions (GHGs), and enhance resilience to climate impacts. Moreover, the technical phase of the first GST and the Synthesis Report of the Sixth Assessment Report (AR6) highlighted that emissions reduction must be further enhanced for 2035 and beyond, to align with pathways to limiting warming to 1.5 °C. In the next NDCs, conditional elements will be key in setting ambitious targets, as they can include enhanced emission reduction commitments. These targets should be more ambitious and aligned with the 1.5°C goal. The NDCs will need to have clear and measurable conditions for achieving conditional targets. These conditions might include mobilization of international climate finance, technology transfer and capacity-building support, with the global community anticipated to extend both technological and financial support to help many lower-middle income and low-income countries meet their conditional targets.

1.2 FOCUS

Understanding aspects of technology development and transfer significantly influences how we enhance and accelerate implementation of climate technologies. This report therefore aims to provide systematic and annual assessments of the current state of technology adoption in selected areas, as well as the feasibility and requisite enabling conditions for technology development and transfer at the sectoral and regional levels.

As in previous years, the report continues to ask the following questions, all within the context of enhancing technology development and transfer:

1. What progress is being made?
2. What has enabled it?
3. Where are the gaps?
4. Building on this understanding, how do we better enhance climate technology development and transfer?

These questions, which provide the overarching guidance for the report each year, are contextualized based on emerging issues in the global climate landscape. In 2022, the CTPR set out a scoping study of the report framework, and an approach for tracking and exploring trends in technological progress, which it applied using data and cases from the Africa region. The 2023 CTPR continued to explore progress, and analysed technology transfer and development issues related to urban transitions in the context of Asia. The focus in this year's CTPR is on renewable energy technologies. Approximately one seventh of the world's primary energy now comes from renewable technologies, including hydropower, solar power, wind power, geothermal energy, wave power, tidal power and modern biofuels. This share represents the combination of renewables in the overall energy mix, which includes electricity, transport and heating (Ritchie, Roser and Rosado 2020). Traditional biomass, which is an important energy source in lower-income settings, is not included here.

In addition, climate technology needs of developing countries can be tracked through Technology Needs Assessments (TNAs). Introduced at COP-7 under the Convention, TNAs are defined as "a set of country-driven activities that identify and determine the mitigation and adaptation technology priorities of Parties," with a particular focus on developing countries. During the TNA process, countries prioritize technologies based on various criteria, including economic, social, and environmental impacts, rather than solely on their potential for climate change mitigation or adaptation. By now, renewable energy emerged as the most prioritized sector, with 95 percent of 79 countries focusing on it (UNEP-CCC 2022).

Further, 170 of the 188 Parties that submitted NDCs by early December 2020 included references to renewables (IRENA 2019). Of these NDCs, 71 per cent specified quantified renewable energy targets that were focused on electricity generation. If all renewable energy targets identified in the 2020 NDCs were implemented, an additional 1,041 gigawatts (GW) of renewables would be added by 2030. This would lead to an increase of nearly 42 per cent in global installed capacity for renewable power generation, reaching an estimated 3,564 GW by 2030. The target set at COP 28, to triple installed renewable power capacity to at least 11 terawatts by 2030, will require all Parties to significantly raise their ambitions and intensify their actions to achieve this goal.

In 2024, the report takes a global approach with a regional breakdown of the results, to allow an assessment of the overall progress on technology development and transfer. With this approach, it is possible to gain insights for tailoring interventions based on specific needs such as infrastructure and regulatory environments, governance and financial structures. While the regional analyses can provide greater contextual depth, information on both the global and regional levels is essential. Global perspectives can inform regional actions, while they also considers interconnectedness, patterns and trends on a global scale.

The focus aligns with the work of the two constituted bodies of UNFCCC under the Technology Mechanism, namely TEC and CTCN, and their joint work programme. TEC strives to promote science-based and systemic approaches, bolstering transformative technology solutions, and focusing on high-impact, high-potential sectors and actions. CTCN seeks to enhance the transformational impact and scale across various areas, using national systems of innovation and digitalization as key enablers.

For 2024, TEC has invited Parties, international organizations and international donors to consider the findings and key messages of the 2022 and 2023 CTPRs. This 2024 report seeks to build on previous efforts by providing policymakers and COP 29 negotiators with recommendations grounded in a systems approach to accelerate the development and transfer of renewable energy technologies.

1.3 STRUCTURE

Part A focuses on the adoption of renewable energy technologies. It details the pace of renewable energy adoption at the global and regional levels, identifies various challenges, and highlights the segments of the energy system that can facilitate the expansion of renewable energy.

Part B investigates feasibility, and the enabling conditions that influence the feasibility and progress of technology development and transfer. Chapter 3 continues to use the global feasibility assessment as set out in the 2022 and 2023 CTPRs, which builds on the work done for the IPCC AR6. Chapters 4 and 5 are thus focused on finance and investments, and innovation and governance of renewable energy technologies, respectively.

Terra, the Sustainability Pavilion, Dubai, United Arab Emirates ©Pexels, Diego F. Parra

Part A

2.

Technology adoption rates

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KEY MESSAGES

- Different regions are scaling their renewable energy capacity at different rates, influenced by each country's existing capacity and the urgency with which they aim to achieve tripling renewable energy capacity by 2030.

- There is a strong correlation between increased adoption rates and a reduction in technology costs. This refers specifically to technologies that are smaller and with more modular features, and low design complexity.

- Advancing and deploying new technologies can boost renewable energy capacity. This encompasses innovations in solar, wind, and energy storage technologies.

- With the integration of energy storage solutions, electricity systems powered predominantly by renewables are rapidly becoming not only viable, but also increasingly cost-competitive when compared with fossil-fuel-based systems. Significant progress can be achieved by prioritizing grid modernization and storage technologies.

- A fully integrated energy system, incorporating grid modernization, advanced control mechanisms, and flexible generation and demand resources, can significantly reduce the need for long-term (seasonal) electricity storage. Strategic deployment of storage remains crucial for grid stability and reliability.

2.1 INTRODUCTION

This chapter focuses on the adoption of renewable energy technologies, details the pace of renewable energy adoption at the global and the regional level, identifies various challenges and highlights the segments of the energy system that can facilitate the expansion of renewable energy.

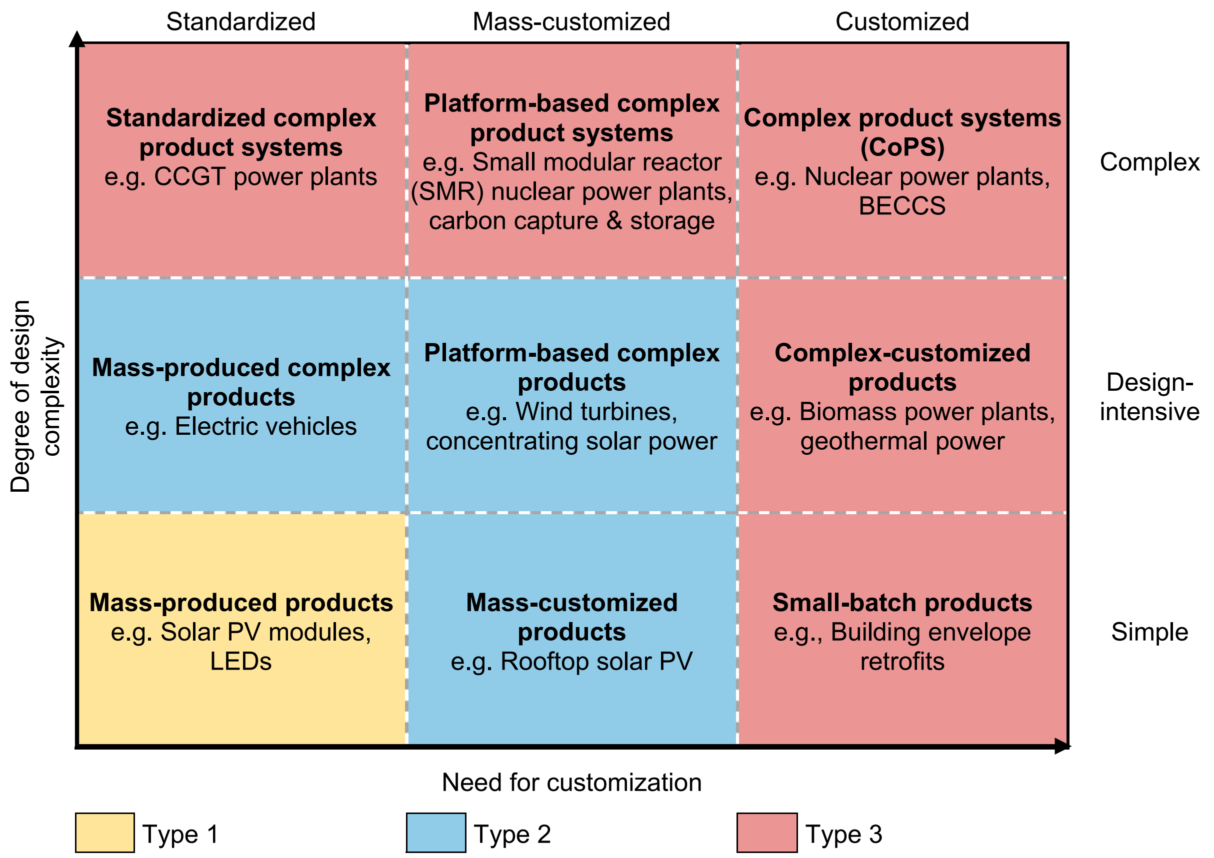
It is important to note that the selection of technologies in this chapter is based on their potential to achieve the tripling of the renewable energy goal, their responsiveness to future climate impacts and consideration of just transition principles, in addition to compatibility with both adaptation and mitigation strategies. As such, this chapter emphasizes the importance of tripling renewable energy and its interconnections with development. This chapter is organized into several sections. It begins with a discussion on the current installed capacity of renewables and outlines the context for tripling renewable energy. This is followed by an analysis of regional contributions towards achieving this goal, highlighting that some countries will require higher growth rates than others. The next section examines the specific components of the energy system that will play a role in expanding renewable energy. The chapter concludes with a discussion on the importance of supportive grid infrastructure and systems operation.

2.2.1 Technology adoption rates

Technology adoption rates of renewable energy technologies vary widely. While solar PV, and wind power to a lesser extent, have seen annual capacity additions which have increased their use significantly, this is not true for other renewable energy technologies, such as biopower, geothermal energy or concentrated solar power. There is a strong correlation between increased adoption and technology cost reductions (see chapter 4 on improving finance for renewable energy technologies). Malhotra and Schmidt (2020) indicated that low-carbon energy technologies with relatively low design complexity, such as solar PV modules and LEDs, have benefited massively from price reductions, primarily through learning by doing and economies of scale in mass manufacturing. To elaborate, the concept of the experience (or learning) curve is highly relevant, which describes the empirical observation that the more technologies are produced and used, the cheaper they become. Behind this experience effect is learning by doing (e.g. on the manufacturing floor), by using (e.g. by operators) and through interaction (e.g. between users and producers of technology), as well as economies of scale (Malhotra and Schmidt 2020). An experience rate (often also referred to as the "learning rate") describes the reduction in a specific cost (e.g. USD/kilowatt [kW] installed) per doubling of the cumulative deployment of a technology.

Recent analyses argue that there are vast differences in learning curves between different energy technologies. These differences stem from technology-inherent characteristics, or in other words, characteristics of a technology that cannot be designed away easily. While Wilson *et al.* (2020) argue that more granular (meaning smaller and more modular) technologies feature higher experience rates, Malhotra and Schmidt (2020) have developed a matrix of three technology types (Figure 2.1), which are defined by their design complexity and their need for customization. Type 1 technologies are fast-learning technologies (high experience rates of around 20 per cent, but sometimes even more), which feature low design complexity (few components, which interact in simple ways) and can be used in many markets or use environments without customization. Solar PV modules and LED light bulbs fall into this category. On the other end of the spectrum are Type 3 technologies, which feature low experience rates (around 5 per cent) and high design complexity (many components that interact in non-linear ways), which may need to be customized extensively to the use environment. Examples of such technologies are geothermal or biomass power plants. Type 2 technologies feature medium levels of complexity and may need to be customized, thus have medium learning rates (around 12 per cent). Competition modelling has shown (and been proven correct by the empirical realities) that differences in experience rates between near-perfect substitutes (such as different renewable energy technologies) are a key determinant of which technologies are more widely adopted and thus outcompete (and eventually lock out) slower learning technologies (Beuse, Steffen and Schmidt 2020; Noll, Steffen and Schmidt 2023).

Figure 2.1 Typology of different energy technologies based on their design complexity and need for customization



Source: Malhotra and Schmidt (2020).

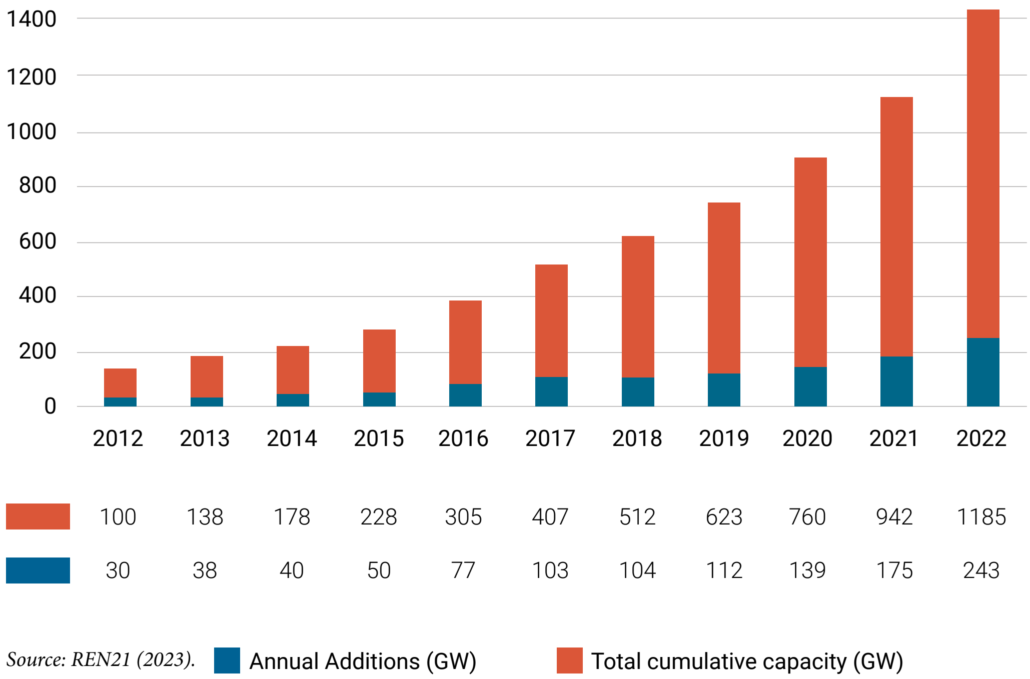
2.2 CURRENT INSTALLED CAPACITY

The pathways assessed by IPCC indicate that the goal of tripling renewable capacity involves increasing it 3.2 to 3.4 times compared with 2022 levels to reach 11.5 TW by 2030 (Grant *et al.* 2024; IEA 2024; IRENA 2024). The amount of renewable energy capacity added to energy systems around the world grew by 50 per cent in 2023, reaching almost 510 GW (IEA 2023e). At present, the total installed capacity of renewables on a global scale is around 3,800 GW, led by solar PV and wind power (IEA, 2024, IRENA, 2024). Total solar and wind capacities in 2022 were 1,185 GW and 906 GW, respectively (Figure 2.2 and Figure 2.3) (REN21 2023).

Accordingly, global solar PV and wind energy capacities grew 170 per cent and 70 per cent, respectively, between 2015 and 2019 (Clarke *et al.* 2022). Linking this to the typology from Malhotra and Schmidt (2020), solar PV has been a major driver behind the increase, accounting for three quarters of all the renewable power capacity additions in 2023 (REN21 2024).

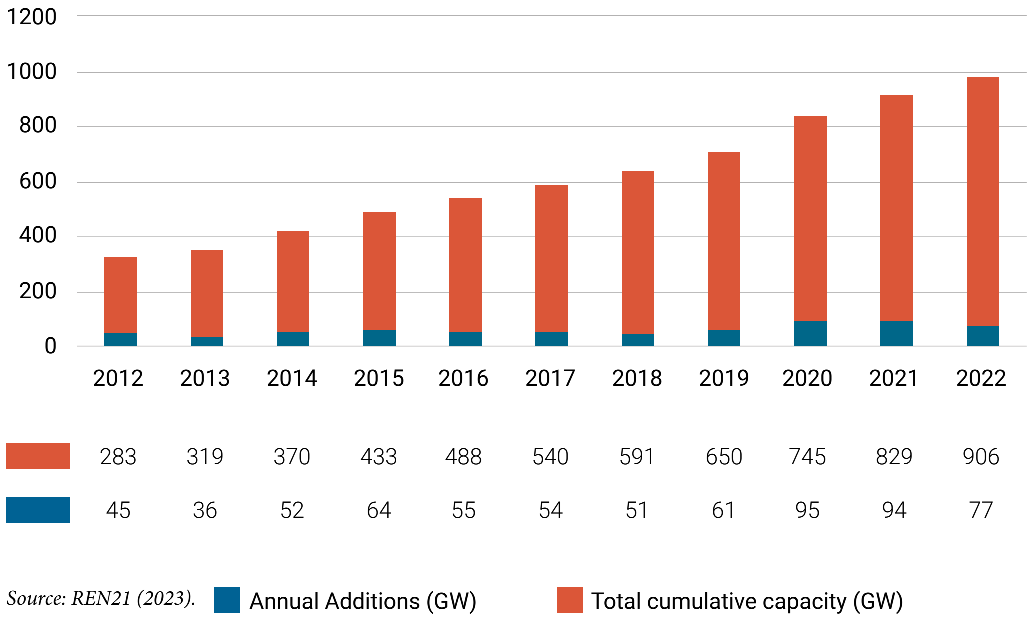
However, alongside these increases in renewable energy, demand for fossil fuels has remained relatively unchanged over the past decades. Meanwhile, global energy demand is expected to increase, creating another uphill battle for higher rates of renewable energy capacity in absolute terms (IEA 2023e). Thus, in many countries, renewables continue to be at a disadvantage when compared with fossil fuels. These hurdles include regulatory restrictions, additional charges for the transmission of green electricity, unfair pricing mechanisms and significant subsidies going towards fossil fuels. In 2022, the International Institute for Sustainable Development found that G20 countries paid out $1.4 trillion in subsidies to coal, oil and gas (Laan and Geddes 2023). Thus, a critical approach needs to be taken to reflect on the present ambitions of both advanced economies and emerging and developing economies, given that there is a diversion from the commitment made at the twenty-eighth session of the Conference of the Parties to the UNFCCC (COP 28) to triple global renewable power capacity by 2030. To meet such ambitions, renewable capacity would need to increase threefold, requiring the annual pace of capacity additions to rise from 336 GW in 2022 to over 1,250 GW by 2030 – an annual average increase of 18 per cent (IEA 2023e). This means that the current pace of globally installed renewably energy capacity would certainly fall below the goal of tripling renewable energy by 2030. According to current IEA forecasts, renewable capacity is expected to increase approximately 2.5 times by 2030, reaching approximately 9 TW (IEA 2024). Bridging this gap demands that renewable energy expands 70 per cent faster between 2022 and 2030 than it did over the past 8 years (Grant *et al.* 2024).

Figure 2.2 Solar PV global capacity and annual additions from 2012 to 2022



Source: REN21 (2023).

Figure 2.3 Wind capacity and annual additions from 2012–2022



Source: REN21 (2023).

Alongside such increases in solar PV and wind energy is the important recognition of off-grid solar PV installations. It is widely recognized that off-grid solar PV systems provide rapid and scalable access to clean energy in developing countries, especially in remote areas (Radley and Lehmann-Grube 2022; Elizondo and Poudineh 2023). This technology is particularly critical for the Global South, including many African countries, which lack grid infrastructure and up-front investment for the system. (See more on financing and investment of RE technologies in Chapter 4). The importance of channelling finance to these regions to provide off-grid solar energy is imperative in addressing the seventh Sustainable Development Goal (SDG) of affordable and clean energy. These systems enable faster deployment by avoiding the need for extensive infrastructure. They also support economic empowerment by facilitating the productive use of energy for small businesses, and are more cost-effective in the long term compared with traditional generators that use fossil fuels. (see Chapter 3, the conditions that not only enable the speed of adoption for off grid technologies but also the fair distribution of benefits and costs). With the rapid adoption of distributed energy technologies, and renewable sources such as solar PV and wind, energy systems have evolved in a way that requires storage for balancing supply and demand effectively.

Energy storage

The growing share of Variable Renewable Energy generation requires the adoption of technologies to balance any fluctuations in renewable energy supply. The adoption of distributed battery energy storage systems is projected to accelerate significantly in developed economies over the next decade, with a compound annual growth rate of 25.7 per cent. In contrast, developing countries are expected to ramp up adoption post-2030 as technology costs decrease, especially in regions with unreliable or costly grid services. Recent analyses indicate that the cost competitiveness of solar-plus-storage is improving rapidly compared with diesel generators and grid-supplied electricity in certain parts of the developing world (Elizondo and Poudineh 2023). Looking deeper into the details, in terms of the types of storage that are likely to be adopted in different regions, Bogdanov *et al.* (2021b) had indicated that in the most developed regions, such as Europe and North America, distributed prosumer batteries, particularly those coupled with high PV capacities, may emerge as one of the most important energy storage technologies. Conversely, in the subbelt countries of the Middle East and North Africa (MENA) and the South Asian Association for Regional Cooperation, utility-scale batteries would contribute to balancing the daily cycles of utility-scale PV generation. The study finds that lower shares of PV in energy supply and reliance on wind energy tend to reduce the battery storage capacity required.

In this respect, the outlook for renewable energy varies significantly at the national level due to differences in energy resource availability, projected energy demand and current renewable energy penetration. (see more in Chapter 3, the conditions needed to facilitate the feasible deployment of large scale energy storage, which includes institutional, and legal frameworks and market mechanisms). In turn, these prospects further affect the structure of other elements of the energy system, including energy storage. Another important aspect which influences energy storage requirements is the legacy power system structure and the level of grid development. The introduction of renewable energy capacity in Europe has proven that in a well-developed, centralized energy system with strong grids, a substantial capacity of Variable Renewable Energy (VRE) can be introduced without the immediate expansion of electricity storage being required. However, in regions with developing power systems, the introduction of electricity storage is crucial, not only for the integration of renewables into mini-grids, but also for reliability.

Reducing the use of traditional biomass

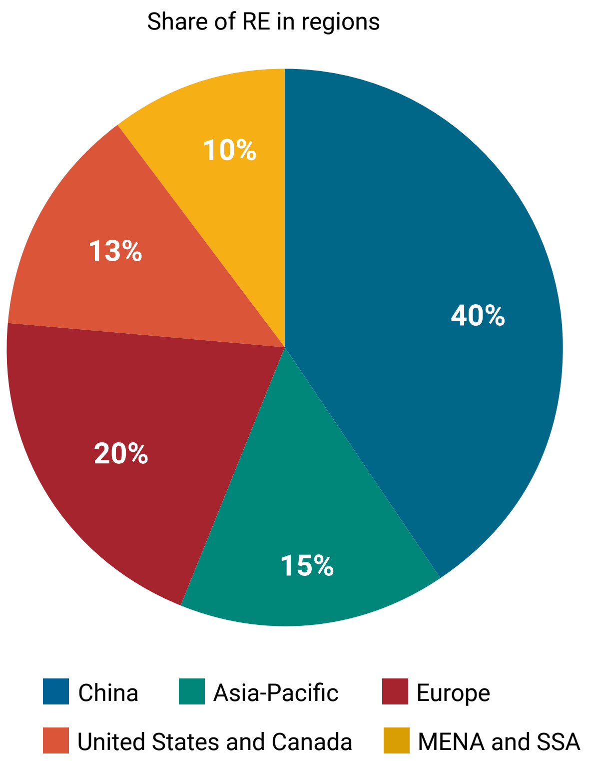
Focusing on a renewable electricity supply in developing countries is crucial. There are significant disparities in fuel sources between countries, and many developing countries still derive a substantial proportion of their energy from traditional bioenergy sources, such as fuelwood and charcoal (IPCC AR6). These energy sources are particularly important in sub-Saharan countries and some Asian countries, such as India, and are used notably for cooking purposes in the residential sector. Africa is still characterized by a high share of traditional bioenergy in both supply and demand. It is thus important to highlight the persistent lack of access to clean, reliable and safe energy in sub-Saharan Africa and certain Asian countries. In this respect, ensuring access to modern, renewable energy sources is crucial, not only for mitigating climate change, but also for addressing critical issues relating to health, equality and human rights. A significant aspect of this effort is the transition away from traditional biomass for cooking, which promises to improve community health in regions without access to modern energy and in areas that are less economically developed (IRENA 2024). The goal of tripling renewable energy adoption thus involves not just overcoming technological challenges, but also addressing issues of access and ensuring that the benefits of these technologies are distributed equitably, as highlighted in SDG 7 (Clarke *et al.* 2022; Sagar *et al.* 2023).

2.3 REGIONAL SHARE OF ACHIEVING THE TRIPLING OF RENEWABLE ENERGY CAPACITY

It is essential to emphasize that attaining the goal of tripling renewable energy capacity hinges on several factors, including the existing installed capacity of various countries, and the scale and pace at which these countries strive to realize this ambition by 2030.

In terms of the distribution of tripling global installed capacity, China would hold the largest share, accounting for 40 per cent (Figure 2.4). This is contingent upon the country achieving 2.5 times its installed capacity base from 2022. European ambitions target an almost doubling of the region's renewable capacity, aiming to contribute 20 per cent (1,590 GW) to the global total. Within Europe, Germany alone represents 34 per cent of this target, with almost a quarter of the region's ambition. Following closely behind are Spain, Italy, France and the United Kingdom, collectively accounting for another third of Europe's ambitious target.

Figure 2.4 The share of tripling renewable energy by region according to collective national energy plans



Source: Adopted from IEA (2024).

In the Asia-Pacific region, the 2030 ambitions, led by India and Japan, represent 15 per cent of the global total. For India, the objective is to achieve 500 GW of non-fossil-fuel capacity (comprising renewable and nuclear sources) by 2030, with renewables accounting for about 485 GW, which equates to 2.6 times the 2022 level. Japan, on the other hand, is aiming for a 36–38 per cent share of renewable electricity generation, equating to an estimated 187–201 GW of capacity. While Asia is the world leader in renewable energy growth rates, it also has the largest number of planned fossil-fuel power plants. Nearly half of the global gas-fired power plant projects are happening in Asia, along with almost 90 per cent of the global coal-fired power plant projects (Grant *et al.* 2024).

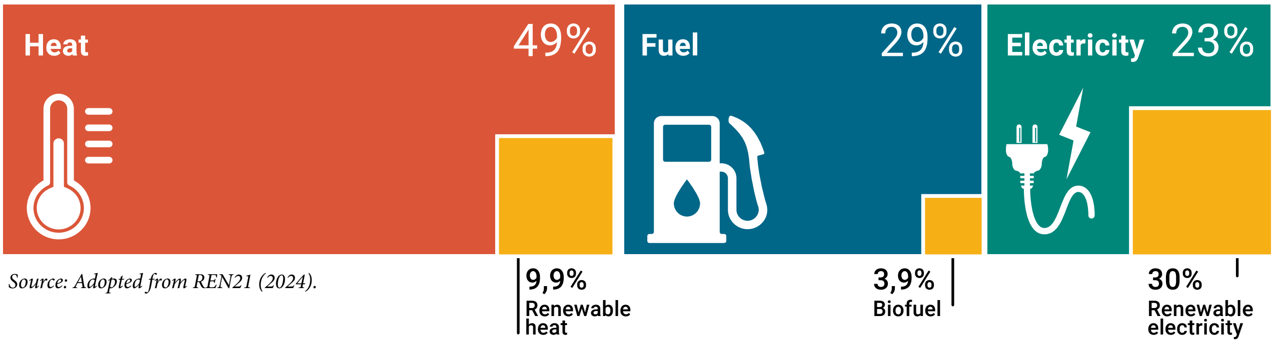
The United States and Canada are collectively targeting nearly 1,000 GW of renewable energy capacity by 2030, doubling their current installed base and constituting 13 per cent of the global total. IEA (2024). In Latin America, the planned increase in installed renewable energy capacity by 2030 amounts to 1.4 times the 2022 installed base if all countries achieve their aspirations. Notably, Brazil alone accounts for approximately half of the region's total ambition. The remaining regions collectively contribute less than 10 per cent to the total global ambition for 2030, despite possessing significant untapped renewable energy potential. Notably, the MENA region exhibits the highest growth factor, given its relatively modest base at present and ambitious 2030 targets. With a goal of installing 200 GW of renewable energy capacity by 2030 – 4.5 times its current installed base – the region is led by Saudi Arabia, Egypt and Algeria (IEA (2024). Favourable solar resources in the region have resulted in some of the lowest bid prices globally in recent years, prompting several countries to establish renewable capacity goals for the first time. Meanwhile, by 2030, sub-Saharan Africa and Eurasia are aspiring to reach 166 GW and 122 GW, respectively, necessitating installed base increases of approximately 3.2 times for the former and 1.3 times for the latter. For comparison purposes, in the Nairobi Declaration on Climate Change, African countries have set a goal of reaching 300 GW of clean power by 2030, up from just 56 GW. The aim is both to address energy poverty and bolster the global supply of cost-effective clean energy for industry (African Union 2023). However, this is conditional on greater support and assistance from more developed countries.

In sub-Saharan Africa, Nigeria, South Africa and Ethiopia account collectively for nearly 60 per cent of the region's ambitions, while in Eurasia, the Russian Federation claims the majority (just over 50 per cent) of the capacity goal, primarily thanks to its existing hydropower fleet. However, only two countries in Eurasia – Uzbekistan and Azerbaijan – have explicitly announced total renewable energy capacity ambitions for 2030. IEA (2024)

2.4 UNPACKING THE GLOBAL ENERGY SYSTEM

In 2020, the global energy supply was predominantly comprised of direct heat, making up 48.7 per cent of the total, followed by fuel (including liquid and gaseous fuels for transport) at 29 per cent. Electricity, which includes usage for heating and transportation purposes, accounted for 23 per cent of the global energy supply (REN21 2024). This trend underscores the increasing dependence on electricity across all sectors to fulfil energy requirements (Figure 2.5).

Figure 2.5 Total final energy consumption and their share of modern renewable energy by energy carrier



Source: Adopted from REN21 (2024).

2.4.1 Electricity

In 2020, traditional biomass still accounted for more than a third of total renewable energy use (Figure 2.6). Between 2015 and 2020, the cost of electricity from solar PV and wind sources decreased by 56 per cent and 45 per cent, respectively, while battery prices fell by 64 per cent (Clarke *et al.* 2022). At present, the relative cost of electricity generation from PV and wind power is cheaper than fossil-fuel-based electricity in many areas.[1] The IPCC Sixth Assessment Report (IPCC AR6), has noted that the weighted average cost of solar PVs in 2019 was $68/megawatt-hour (MWh), falling near the bottom of the range of fossil-fuel prices (Clarke *et al.* 2022). The reasons for these dramatic reductions in costs, are the result of several factors, including reduced silicon costs, increased automation, lower profit margins, enhanced efficiency and a range of incremental improvements (Clarke *et al.* 2022).

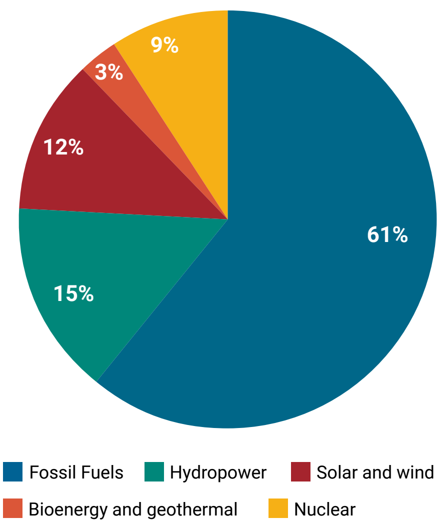
Cost reductions in wind power are driven mainly by larger-capacity turbines, larger rotor diameters and taller hub heights. These developments have not only resulted in reduced costs, but have also enhanced efficiency and wind capacity factors over the last decade. For instance, taller towers provide access to higher wind speeds, thus increasing the amount of energy captured (Beiter *et al.* 2021).

To keep rising global temperatures below 1.5°C throughout this century, one suggestion is that renewables should represent 33–38 per cent of total energy consumption by 2030 (IEA 2024). In other words, this means tripling the current share. In the power sector specifically, renewables would need to account for 60–65 per cent of electricity generation by 2030 (IEA *et al.* 2024). Reducing GHGs through electrification also provides known co-benefits. In particular, shifts to public transport can enhance health and employment, while also eliciting energy security and delivering equity (Clarke *et al.* 2022).

Although the share of solar and wind energy has grown over the last 10 years, it remains low compared with other sources, such as fossil fuels, in terms of global electricity generation (Figure 2.6). Globally, hydropower continues to be the predominant source of renewable energy, with wind and solar PV following behind (Figure 2.6). Here, it is important to note that countries which are overly reliant on hydropower for generating energy are vulnerable to the impacts of climate change. Specifically, in Latin America, hydropower accounts for 45 per cent of total electricity generation (IEA 2021). The impacts of climate change include rising temperatures, fluctuating rainfall patterns and the increasing occurrence of extreme weather events, such as floods and droughts. These all have major knock-on effects on streamflow and water availability, which in turn affect hydropower generation. Thus, there is a need to reflect on the sustainability of hydropower as the primary renewable source, as well as to diversify renewable energy options in the region. (see also the socio-cultural and environment trade offs associated with hydroelectric power in Chapter 3).

1 Purely from the cost of generation, renewable energy is relatively cheaper than electricity produced using fossil fuels. However, when including affordability as a consumption issue, the intermittency of renewable energy may require storage to ensure a reliable supply. As such, the cost of supply may not be as cheap in comparison.

Figure 2.6 Share of renewable energy electricity generation by energy source in 2022



Source: REN21 (2023).

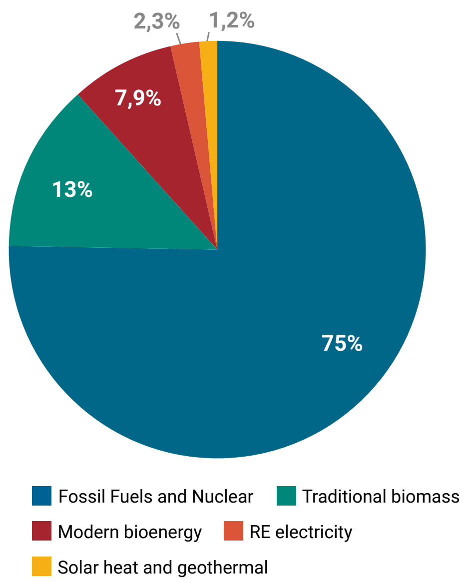
In terms of net-zero energy systems, an increasing dependency on the greater utilization of electricity for various applications is necessary (Clarke *et al.* 2022). According to the IEA (2023e), the electrification of energy systems can provide a significant decline in energy intensity, thanks to the efficiency of converting electricity into energy services, which surpasses incumbent fossil-fuel technologies. Notably, electric vehicles (EV) are two to four times more efficient than current internal combustion engine vehicles. In addition, heat pumps are three to five times more efficient than fossil-fuel boilers, while induction stoves exhibit approximately twice the efficiency of their gas-powered counterparts (Gielen *et al.* 2019; IEA 2023e).

Electrification and the enhanced integration of the electricity system with other sectors will fundamentally reshape the operational and planning framework of future energy infrastructure (Clarke *et al.* 2022). It is anticipated that electricity will meet at least 30 per cent of the world's final energy requirements (IRENA 2024). Such an increase in demand for electricity will require generation capacities to be upscaled very quickly. To fulfil climate targets and avoid stranded fossil-based generation assets, these new capacities must be renewable. Electrification of the heat and transport sectors creates possibilities, but also a need for renewable energy capacities to grow quickly in the coming decade.

2.4.2 Heat as an energy end use

Globally, heat represents the most substantial energy end use, constituting half of global final energy consumption at 175 EJ (IEA *et al.* 2023). Industrial processes account for 53 per cent of the total final energy consumed for heat. Residential and commercial buildings use another 44 per cent of this energy to heat spaces and water, as well as for cooking, to a lesser degree. The remaining energy is utilized in agriculture, mainly for heating greenhouses (IEA 2023d). Fossil fuels (coal, gas and oil) currently dominate the heating sector, with renewable energy sources fulfilling less than a quarter of the global heat demand in 2021, of which traditional biomass constituted half of this portion. The IEA has noted that heat pumps and district heating networks represent important low-carbon, high-efficiency heating technologies in reducing greenhouse gas emissions (IEA 2023a; IEA 2023b). Furthermore, Bogdanov *et al.* (2021) have noted that as an increasing amount of renewable energy is deployed, heat pumps and electric heating systems are likely to replace oil and gas boilers in both residential buildings and industrial facilities.

Figure 2.7 Share of renewable heat production by energy source in 2020



Source: REN21 (2024).

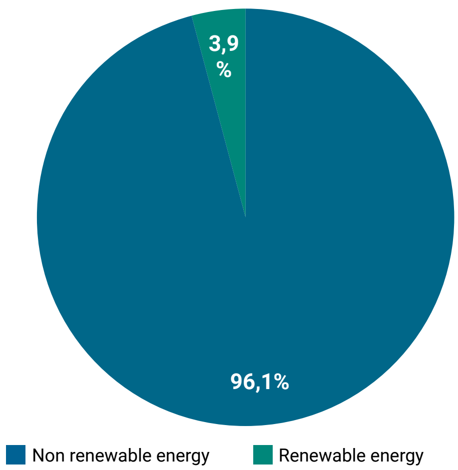
Renewable sources contributed a modest 24 per cent to the energy utilized for heat, with traditional biomass representing more than half of this share, predominantly in sub-Saharan Africa and Asia (Figure 2.7). When excluding traditional biomass uses and the ambient heat captured by heat pumps (for which data is limited), direct renewable heat consumption rose by 0.9 per cent year-on-year to just over 18 EJ in 2019. This accounted for 10.4 per cent of the total energy consumed for heat, a mere increase of 2 percentage points in 10 years (IEA *et al.* 2024).

Looking ahead to 2050, heat pumps and electrical heating should play a significant role in the heat sector (Bogdanov *et al.* 2021b), with a share of over 40 per cent of heat generation. Heating using synthetic e-fuels and sustainable biofuels contributes to fulfilling heat demand for industrial processes. Although the heat sector represents the largest energy end use globally, it has received minimal policy support regarding energy efficiency, conservation and material efficiency. Heat for industrial processes requiring temperatures greater than 150°C,[2] such as those needed in cement and steel, for example, are mostly dependent on fossil fuels (Ghoneim, Mete and Hobley 2022; IEA 2023c). Industrial processes of this nature are challenging to decarbonize and are not typically powered by renewable energy. Instead, they often rely on emerging technologies, such as green hydrogen. Greater focus is thus needed on the role of renewable heat technologies and reducing the inefficient and unsustainable use of biomass.

2.4.3 Transport as an energy end use

Liquid biofuels, primarily crop-based ethanol and biodiesel mixed with fossil-based transport fuels, accounted for 90 per cent of the renewable energy used in transportation (IEA *et al.* 2024). The rest primarily came from renewable electricity powering vehicles and trains, which saw a year-on-year increase of 0.02 EJ in 2020, marking the second-largest growth since 1990. This rise was partly driven by the growing number of EVs, which increased from 7.1 million in 2019 to 11.3 million in 2020. Recent advances in battery storage make EVs the most attractive alternative for light-duty transport (Clarke *et al.* 2022). The electricity for these vehicles is increasingly sourced from renewables, with the share of renewable electricity in transport rising from 20 per cent in 2010 to 28 per cent in 2020. This growth in renewable electricity usage, coupled with a general decline in fossil-fuel demand for transport, led to the second-largest annual increase in the renewable fuel share for transport since 1990, reaching 4 per cent in 2020, up from 3.6 per cent in 2019.

Figure 2.8 Renewable share of total final energy consumption in transport in 2021



Source: REN21 (2024).

2 Please see this website for further details: https://www.irena.org/Innovation-landscape-for-smart-electrification/Power-to-heat-and-cooling/Status#:~:text=Heating%20and%20cooling%20accounts%20for,energy%2Drelated%20carbon%20dioxide%20emissions.

Despite the notable increase in the use of renewable energy in the transport sector, the sector demonstrated the lowest penetration of renewable energy among end uses in 2020, comprising only 4 per cent of final energy consumption in the transport sector globally (Figure 2.8) (REN21 2024). A significant increase in effort is thus required to enhance the utilization of renewables in transport and heating, employing both direct methods (such as bioenergy, solar thermal and geothermal energy, along with ambient heat) and indirect approaches (such as electrification), while simultaneously advancing energy-conservation measures.

In net-zero energy systems, it is anticipated that a significant proportion of transportation, particularly road transportation, will become electrified. This includes two- and three-wheelers, as well as light-duty vehicles and buses, which are especially suited to electrification. More than half of passenger light-duty vehicles across the world are expected to be electrified in these systems (Clarke *et al.* 2022). In this respect, road transport holds the highest potential for electrification. According to IRENA's 1.5°C scenario, key drivers of this growth include the successful launch of new EV models, financial incentives and improvements in charging infrastructure. At the same time, transport electrification and the development of the charging infrastructure may provide multiple benefits to both the vehicle owners and the system, enabling flexible, smart charging of vehicles and providing the system with access to part of the vehicles' fleet battery capacity (Bogdanov and Breyer 2024).

While transitioning to electrical power is crucial to reducing carbon emissions for various applications, certain sectors, such as long-distance transport (e.g. freight, aviation and shipping), pose challenges for electrification. For these sectors, alternative fuels or energy carriers, such as biofuels, hydrogen, ammonia or synthetic methane may be necessary (Clarke *et al.* 2022; Bogdanov *et al.* 2024). According to most projections, hydrogen demand is expected to increase gradually, becoming particularly valuable as the energy system shifts towards predominantly low-carbon sources. However, there are vast differences in the potential for hydrogen to reduce carbon emissions depending on its production method. Grey hydrogen made from natural gas or methane has limited mitigation potential compared with green hydrogen produced using renewable electricity. However, current availability for the latter is limited.

2.5 SUPPORTIVE INFRASTRUCTURE FOR GRID INTEGRATION

A significant barrier to the rapid expansion of renewable energy is the insufficient investment in grid infrastructure. As of 2023, approximately 3,000 GW of renewable energy projects were stalled in grid queues, highlighting an increasing bottleneck in the system (REN21 2024). This issue affects both advanced economies and emerging and developing countries alike. The development lead times for grid infrastructure improvements are substantially longer than those for wind and solar PV projects, thereby impeding the pace of renewable energy deployment (IEA 2023e). Grid bottlenecks are expected to create substantial challenges and result in higher curtailment rates in numerous countries, as grid expansion struggles to keep up with the rapid installation of VRE sources (IEA 2023e). It is therefore essential to prioritize grid expansion in emerging and developing markets to unlock their renewable energy potential and support green industrialization and development goals. Regional interconnections enable the efficient transmission of renewable energy sources, enhancing grid stability and supporting the integration of larger shares of renewables across regions and continents.

2.6 SYSTEM OPERATIONS: STORAGE, TRANSMISSION, SECTOR COUPLING AND DEMAND-SIDE MANAGEMENT

Accelerating the deployment of renewable energy in electricity, heat and transport is essential for achieving universal access to affordable, reliable, sustainable and modern energy.

High penetration of wind and solar power further introduces technical and economic challenges due to their spatial and temporal variability, short- and long-term uncertainty, and non-synchronous generation. These challenges become increasingly critical as the share of renewables approaches 100 per cent (Clarke *et al.* 2022). Despite the presence of ongoing operational, technological, economic, regulatory and social obstacles, various systemic solutions have been devised to incorporate substantial amounts of renewable energy. One of these solutions involves enabling flexible electric loads and the strategic use of EVs and smart appliances, for instance, to shift electricity demand and restore balance to the grid. For an effective integration of large shares of renewables, a diverse array of strategies will be needed. These include system integration, sector coupling, energy storage, smart grids, demand-side management, sustainable biofuels, and electrolytic hydrogen and its derivatives, among others (Gielen *et al.* 2019; Clarke *et al.*, 2022).

The deployment of integration options hinges on various factors, such as their relative costs and benefits, regulatory frameworks and the design of electricity markets. Significant uncertainties exist concerning future technology costs, performance, availability, scalability and public acceptance. Interestingly, the economic value of renewable electricity can decline as its deployment grows. This is due to the increased integration of renewable energy leading to technological, regulatory, market and operational challenges that create uncertainties about its competitiveness (Clarke *et al.* 2022). The literature on 100 per cent renewable energy systems is an emerging subset of deep decarbonization literature (Breyer 2022; Clarke *et al.* 2022; IRENA 2024). There is broad agreement that more research is needed on the role of renewable energy in sectors beyond electricity, as well as on alternative fuels for hard-to-electrify sectors (Clarke *et al.* 2022). Therefore, the approach to tripling renewable energy should be pursued in a balanced manner.

The potential dominance of renewable powered electricity systems in the coming decades signifies a progressive shift. However, achieving full renewable energy integration across the entire energy landscape poses formidable challenges. For example, the assimilation of substantial shares of variable solar PV and wind power within electricity grids necessitates a multifaceted approach. This entails leveraging battery technology and other forms of storage, augmenting transmission infrastructure, integrating flexible and non-renewable generation, deploying advanced controls and fostering greater demand-side responses (Clarke *et al.* 2022; IEA 2023e). An imperative for low-carbon energy system transitions is the enhanced integration across energy system sectors and scales. Facilitating a synergy between the electricity sector and end-use sectors holds promise for the seamless incorporation of VRE options. This integration extends across various spatial scales, encompassing district, regional, national and international domains, thereby fostering synergies and cost efficiencies in the pursuit of sustainable energy transitions.

Energy-storage technologies, such as batteries, pumped hydro storage and hydrogen storage, offer a diverse range of system services. While lithium-ion batteries have gained attention due to falling costs and increasing installations, achieving very high renewable shares typically requires either dispatchable generation or long-duration storage, alongside short-duration options. Energy storage technologies are part of a broader range of options for providing grid services, including synchronous condensers, demand-side measures and inverter-based technologies.

To balance differences in resource availability, high renewable systems are likely to require investments in transmission capacity and changes in trade patterns. These enhancements may also require the expansion of balancing regions to leverage geographical smoothing. Sector coupling involves the increased electrification of end uses and pathways for electricity conversion to other forms (Power-to-X), such as creating synthetic fuels like hydrogen (Ueckerdt *et al.* 2021). This approach can enhance system flexibility significantly through the utilization of advanced technologies. In this respect, implementing flexibility technologies and advanced control mechanisms for integrated energy systems – such as those connecting electricity, heating and cooling, gas and hydrogen, and transportation – can significantly reduce future investments in low-carbon energy infrastructure. All the balancing options discussed will coexist and complement each other in future energy systems.

Some studies modelling the transition of the energy system beyond the power sector and considering all the key balancing options show that if the flexibility technologies and advanced control mechanisms are introduced and full-sector coupling is reached, the integrated energy system will not require seasonal electricity storage (Bogdanov *et al.* 2021b) and may operate with a relatively small short-term electricity storage capacity (Bogdanov and Breyer 2024). In turn, this will enable a more regionalized system that is less dependent on grid integration. As such, the more sector coupling and demand response that is enabled, the more battery costs are reduced, with fewer interregional grids needed.

The de-fossilization of transport via electrification and synthetic e-fuels, and switching to synthetic e-chemical precursors in the chemical industry, would represent key enablers for the flexible operation of the energy system and a reduction in the need for electricity storage capacity. Seasonal fluctuations of the VRE supply may be compensated by the seasonal operation of electrolysers, peaking in periods with surplus renewable energy and reducing down to zero in periods with a deficit of renewable energy. This may also be achieved by buffering hydrogen storage, as well low-cost e-fuels and e-chemicals storage. The option to operate in this way will depend on regional renewable energy potential and demand patterns. However, even in regions with high seasonality and an energy-intensive economy, the renewable energy capacities needed to satisfy the demand for e-fuels for transport and e-chemicals for industry would cover the inflexible demand for residential power supply in deficit periods (Bogdanov *et al.* 2021). Smart charging and vehicle-to-grid technologies applied to EVs may partially substitute utility-scale batteries in regions with well-developed grids and infrastructure (Bogdanov and Breyer 2024).

2.7 CONCLUSIONS

The aim of this chapter was to outline the context in which the goal of tripling renewable energy adoption could be achieved. This has several implications, including the need for countries to raise their ambitions for their next set of NDCs and to develop long-term strategies for low emission development, ultimately targeting net-zero emissions by 2050. The chapter specifically examined the progress that renewable energy has made in various parts of the energy system, namely electricity, heat and transport. Of notable mention is the need to consider how the adoption of climate technologies, such as renewables, intersects with various societal priorities.

While the costs and benefits of climate mitigation are often evaluated purely in terms of the economic outcomes, such as the effects on gross domestic product or changes in consumption value, it is essential to adopt a broader perspective which considers the interlinkages of progress in energy transitions and development priorities, such as those defined in the SDGs. Access to and benefits from technological advancements are not neutral; they depend on user access to financial, social, physical and informational capital. Moreover, in terms of innovation, there is also the importance of the availability of high-quality networked infrastructure, capital intensity and a good supply of skilled labour, as well as access to products and services. Thus, concentrating mainly on aggregate economic outcomes overlooks the distributional impacts of both technology selection and progress.

The adoption of renewables has advanced significantly in the electricity sector. Consequently, there is a pressing need to construct a substantial amount of new electricity capacity and infrastructure to accommodate the demands of these sectors (IRENA 2024). Several reports have noted that a substantial growth in the role of electricity in total final energy consumption is expected in industry, transportation and buildings, due to trends such as grid expansion, sector coupling and a global increase in the deployment of electric appliances and other enabling technologies over the next 30 years (IRENA 2024; REN21 2024). Achieving net-zero energy systems requires a shift towards electricity for various purposes. This transition encompasses the electrification of passenger transportation, including light-duty EVs, two- and three-wheelers, buses and rail transport. Furthermore, it extends to various energy needs associated with buildings, such as heating and cooling, which are poised to transition to electric power through heat pumps, for instance, as well as through district heating and cooling.
Nevertheless, while expanding the deployment of renewable energy presents challenges in fully supplying the energy sys-

tem, integrating substantial amounts of variable solar PV and wind power into electricity grids is crucial. This integration can be achieved by using batteries and other storage technologies, making improvements to transmission infrastructure, and utilizing flexible non-renewable generation capabilities, advanced control systems and enhanced demand-side responses. Substantial investments in grid infrastructure are essential to increasing flexibility while maintaining reliability concerning voltage fluctuations, frequency variability and VRE support (Renné 2022).

Moreover, it is crucial to acknowledge that a significant proportion of renewable energy, primarily traditional biomass, continues to be utilized. This underscores the persistent challenge of inadequate access to clean, reliable and safe energy in regions such as sub-Saharan Africa and parts of Asia. Ensuring widespread access to modern renewable energy sources is therefore essential, not only to combat climate change but also to tackle pressing issues, such as health disparities, social equity and human rights concerns.

In addition to expanding renewable energy beyond electricity, there is a need to increase the use of renewables in transport and heating. This can be accomplished through direct means, including bioenergy, solar thermal energy, geothermal energy and ambient heat. Furthermore, Power-to-X technologies, such as power-to-fuels (involving green hydrogen, synthetic methane, methanol and other e-fuels), will play a crucial role in connecting low-cost variable renewable electricity with demand across all energy-sector segments where direct electrification is not possible (Bogdanov *et al*. 2021b).

Solar panel photovoltaic in a rural area ©Shutterstock

Part B

3.

Feasibility assessment

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KEY MESSAGES

- Countries need to set more ambitious renewable energy targets in their updated Nationally Determined Contributions. This involves aligning national policies to achieve the goal of tripling renewable energy capacity by 2030. Hence, institutional capacity, along with supportive policies, regulations and standards, needs to be strengthened to improve the overall feasibility of those technologies that scored the least.

- Globally, solar and wind power are highly feasible considering institutional, economic, technological, geophysical, and socio-cultural dimensions. However, data gaps may still be limiting regional expansion.

- Several renewable energy technologies meet both mitigation and adaptation goals, while also being of benefit to the Sustainable Development Goals. This relates to electricity generation and energy storage, and to the resilience and reliability of these systems.

3.1 INTRODUCTION

This chapter evaluates and updates the feasibility assessment (FA) of the adaptation and mitigation technologies comprising the energy-system transition, as defined by the Sixth Assessment Report (AR6) from the IPCC. The Special Report on Global Warming of 1.5ºC (SR1.5) concludes that to comply with the Paris Agreement, emissions need to be reduced by 45 per cent by 2030, meeting net zero by 2050 (Intergovernmental Panel on Climate Change 2022). As such, the present chapter assesses technologies that are key to this transition. Not only does it cover both adaptation and mitigation, but it also places an emphasis on technologies with very strong synergies between mitigation, adaptation and the SDGs. There is also a particular focus on technologies that have the potential to support the transition away from fossil fuels, as agreed upon at the COP 28 in 2023 and in line with achieving the long-term temperature goals set by the Paris Agreement, with due consideration of the equitable sharing of benefits and costs. Specifically, at COP 28, the Heads of State and governments pledged to triple renewable energy capacity to at least 11,000 GW and double energy efficiency by 2030 (COP 28 2023).

This chapter will investigate the following questions:

1. What is the feasibility of renewable energy technologies? What are the demandmitigation side solutions for different types of energy needs and different scales, from community to global?

2. What are the main opportunities and barriers in implementing renewable energies and demand-mitigation technologies in energy-system transitions?[3]

3. What are the relationships between energy-system transitions and actions in other system transitions, including those relating to technologies?

4. How can energy-system transitions foster a just energy transition and support climateresilient development?

This chapter employs the well-established FA methodology, originally used in report SR1.5 from the IPCC. For full details on how the FA approach was applied for the purposes this chapter, please refer to the Appendices A and B.[4]

The literature for the FA builds upon the AR6 report from the IPCC. As such, the present chapter provides an update, assessing the literature available from September 2021 to September 2024, with a focus on indicating the feasibility of technologies to limit the global temperature increase to 1.5ºC in accordance with the Paris Agreement. The FA has been recognized as being a useful tool for decision-making, as it provides immediate feedback about which technologies are feasible at this particular moment in time, allowing for the prioritization of funding options and implementation. At the same time, this approach provides clear indications of barriers and knowledge gaps for options that, although desirable, may be less feasible. This allows for a specific consideration of what would be required to improve their feasibility.

This chapter adopts a system transitions framework to provide a link between adaptation and mitigation responses, and does so by bringing together the sociotechnical transitions required to reduce emissions and the socioecological resilience needed to lessen vulnerability. The systemtransitions framing is critical to understanding the role of technologies in achieving the more fundamental climate and sustainable development transformations. This implies shifting attention away from technologies that address opportunities for mitigation or adaptation in the energy sector to taking a more integrated and systems focused perspective of transitions. Thus, the technologies are evaluated based on their ability to support cross-cutting issues, such as health and education, as expressed in the 2030 Agenda for Sustainable Development, and their capacity to support a just transition towards net zero (sometimes referred to as "carbon neutrality") by the middle of the century is also examined.

3 System transitions involve a wide portfolio of mitigation and adaptation options which enable significant reductions in emissions and transformative adaptation across all sectors. The systems are as follows: energy; industry; cities, settlements and infrastructure; land, ocean, food and water; health and nutrition; and society, livelihood and economies.

4 Appendices A and B are available at https://unepccc.org/climate-technology-progress-reports/

3.2 FEASIBILITY ASSESSMENT ACROSS THE ENERGY SYSTEM TRANSITION

3.2.1 Selection of technologies within the energy system transition framework

Table 3.1 shows the technologies that have been selected and assessed in this chapter. The systems transition frameworks from the AR6 WG2 and WG3 reports were applied to select these options from the full list of technologies detailed in the AR6 reports. These options therefore show strong links between adaptation and mitigation.

Table 3.1 List of energy technologies considered for the feasibility assessment

Adaptation	Mitigation
Resilient power systems	Solar energy
Energy reliability	Wind energy (onshore and offshore combined score)
Water use efficiency	Hydroelectric power
*Smart grids/digitalization	Geothermal energy
	Energy storage (pumped storage hydropower [PSH] and battery energy storage [BES]) for low-carbon grids
	Demand mitigation in buildings and public transportation
*While smart grids increase the reliability of energy systems, they are currently listed as a separate option. This is because energy reliability technology also includes energy generation, not just energy transmission and distribution.	

The selection includes technologies that are deemed viable to replace fossilfuel generation and reduce demand in the short-term. Energy sources, such as solar photovoltaics (PV), hydroelectric power, wind and geothermal energy, have been selected for their mitigation potential, as well as their potential to provide broader benefits for mitigation and adaptation through supporting a range of technologies. Sustainable water management, energy system reliability and resilient power systems, which have been evaluated with their adaptation potential in mind, also contribute to mitigation strategies. Energy demand management options, which include several mitigation technologies focusing on buildings and public transportation, as well as energy storage technologies, have also been included in this FA. (See Table 3.2)

In-keeping with the theme of the 2024 CTPR, we also examined a subset of technologies through regional perspectives. These are solar PV (Asia and Central/Latin America) and hydroelectric solutions (all regions). The global share of renewables in power generation and heat consumption for the year 2022 were 29 per cent and 11 per cent, respectively (International Energy Agency [IEA] 2024b).

However, renewable power capacity is not distributed equally across the world, with the G20 countries accounting for almost 90 per cent of the global share (IEA 2024a). Thus, it is important to examine how feasibility varies on a regional basis across the globe, in addition to identifying barriers and knowledge gaps in the literature.

3.2.2 Assessment approach for this chapter

Figure 3.1 illustrates the eight-step process followed using the multidimensional FA for different adaptation and mitigation technology options (Singh *et al.* 2020; Steg *et al.* 2022). The six feasibility dimensions (economic, technological, environmental, geophysical, sociocultural and institutional) from the global-level analysis conducted by the IPCC in AR6 were applied. Indicators were then developed for the dimensions, and the adaptation indicators from WG2 and the mitigation indicators from WG3 were followed.

In Table 3.2, the indicators chosen for the technological feasibility dimensions relating to adaptation and mitigation are shown. The differences between these indicators highlight how key characteristics differ in terms of evaluating feasibility for adaptation and mitigation. These indicators represent the most commonly identified indicators throughout the literature as a whole, and can be applied to the global context. For simplicity and comparability purposes, we also used these indicators for the regional scales in this report. However, if this exercise were to be repeated for a specific country or subregion, this indicator list should be reviewed to determine its applicability and relevance to the dimensions that are important in that location. One limitation of this methodology, as developed and applied by both the IPCC and in this report, is that the indicators used at the global level may not always be relevant or important when used with regional or other scales, thus fail to identify specific local barriers which need to be addressed. In spite of this, the FA approach serves as a guide on how to carry out the assessment at different levels and with prioritized indicators for specific contexts. For full details on the FA approach, please refer to Appendices A and B.

3.2.3 Feasibility assessment results

In Table 3.2, we show the FA for adaptation (panel A) and mitigation (panel B), as well as a regional assessment for solar panels (panel C) as well as Hydroelectric energy (Panel D). Here, we discuss these results and the implications for the feasibility of these renewable energy technology options.

3.2.3.1 Adaptation

The adaptation options assessed for energy system transitions are resilient power infrastructure, reliable power systems and water use efficiency, the latter of which focuses primarily on water efficiency and cooling for the generation of electricity from all types of sources. Broadly speaking, the FA for these three options has not changed significantly since AR6. Energy reliability (such as through the diversification of generation sources, the use of energy storage, robust maintenance and monitoring plans, and building redundancy measures, among others) and the resilience of the power infrastructure (including generation, transmission and distribution) remain a focus in the face of increasing extreme weather events and their impacts. However, since the AR6 report, we have seen an increased amount of literature on the role of distributed generation and long and shortterm energy storage as specific options to increase the resilience of power systems, along with their associated synergies with emissions reductions and the achievement of the SDGs, in a just, equitable and inclusive manner.

Barriers remain primarily within the institutional dimensions, highlighting the need for improved regulatory frameworks and codes aimed at making infrastructures more resilient in a changing climate, in addition to the need for crosssectoral coordination and the prioritization of proactive adaptation. For all three options, limited evidence is available for some of the indicators within the institutional, social and geophysical dimensions, and a knowledge gap thus remains. Furthermore, these three options have been assessed globally as there is no evidence of regional differences within the dimensions.

Box 3.1: Mitigation and adaptation feasibility for smart grids/digitalization

Introduced in this chapter is the FA of smart grid/digitalization technologies for climate adaptation and mitigation. At the global scale, smart grid and digitalization technologies have a medium technological feasibility for adaptation. The emergence and innovation of smart grid-related technologies, such as artificial intelligence (AI), the Internet of things (IoT) and 5G can contribute to a more resilient power grid (Dong and Zhang 2021; Babazadeh *et al.* 2022) by reducing the impacts of power outages (Aghahadi *et al.* 2024). Additionally, emerging technologies, such as AI and edge computing, offer key enhancements to improve the forecasting of intermittent renewable energy sources (Fan *et al.* 2021; Ahmad *et al.* 2022; Meenal *et al.* 2022; Habbak *et al.* 2023), thus improving grid reliability.

When smart grids are integrated with renewable energy sources, they can contribute to lowering emissions from the power sector while simultaneously enhancing resilience. Features such as real-time outage detection and automated response systems thus contribute to adaptation and mitigation. Technological feasibility, however, is also constrained by challenges related to the increased vulnerability of smart grids. For example, Babazadeh *et al.* (2022) discuss how interdependencies of the electrical grid with other systems can lead to complexities and unforeseen effects. There is also the potential for increasing vulnerability to cyberattacks (Jasiûnas, Lund and Mikkola 2021), which can have adverse, knock-on effects on society and institutions alike.

While the evidence on economic feasibility is limited, smart grids may enable cost savings for customers, despite presenting initial cost barriers (Kumar *et al.* 2021). At the global level, there is limited evidence of the institutional feasibility of smart grids. However, in parts of Asia (India, Nepal and Pakistan), institutional feasibility is low due to barriers with political acceptance and institutional capacity (Asaad *et al.* 2021; Raza *et al.* 2022; Bhattarai *et al.* 2023; Nazir and Sharifi 2024). Finally, there is also limited evidence to evaluate environmental and ecological feasibility, as well as a recognized need for research to better characterize the environmental impact of smart grids (Moreno Escobar *et al.* 2021; Lamnatou, Chemisana and Cristofari 2022; Durillon and Bossu 2024).

3.2.3.2 Mitigation

Solar energy

Overall, solar power generation has a high feasibility. All dimensions scored highly in this regard, except for institutional. Our global findings are consistent with the results reported in the IPCC's Working Group 3 contribution to AR6. However, we have highlighted some additional conditions to enhance the feasibility of solar PV to achieve the target of tripling renewable energy sources by 2030. The effects of competition for natural resources can be reduced by increasing the rates at which panels are recycled and by enhancing recycling techniques (Teixeira, Brito and Mateus 2024). Given that the full life cycle of a technology is considered in this assessment, there is also a need to minimize any potential negative impacts on the environment at the end of service life, namely ecotoxicity if solar PV panels are not disposed of correctly (Zhang *et al.* 2023). Ecological risks extend to the recycling process due to techniques such as thermal and hydrometallurgical treatments (Martínez *et al.* 2024). Additionally, effective legislation, consistent incentive policies, financing and proper planning to increase the transmission capacity are also needed to support this expansion.

We have also extended these findings to Asia and Latin America, where sufficient literature exists to carry out a FA. For these two regions, we reveal a lower feasibility in terms of the institutional dimension. This is caused by the need for legal frameworks (Espinoza *et al.* 2019) or by the burdensome administrative requirements in place at present (Do *et al.* 2020). For example, in China, the Government's supportive policies led to overproduction and the curtailment of solar power capacity in some regions (Corwin and Johnson 2019). The lower score for simplicity in the Asian region also reflects the lack of standardized technology, technical experts and limited capacity to produce the specialized equipment needed for complex solar photovoltaic technologies, such as building-integrated solar PV (Shukla *et al.* 2018). (As explained in Chapter 2, the less complex and smaller and more modular the RE technology the more likely these are adopted).

Wind energy

Onshore and offshore wind energy generation both show medium to high feasibility for all dimensions. As such, these types of production were combined for the purposes of this FA, in spite of certain unique characteristics. While most indicators are consistent with AR6, wind energy has become increasingly competitive in terms of cost and the technology is now globally mature (Sergiienko *et al.* 2022). The levelized cost of energy for wind power has dropped thanks to improvements in turbine technology, economies of scale and better grid integration (International Renewable Energy Agency [IRENA] 2024). However, discrepancies still exist in terms of financing for offshore wind power, where the cost of capital (CoC) is substantially higher due to the complexities involved in construction (for more details, see Chapter 4). For onshore and offshore wind power, further technological innovations are required for scalable deployment to meet future energy demands and grid stability requirements for balancing variable renewable energy (Bianchini *et al.* 2022; Veers *et al.* 2022; Desalegn *et al.* 2023).

Public support for wind energy varies and has been subject to misinformation (Winter *et al.* 2022). For onshore wind power, local projects can evoke resistance because of the visual and noise impact, in addition to land use (Sander, Jung and Schindler 2024). However, job creation and community involvement in the planning process can increase local acceptance (Ruddat 2022; Takeuchi 2023). At the institutional level, wind energy is supported through engagement with local stakeholders, the equitable distribution of benefits (Weber 2023; Zhang *et al.* 2024) and an enhanced legal and regulatory framework (Herrera Anchustegui and Radovich 2022; Nieuwenhout 2023). Wind energy provides environmental benefits over conventional fossilfuelled power plants, especially in reducing GHGw emissions, air pollutants and water consumption (Chen and Su 2022; Rashidi *et al.* 2022; Sander, Jung and Schindler 2024; Saravanan *et al.* 2022). However, the effects of wind energy on local biodiversity must be addressed through better planning (Galparsoro *et al.* 2022).

Hydroelectric power

Feasibility for hydroelectric power is provided for the following categories: 1) Conventional power generation at large reservoirs and 2) generation at existing infrastructures with runofriver (ROR) operations or smaller storage that is constrained by other purposes (e.g. flood control, water supply). Major distinctions between these categories are evident in the relatively lower number of unexploited sites, lower levels of public acceptance and greater distributional impacts for new facilities with large reservoirs.

Technological feasibility for hydroelectric power in both categories remains high, with greater efficiencies than other renewables, mature technical solutions and numerous opportunities to leverage existing water and civil infrastructure. Drought and extreme rainfall due to climate change leads to a revised feasibility in geophysical resources for large storage or ROR hydroelectricity. Medium institutional feasibility remains consistent for both categories and aligns with the AR6 study, with hydroelectricity frequently not being included in many countries' net-zero goals and incentives for renewable energies often being heavily constrained (e.g. only applying to certain scales). Environmental-ecological feasibility for these facilities is lower than in the AR6 study, reflecting an increasing recognition of greenhouse emissions (especially methane) from reservoirs in tropical regions.

Box 3.2: Public acceptance of hydroelectric power (dams)

Public opposition to large hydropower developments stems from the displacement of Indigenous and historical communities, in addition to the degradation of environmental and ecological quality (Venus, Hinzmann and Gerdes 2022). Eutrophication, altered aquatic habitats and fragmented waterways are central to concerns about preserving the recreational and cultural use of rivers. The Ribeirão Dam on the border of Bolivia and Brazil exemplifies the low levels of public acceptance surrounding large reservoir hydropower, with public protests and a coalition of dozens of civil society organizations signing a public letter to the presidents of both countries to voice their opposition to the project in 2023. Feasibility in other regions with transboundary water systems is hindered by limited institutional capacities to handle complex international land and resource disputes, or to implement consistent protocols for assessing and ensuring sustainability in the design and operation of hydropower facilities (Mandai *et al.* 2024; Roquetti *et al.* 2024).

Geothermal energy

Geothermal energy has a medium feasibility score overall. Consistent with the AR6 assessment from the IPCC, the technological feasibility of geothermal energy remains high, driven by the simplicity, scalability and maturity of the technology. Unlike intermittent renewable sources, geothermal energy's ability to provide baseload generation presents economic opportunities not afforded to wind and solar power. Medium economic feasibility is reported thanks to the overall competitive costs of generation, despite high capital costs and long payback periods. The score for geophysical feasibility is medium, characterized by an abundant physical resource (i.e. heat) at large sites.

The environmental-ecological domain has a medium feasibility, representing an increase from the low feasibility level reported in the AR6 report. This is due to the reduced negative impact on water quantity and quality due to re-injection techniques and the use of closed-loop systems (United States Department of Energy 2019; Soltani *et al.* 2021; Sharmin *et al.* 2023). A medium sociocultural feasibility is reported due to mixed (although mostly positive) social acceptability levels. Geothermal energy also offers other advantages, such as increased energy access and security (Pellizzone *et al.* 2015; Shortall, Davidsdottir and Axelsson 2015; Hazboun and Boudet 2020; Soltani *et al.* 2021; Greiner, Klagge and Owino 2023; Krasnodębski 2023; Renoth *et al.* 2023; Idroes *et al.* 2024). Finally, the institutional feasibility is revised from a high to a medium level, mainly due to studies documenting the presence of institutional barriers that are limiting the wider adoption of the technology (Soltani *et al.* 2021; IRENA and International Geothermal Association 2023; Krasnodębski 2023; United States Department of Energy 2024).

Energy storage

Energy storage plays a critical role in temporally shifting electricity from when it is produced to when it is needed, thus supporting the variable generation arising from wind and solar power. To feasibly serve the electricity demanded by society and the economy, energy storage is needed on both a short-term basis (such as storing energy produced at solar noon until the evening when demand peaks) and on a longer-term basis (beyond intra-day storage up to and including seasonal storage) for many other renewable energy technologies.

Energy storage is a broad subject and encompasses many technologies and approaches. However, in this FA, we are evaluating those that are used most widely at present, which are electrochemical battery energy storage (BES) and pumped storage hydropower (PSH). Electrochemical energy storage can also include hydrogen fuel cells. However, as their use is still limited to specialized scenarios and as large-scale systems of hydrogen distribution are not yet in place, they were not considered in this assessment. Compressed air energy storage, while promising, is very geographically limited. Geological constraints make feasibility low in most places. As a result, it was not assessed.

As of 2021, PSH accounted for approximately 90 per cent of total global electricity storage (IEA 2023a). From a global perspective, PSH has a medium feasibility overall. However, its technological feasibility is high, as it is a relatively simple, scalable and mature technology which is deployed widely across different parts of the world. From an economic perspective, PSH has medium feasibility due to high up-front costs. However, it boasts positive effects in terms of employment and economic growth. PSH has a medium geophysical feasibility, although resources are largely limited to areas with a moderate to high relief (elevation change) and require large amounts of land. Environmental-ecological feasibility is also medium, as using concrete for reservoirs could negatively affect air quality and the water systems can be prone to periodic eutrophication (Ali 2023; Altea and Yanagihara 2024). Likewise, sociocultural feasibility is medium as well, as public acceptance can hinder project development. Institutionally, PSH is generally accepted from a political perspective and comes up against few hurdles in terms of coordination. However, it does face legal and administrative challenges, owing to regulatory requirements that can stifle project development.

BES is growing rapidly in both grid-connected and stand-alone energy systems thanks to the critical role it plays in balancing intermittent renewable resources. BES is still advancing technologically, largely because of the electric vehicle industry, and such advances continue to bring the cost of BES down (Farghali *et al.* 2023; Zhao *et al.* 2023; Chatzigeorgiou *et al.* 2024). At present, BES is often considered to be economically feasible or is expected to become so in the near future. However, competition for resources and manufacturing capacity between stationary and automotive battery applications may slow largescale deployment on the grid. Institutional and legal frameworks and market mechanisms are evolving to be able to accommodate energy storage, but these are currently insufficient in most locations to fully integrate largescale energy storage. As such, BES has the potential to improve resiliency and energy equity, but this is not an automatic outcome of using distributed energy storage and must be addressed deliberately.

Furthermore, the environmental impact of batteries depends heavily on their composition and where they are manufactured and recycled. For example, the extraction of lithium is noted as a particular concern to the environment and to those working in mining. Misgivings also surround lead, another common battery material, as improper disposal can lead to soil and water contamination. As such, the environmental and working conditions experienced during battery manufacture very much depend upon the location of the factory: Nations with stricter regulations for both environmental and workforce protection have safer manufacturing processes, but often have a lower manufacturing capacity.

Demand mitigation

The FA shows that demand mitigation has high feasibility for buildings and public transport. They are both cost-effective and offer many co-benefits, ranging from job creation to the reduction of energy poverty and improved indoor comfort.

In the FA, demand mitigation focuses on energy use in buildings. This is because current building stock is dominated by buildings built before 2010, and their poor energy performance offers an untapped potential for energy savings. The retrofitting of existing buildings is assessed to have high feasibility thanks to the positive impact on the environment, local job creation, increased indoor comfort and improved air quality. Retrofitting also has strong synergies with adaptation, by reducing the impact of heatwaves, for example.

Another advantage to retrofitting existing buildings is the potential reduction in pressures surrounding land use, by preventing the need for new construction. Looking beyond the associated reductions in energy use and GHG emissions, other pollutants (such as NOx) and fine particulate matter ($PM_{2.5}$) are reduced thanks to the need for local energy generation being avoided. Although the FA shows that political support does exist for energy renovations, there is a lack of governance, as well as institutional and administrative capacity, at the local level in terms of capacity-building, regulation or code enforcement, and financing (Bertoldi 2022).

Box 3.3: Finance for the renovation of existing buildings

Energy-demand mitigation in the renovation of existing buildings has high technological feasibility (Van Nguyen *et al.* 2024). However, the complexity of renovating existing buildings to improve their energy efficiency poses some considerable challenges, including a low level of awareness among end users in terms of energy savings and other co-benefits, a reluctance to face the hassles of renovations, and a lack of availability and access to financing (Ma *et al.* 2022; Weerasinghe *et al.* 2024). In this respect, one-stop shops for assisting endusers during the whole renovation process have been proven to be effective (Bertoldi 2022).

When launching low-energy renovation programmes, local and national policymakers should also consider that the rental cost or purchase price will increase as a result of the investment costs associated with the energy renovation. This can cause low-income populations to move out of buildings, resulting in gentrification in the city (Sundling and Szentes 2021). Well-designed renovation programmes need to avoid possible gentrification by establishing appropriate rent increases, for example. Another key barrier that hinders a large-scale deployment of building renovation is the financing required to overcome the initial investments (Albrecht and Hamels 2021). Given that low-income families often lack the capital for the initial investments required, long-term financing mechanisms, such as green mortgages, targeted grants and low interest loans, can address some of these issues (Bertoldi 2020). However, it should also be noted that different ownership models (i.e. whether someone is the owner of an individual house or co-owns a building with other tenants) present varying complexities when implementing greater energyefficiency measures (Sundling and Szentes 2021; Triantafyllopoulos 2024).

While the FA concentrated mainly on the energy renovation of existing buildings, it also considered technologies for the construction of new buildings, in particular net-zero energy buildings. Residual building energy demand should be minimized (Bertoldi 2022) if the global energy supply in 2050 is to be fully decarbonized.

Public transport is a key mitigation option in demand-side focused technologies and has a high feasibility score. This high feasibility is due to improvements in environmental attributes (such as improving air quality) and the potential for enhanced mobility, with less congestion and more road space for citizens (Anciaes and Alhassan 2024). However, transportation infrastructure in the Global South differs significantly from the Global North. While in the Global North, cars, trains and buses are the subject of electrification, tuk-tuks, boda-bodas, minibuses and twowheelers are more common in the Global South. This brings into focus the different technological and economic challenges in these contexts in shifting from the status quo. In this respect, shifts towards electric mobility are accompanied by equity concerns, with the success of new transportation systems hinging on addressing longstanding issues, such as car dependency, social equity and safety (Siddiqui *et al.* 2024; Vecchio *et al.* 2024). As such, public transport is not widely evaluated as an adaptation. However, it does present substantial cobenefits for adaptation, as identified in the mitigation FA and other linkages to sustainable development, in particular SDGs 3, 11 and 13. In brief, sustainable public transport can improve livelihoods, adaptive capacities and equity (Sharifi 2021).

However, insufficient funding hinders progress. This is especially true in the Global South, despite the presence of climate financing and development assistance which supports transportation greening initiatives. Infrastructure projects are often delayed or scaled back due to capital shortages, while the rising costs of materials and labour add to the challenges of implementing largescale transportation upgrades. Cities, particularly in the Global South, are facing several barriers to raising finance for sustainable transport infrastructure investments, including: reduced financial autonomy (e.g. the capacity to collect taxes in cities, in addition to public debt limits); a lack of institutional and technical capacity to prepare investmentgraded projects, issue green bonds and establish public-private partnerships (PPPs); and low creditworthiness, which limits access to the international financial market (Camargo-Díaz *et al.* 2023). However, PPPs have been proven to be a viable solution for attracting private sector finance for sustainable publictransport infrastructure (Alnour, Awan and Hossain 2024). Value capture has been a source of financing for transport infrastructures in a few cities in the Global North, such as London, New York and Copenhagen (van Zoest and Daamen 2024). Under a value-capture scheme, cities recover part of the value generated for the private sector by the public investments through taxes or other mechanisms (Song *et al.* 2019).

Box 3.4: Public Transportation: Innovative practices and barriers to transforming transportation systems

The transportation sector is increasingly challenged by rapid environmental changes and economic shocks. Central to these efforts is the promotion of public, shared, and non-motorized transport. This is supported by combining land use and urban planning with public transport, in particular the Transit-Oriented Development (TOD) concept (Nigro *et al.*, 2019), which emphasizes high-density, mixed-use areas near public transport hubs (L. Wang & Xia, 2024), has shown promising results in reducing greenhouse gas emissions by promoting the use of public transport and at the same time walking and cycling within the hubs. Residents in TOD areas tend to drive less, contributing to lower emissions (Monteiro *et al.*, 2024; Nahlik & Chester, 2014). The TOD concept also highlights the high institutional feasibility, especially in settings where there is already integrated governance across urban planning, mobility and climate/energy (Quintero-González, 2019).

As urban planners strive to meet climate targets, significant attention is being paid to transforming transportation systems (Naimoli & Wilcox, 2023). Public transportation infrastructure remains a challenge for many cities (Sundqvist & Tuominen, 2024). This has led to an increased focus on understanding the social, political, and institutional barriers to decarbonizing infrastructure (Eisenberg *et al.*, 2024; Goedeking, 2024) and a larger emphasis on environmental justice and mitigating social vulnerabilities in transportation sector planning. To achieve these goals, new modelling technologies and frameworks have emerged, allowing urban planners to explore multiple scenarios for decarbonizing the transport sector, while factoring in geophysical, environmental, technological, economic, socio-cultural, and institutional challenges (Bills, 2024; Ortúzar & Willumsen, 2011). However fragmented governance and lack of coordination among different level of institutions may result in unsustainable solution such as expansion of roads and airports (Kigochi, 2024).

Table 3.2 Feasibility results

Part A: Adaptation (adapted from WG2)

FA results for Adaptation

Feasibility Dimensions	Technology	Resilient power system	Energy reliability	Water use efficiency	Smart grid digitalization
	Overall feasibility across dimensions	High	High	High	LE
Geophysical	Physical feasibility/potential	N/A	N/A	Medium	N/A
	Hazard risk reduction potential	N/A	N/A	High	N/A
	Land use	High	N/A	High	N/A
Environmental-ecological	Ecological impacts	Medium	NE	High	LE
	Adaptive capacity / resilience	High	High	High	LE
Technological	Technical potential	High	High	High	High
	Risks mitigation potential	High	High	High	Medium
Economic	Socioeconomic vulnerability reduction potential	High	High	High	NE
	Employment, economic growth and productivity enhacement potential	Medium	Medium	NE	LE
	Microeconomic viability	High	High	High	LE
	Macroeconomic viability	High	Medium	High	NE
Socio-cultural	Socio-cultural / Public acceptability	High	High	LE	LE
	Social co-benefits	High	High	LE	LE
	Social and regional inclusiveness	High	High	NE	LE
	Gender equity	Medium	LE	NE	NE
	Intergenerational equity	Medium	LE	NE	NE
Institutional	Political acceptance	High	High	Medium	NE
	Legal and regulatory acceptability	Medium	Medium	LE	LE
	Institutional capacity and administrative feasibility	Medium	Medium	Medium	LE
	Transparency and accountability potential	Medium	NE	NE	NE

Assessed feasibility levels: Low, Medium, High

N/A = Not applicable

LE = Low evidence

NE = No evidence

Part B: Mitigation

FA results for Mitigation

Feasibility Dimensions	Technology	Solar energy	Wind energy (off/on shore)	Hydro-electric: Large dams	Hydro-electric: Run of river	Geothermal	Energy storage: PSH	Energy storage: BES	Demand Mitigation: Buildings	Demand Mitigation: Public transport
	Overall feasibility across dimensions	High	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Geophysical	Physical feasibility/potential	High	High	Medium	Medium	Medium	High	High	High	High
	Geophysical resources	High	High	Medium	High	High	Medium	Medium	N/A	High
	Land use	Medium	High	Low	Medium	Medium	Medium	LE	High	High
Environmental-ecological	Air Polution	High	High	Medium	High	Medium	Medium	Medium	High	High
	Toxic waste, Ecotoxicity eutrophication	Medium	Medium	Low	Medium	Medium	Medium	Medium	N/A	LE
	Water quantity and quality	High	High	Low	Low	Medium	Medium	Medium	N/A	LE
	Biodiversity	High	Medium	Low	Low	Low	Medium	LE	Medium	High
Technological	Simplicity	Medium	High	High	High	High	Medium	High	Low	Medium
	Technological scalability	High	Medium	High	High	High	High	High	Medium	Medium
	Maturity and technology readiness	High	Medium	High	High	High	High	Medium	High	High
Economic	Costs in 2030 and long term	High	High	Medium	Medium	Medium	Low	High	High	High
	Employment effects and economic growth	High	High	High	Medium	Medium	High	High	High	Medium
Socio-cultural	Public acceptance	Medium	Medium	Low	Medium	Medium	Low	High	Medium	Medium
	Effects on health and well-being	High	Medium	Medium	Medium	LE	Medium	High	High	High
	Distributional effects	High	Medium	Low	NE	Medium	Medium	Medium	Low	High
Institutional	Political acceptance	Medium	Medium	LE	High	High	Medium	Medium	Low	Medium
	Institutional capacity, governance, cross-sectorial coordination	Medium	Medium	Medium	Medium	Medium	Medium	Low	Medium	High
	Legal and administrative capacity	Medium	Low	LE	Medium	Medium	Low	Medium	Medium	Medium

Assessed feasibility levels: Low, Medium, High

N/A = Not applicable

LE = Low evidence

NE = No evidence

Part C: Solar energy (regional results)

Regional FA results for Solar PV

Feasibility Dimensions	Region	GLOBAL	ASIA	CENTRAL/ SOUTH AMERICA
	Overall feasibility across dimensions	High	Medium	Medium
Geophysical	Physical feasibility/potential	High	High	High
	Geophysical resources	High	High	Medium
	Land use	Medium	Medium	Medium
Environmental -ecological	Air Polution	High	High	LE
	Toxic waste, Ecotoxicity eutrophication	Medium	Medium	N/A
	Water quantity and quality	High	High	N/A
	Biodiversity	High	Medium	N/A
Technological	Simplicity	High	Medium	LE
	Technological scalability	High	High	Medium
	Maturity and technology readiness	High	High	LE
Economic	Costs in 2030 and long term	High	High	Low
	Employment effects and economic growth	High	Medium	High
Socio-cultural	Public acceptance	Medium	High	High
	Effects on health and well-being	High	High	High
	Distributional effects	High	Medium	High
Institutional	Political acceptance	Medium	Medium	Low
	Institutional capacity, governance, cross-sectorial coordination	Medium	Medium	Low
	Legal and administrative capacity	Medium	Low	Low

Assessed feasibility levels: Low, Medium, High

N/A = Not applicable

LE = Low evidence

NE = No evidence

Part D: Hydroelectric energy

Regional FA results for Hydroelectric power (Large dams)

Feasibility Dimensions	Region	GLOBAL	AFRICA	ASIA	AUSTRALIA	CENTRAL/ SOUTH AMERICA	EUROPE	NORTH AMERICA	SMALL ISLANDS
	Overall feasibility across dimensions	Medium	-	-	-	-	-	-	-
Geophysical	Physical feasibility/potential	Medium	High	High	High	High	Low	Low	NE
	Geophysical resources	Medium	Medium	Medium	Medium	Medium	Medium	Medium	NE
	Land use	Low	Low	Low	LE	Low	Low	Low	NE
Environmental -ecological	Air Polution	Medium	Medium	Medium	NE	Medium	Medium	Medium	NE
	Toxic waste, Ecotoxicity eutrophication	Low	NE	NE	NE	NE	LE	LE	NE
	Water quantity and quality	Low	Low	NE	NE	NE	NE	Low	NE
	Biodiversity	Low	LE	LE	NE	LE	LE	LE	NE
Technological	Simplicity	High	NE	NE	NE	NE	NE	NE	NE
	Technological scalability	High	NE	NE	NE	NE	NE	NE	NE
	Maturity and technology readiness	High	NE	NE	NE	NE	NE	NE	NE
Economic	Costs in 2030 and long term	Medium	NE	NE	NE	NE	NE	NE	NE
	Employment effects and economic growth	High	LE	LE	NE	LE	LE	LE	NE
Socio-cultural	Public acceptance	Low	LE	LE	NE	Low	Low	Low	NE
	Effects on health and well-being	Medium	LE	NE	NE	NE	NE	NE	NE
	Distributional effects	Low	Low	Low	NE	LE	NE	NE	NE
Institutional	Political acceptance	LE	NE	LE	NE	NE	NE	Medium	NE
	Institutional capacity, governance, cross-sectorial coordination	Medium	LE	LE	NE	NE	NE	Medium	NE
	Legal and administrative capacity	LE	LE	LE	NE	NE	NE	Medium	NE

Assessed feasibility levels: Low, Medium, High

N/A = Not applicable

LE = Low evidence

NE = No evidence

3.4 SYNERGIES AND TRADE-OFFS OF TECHNOLOGY PORTFOLIOS EVALUATED THROUGH A SYSTEMS TRANSITION FRAMEWORK

The systems framework is consistent with the understanding that there is no "one-size-fits-all" technological solution or transition. For example, any given technology may differ in the feasibility and effectiveness of relevant features, such as access, coverage and infrastructure conditions, such as whether a community is isolated and off-grid, isolated with distributed generation through community systems, hybrid or fully connected to the grid. Taking a systembased approach allows for a more holistic review of a portfolio of options which can support the transition.

This framework also makes it easier to evaluate an energy system transition in relation to other system transitions. The systemstransition framework can be used to evaluate how to maximize synergies, while identifying and minimizing trade-offs between energy system technologies and other systems, with respect to how energy transitions link to other system transitions. In this way, this approach puts energysystem transitions at the centre of the transformations that underpin the climate-resilient development pathways to achieve the Paris Agreement goal of limiting the increase in global temperatures to 1.5°C above pre-industrial levels, and comply with the 2030 Agenda for Sustainable Development, as a condition for resilience. For example, this includes the capacity to evaluate the interlinkages between biomass, agriculture and water, the use of stand-alone systems in system transitions, and the electricity used for data and earlywarning systems to improve health in both urban and rural settings.

Annex 1 offers a more detailed analysis of the main synergies and trade-offs between mitigation, adaptation and sustainable development for each technology, highlighting also that a mix of technologies is needed to achieve the various climate goals and SDGs. Furthermore, it shows how the different technologies complement each other.

Resilient power infrastructure and reliable power systems show positive effects on several SDGs when they are well adapted to the specific local context (Annex 1). These types of technologies align with a trend towards smart cities and have the potential to reduce inequality and poverty by reaching informal and marginalized settlements. However, whether such systems are used is conditioned by a government's capacity to ensure a fair distribution of technological resources, as well as its ability to regulate and finance the implementation and maintenance of such technology.

Water use efficiency mainly benefits SDG 6 (clean water and sanitation) but also has cobenefits with other SDGs that depend on water. A more efficient use of water for the cooling of plants which generate electricity can pave the way for improved watershed management and other uses, which also augments the resilience of ecosystems. This option also enables plants to reduce their costs.

Smart grids and digitalization technologies play a relevant role in adaptation as their potential self-healing capabilities can enhance grid reliability against a backdrop of climate change (Nyangon 2024). However, the digitalization of the grid could enable an increase in energy consumption (Babazadeh *et al.* 2022), posing potential challenges for mitigation efforts without the adequate integration of renewable energy. Integrating renewable energies with a smart grid may be enhanced through the application of emerging technologies, such as AI, to improve forecasting for intermittent renewable energy sources (Meenal *et al.* 2022). However, reducing the environmental impact of these technologies by using smart grids may conflict with minimizing short-term financial costs (Judge *et al.* 2022; Durillon and Bossu 2024) and will require robust regulations which account for the longterm economic implications of climate change (See Chapter 5 on innovation and governance on digital technologies). There may also be a tradeoff between computational cost and prediction accuracy, adding another layer of complexity to decisions surrounding smart grid implementation (Kaur *et al.* 2022).

For mitigation technology groupings, solar and wind energy represent the cheapest and cleanest sources of energy in synergy with SDG 7 and SDG 13. Compared with other forms of energy generation, these technologies remain less polluting, despite the possibility of negative impacts on local economic activities and the environment (see Annex 1), mainly due to the need to dedicate large areas to energy production, meaning that attention needs to be paid to how locations are selected for energy production structures. Combining solar and wind (onshore and offshore) power generation can improve efficiency on a large scale, as well as reduce variability, making those technologies seem quite promising to the system transition (López Prol *et al.* 2024). Hybridization with conventional and PSH may also improve reliability (Roy *et al.* 2022).

While geothermal power is fairly efficient when compared with the other technologies available, it shows complex linkages with the SDGs that hinge on many conditions. Although this form of energy can increase sustainable management and the efficient use of natural resources, with synergies to SDG 12, there is a risk of pollution of water sources that needs to be controlled continuously, as does the high volume of water required for cooling (Gonzales-Zuñiga *et al.* 2018), although this can be recycled in a closed cycle. Other challenges that need to be overcome for the implementation of geothermal energy include the initial cost of implementation, the availability of reservoirs (which is limited) and other risks, such as rising temperatures in the surrounding area.

Hydroelectric power contributes to the achievement of SDG 7 and SDG 13. However, some sociocultural and environmental trade offs with other SDGs (Annex 1) are related to the implementation of huge hydroelectric power generation structures that require the flooding of large areas, transforming local ecological and cultural dynamics which affect local, traditional and Indigenous communities directly.

Energy storage technologies can be a decisive factor for resilience in climate change, considering changes in the availability and stability of local natural resources, but also during emergency situations, presenting positive effects not only for mitigation but also for adaptation. Both of the technologies evaluated (PSH and BES) have certain negative impacts on the environment which are still relevant. PSH can have a negative effect on the site where the storage structure is located, while BES can contaminate the site when disposed of after use.

Demand mitigation in buildings has benefits for the sustainability of the urban and social environment, both in relation to retrofitting strategies and new constructions. The adoption of strategies that ensure that all new constructions meet energy efficiency criteria are key. This requires updating urban and building regulations and codes to include adaptive parameters, control and monitoring mechanisms, and tax-incentive measures to prevent the cost and responsibility of reducing energy consumption from falling primarily to the individual (Bertoldi 2022; Di Foggia 2018). Further benefits are achieved by adapting urban form, paying particular attention to stopping the reproduction of an unsustainable and vulnerable urbanization pattern which, among many other characteristics, produces a fragmented and sprawling territory. This is also critical to unlocking the benefits of the transport sector for urban resilience and sustainability. When applied in an articulated and intersectoral manner, proper land use, density and transport planning can contribute to adaptation and mitigation, and can also play a fundamental role not only in reducing emissions, but especially in territorial and climate justice, improving mobility and access to the city and its services, even in disaster situations. In terms of mitigation, a common strategy in the transport sector focuses on replacing the vehicle fleet with electric vehicles, which may present trade-offs with equity and the environment.

3.5 ENABLING CONDITIONS

The FA can inform the selection of technologies to be implemented and data gaps to be addressed. The effectiveness of technologies also depends on a series of enabling conditions to achieve their potential. Here, we discuss governance, financing and institutions as key enablers. We also highlight innovation, specifically the potential for AI and machine learning (ML), across these enablers.

Governance provides a useful lens through which to understand how decision-making processes and distributions of power can affect the implementation and outcomes of renewable energy technologies. Specifically, for energy transitions, governance structures can determine not only the speed of implementation, but also whether the benefits and costs are equitably distributed (Goldthau 2014). The importance of establishing an appropriate governance structure can be explored by considering off-grid and on-grid distributed generation systems. For off-grid systems, communitylevel governance structures, including associations, committees and cooperatives, is critical to their success. Defining the roles and responsibilities of each member, as well as their rights, helps to balance the power dynamics within these structures. This can be especially critical for ensuring more evenly distributed benefits between men and women (Johnson, Gerber and Muhoza 2019), as well as for ensuring that marginalized groups and Indigenous Peoples have an equal voice in decisionmaking processes. This can be contrasted with renewable energy communities for gridconnected systems, such as renewable energy communities in Europe. In a similar way to our stand-alone system, governance needs to be linked to community decisionmaking and empowerment (Van Veelen 2018). In addition, multilevel governance is also crucial, as islegislation to allow and provide guidance for these governance structures, such as the 2019 European Clean Energy Package (Lowitzsch, Hoicka and van Tulder 2020).

The capacity of institutions to support these transitions with supportive legislation and policies is especially important. Institutions, whether national governments or local regulatory bodies, play a crucial role in establishing clear regulatory frameworks. For example, permission processes can be time-consuming, expensive and complex, causing considerable delay to projects (Eleftheriadis and Anagnostopoulou 2015). Other gaps in the regulatory framework can also hinder the effectiveness of technologies, including safety and quality codes and standards, or energyefficiency standards. Weak regulatory environments can lead to the installation of substandard or unsafe equipment, reduced operational efficiency and higher longterm costs for energy systems. Similarly, the absence of energy efficiency standards can undermine the potential savings and environmental benefits of renewable technologies, particularly in energy storage, buildings and grid infrastructure (Seetharaman *et al.* 2019; Ukoba *et al.* 2024). In addition to regulatory frameworks, challenges exist for educational institutions in terms of skill formation and training to ensure labour capacity, along with issues for managing cycles in workforce demand

Finance and investment for the renewable energy sector has been one of the more positive aspects of the energy transition, with costs falling rapidly (IRENA and Climate Policy Initiative 2023). In regions with high solar irradiation and strong, complementary policies supporting climate mitigation and renewable energy implementation, these technologies are now cost-competitive with traditional energy sources (See more on Chapter 4). However, in many developing countries, financial barriers persist, including perceptions of risk and challenges for access to capital, in addition to gaps and mismatches in financial flows (Kreibiehl and Yong Jung 2023). Addressing barriers to finance and investment in these countries is critical to achieving the potential for these technologies to contribute to climate mitigation. For more details about the state and trends surrounding renewable energy and how to improve the enabling environments for investment and finance, see Chapter on investment and finance.

Across these enablers is the critical role of innovation in creating the enabling conditions for progress in climate technology. For example, AI and ML have the potential to unlock new opportunities for renewable energy technologies. While physical infrastructure, governance structures, and access to and the availability of finance remain vital to expanding the capacity of renewable energy technology, these innovations can support the mapping of resources (e.g. rooftop solar mapping capacity expansion) and enhance energy access and efficiency. More information is available in Chapter 5 on innovation and governance.

3.6 CONCLUSIONS

The results of this FA show that some highly feasible renewable energy technologies exist for energy system transitions, as do options with significant synergies between mitigation, adaptation and sustainable development. However, regional results mostly indicate low or no evidence, pointing to significant knowledge gaps. Cobenefits with SDGs highlight that implementing these technologies can be consistent with expanding justice and equity by understanding and prioritizing the local context and the needs of the most vulnerable groups.

The system transitions approach helps to ensure that mitigation and adaptation are considered in tandem, and reduces the risk of maladaptation and inequality. For example, energy renovations for buildings offer an opportunity to combine mitigation with adaptation, thanks to the synergies being well aligned with several SDGs. Such renovations also offer the opportunity to install on-site renewables, particularly solar panels. This FA also highlights supportive technologies and the enablers needed for renewable energy expansion. To give an example, for renewable energies to be effective, national transmission, distribution and storage systems need to be accounted for. In many countries, grids are run at full capacity and do not allow for any additional generation, thus hindering available investment and planning for renewable energy projects, as well as efforts to provide incentives for investment and planning in transmission. As a result, expanding capacities and incorporating smart grids can increase the effectiveness of these technologies significantly.

Equity and justice are at the heart of a just energy transition, and together with a systemtransitions approach, lead us on a path towards climate-resilient development. The focus on scales and local contexts highlights the different facets of a just energy transition, ranging from decarbonization and increased renewable energy generation to electricity access. Likewise, the notion of a just transition also encompasses poor, marginalized and informal areas of the city, to avoid maladaptation (and thus reproducing inequalities) when technologies and structures for energy efficiency are introduced into the urban system. Considering poor, marginalized, vulnerable and informal communities when designing the implementation of these technologies helps to make the energy transition more inclusive, ensuring that no one is left behind.


Hydro project near Tosh, Himachal Pradesh ©Unsplash, Devansh Sharma

4.

Investment and finance

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KEY MESSAGES

- Renewable energy technologies, especially solar and wind technologies, have seen rapid cost reductions. China, OECD countries and some emerging markets lead in financial commitments and renewable energy investments.

- Despite technological maturity and ample potential, renewable energy investment remains very limited in many developing countries and is not growing in other emerging economies. It's essential to implement policies and regulations that support renewable energy investments. This includes removing fossil fuel subsidies, setting up effective carbon pricing, and adjusting market structures to facilitate the deployment of renewable energy.

- The persistently high cost of capital in many developing countries is an important investment barrier. Holistic policy mixes that address the energy sector, the financial sector and the economy more broadly are needed to reduce these costs.

- Investment support – including through derisking instruments – by multilateral development banks and climate finance institutions remains crucial for upscaling deployment of renewable energy technologies in most developing countries.

- The current investor landscape is dominated by large private investors, revealing opportunities for alternative ownership structures that can support communities in generating broad societal benefits and fostering just transitions.

4.1 INTRODUCTION

The renewable energy sector has attracted the most financing for climate technologies. With costs falling rapidly, this investment largely aligns with the first generation of NDCs and their strong focus on renewable energy technologies to meet mitigation goals (IRENA and IPC 2023). The falling costs of solar PV and wind turbines have rendered these technologies competitive in many contexts, particularly where physical resources are abundant (e.g. regions with high solar irradiation), where the negative climate externalities of fossil fuel-based power generation are being addressed (e.g. carbon taxes or in countries subject to or linked to the European Union emissions trading system), and where there are complementary policies to lower CoC and risks (Vartiainen *et al.* 2019). However, the investment gap compared to the potential for these technologies to contribute to climate mitigation remains substantial (Kreibiehl *et al.* 2022) – mainly in developing countries with sector-level financial barriers. Thus, this chapter focuses on evaluating finance and investments for key renewable energy technologies in the context of the COP 28 decision to triple current global renewable energy capacity by 2030 and within the context of just transitions by addressing the following questions:

1. What are the key metrics for tracking investment and finance for renewable energy technologies?
2. What are the state and trends of renewable energy technologies investment on these key metrics?
3. How do these metrics inform investments in renewable energy technologies to support just transitions?
4. What are key policy intervention points for reducing the CoC for renewable energy technologies and improving finance availability and equity?

Selected because of the overall maturity of the technologies and their importance to the energy transition, this chapter evaluates the progress on four key technologies that are critical for meeting GHG mitigation goals: solar PV plants, onshore wind turbines, offshore wind turbines and hydropower plants. These technologies will also have to deliver the majority of capacity additions to reach the target of tripling renewable energy capacity by 2030, as per the COP 28 decision. We focus on the metrics and data that provide insights into key important determinants for global deployment, including financial flows, the investor landscape and the CoC for renewable energy technologies. We also situate these metrics in discourses on just transitions and equity by discussing issues of risk and unfair penalties that may be embedded in these metrics, the benefits, trade-offs and governance between public and private sector investment, and the links to broader economic and sustainable development. We conclude by discussing how these metrics can inform policy interventions. This chapter paves the way for selecting indicators, metrics and approaches that can be used in subsequent CTPRs to track finance over a range of climate technologies and within the context of the Global Stocktake (GSTs).

4.2 THE RENEWABLE ENERGY TECHNOLOGY FINANCE LANDSCAPE

Climate technology finance encompasses the allocation of financial resources from local, national or transnational financing (from public, private and alternative sources) to development and deployment of technologies that are used primarily for climate change mitigation. To develop metrics, it is first necessary to evaluate the structure of the renewable energy technology finance landscape. Here, we discuss our selection of three key indicators: the investment volume in asset finance, CoC and the landscape of investor types. We also discuss how these measures vary by country and context .

4.2.1 Upstream and downstream investment capital

Two types of investment capital are employed for climate technologies: (1) financing the research and development (R&D) of new technologies, including during the R&D phase and during the pilot/demonstration phase (sometimes termed "upstream finance"), and (2) financing assets, i.e. the large-scale deployment of a technology once it is mature enough to be commercialized at scale (sometimes termed "downstream finance", or simply "asset finance").

For the more mature technologies that are the focus of this chapter, downstream finance is critical for ensuring deployment. Compared to fossil fuel-based power generation technologies, where a substantial share of the levelized cost of electricity is fuel cost, renewable energy technologies are very capital-intensive. Thus, the availability and CoC for plant investments, or asset finance, is vital for understanding deployment, and thus, the mitigation progress (Schmidt 2014; Schmidt *et al.* 2019; Steffen 2020; Ameli *et al.* 2021). Accordingly, the investment volume in asset finance is an important metric for momentum in renewable energy investments, and hence deployment.

Public R&D and pilot/demonstration finance are the main components of upstream finance for bringing early technologies to market. The major renewable energy technologies considered in this chapter (solar PV, onshore wind, offshore wind and hydropower) have reached high technology maturity. Thus, on a global scale, mobilizing upstream finance is less of a concern, and downstream finance is the appropriate focus. However, upstream financing is still necessary. As approximately 35 per cent of emission reductions by 2050 are expected to result from technologies under development (IEA 2023c), upstream financing should focus on a smaller number of less mature technologies, e.g. floating solar PV or closed-loop geothermal systems (Technology Executive Committee [TEC] 2021; IEA 2023b). Upstream finance is also needed when technologies that might be mature at the global level require substantial adaptation to local contexts due to technology-inherent characteristics (e.g. biomass plants relying on different local feedstocks, wind turbines requiring adaptation for specific wind classes) (Huenteler, Niebuhr and Schmidt 2016; Steffen *et al.* 2018).

4.2.2 Cost of capital, debt, and equity ratios and investor landscape

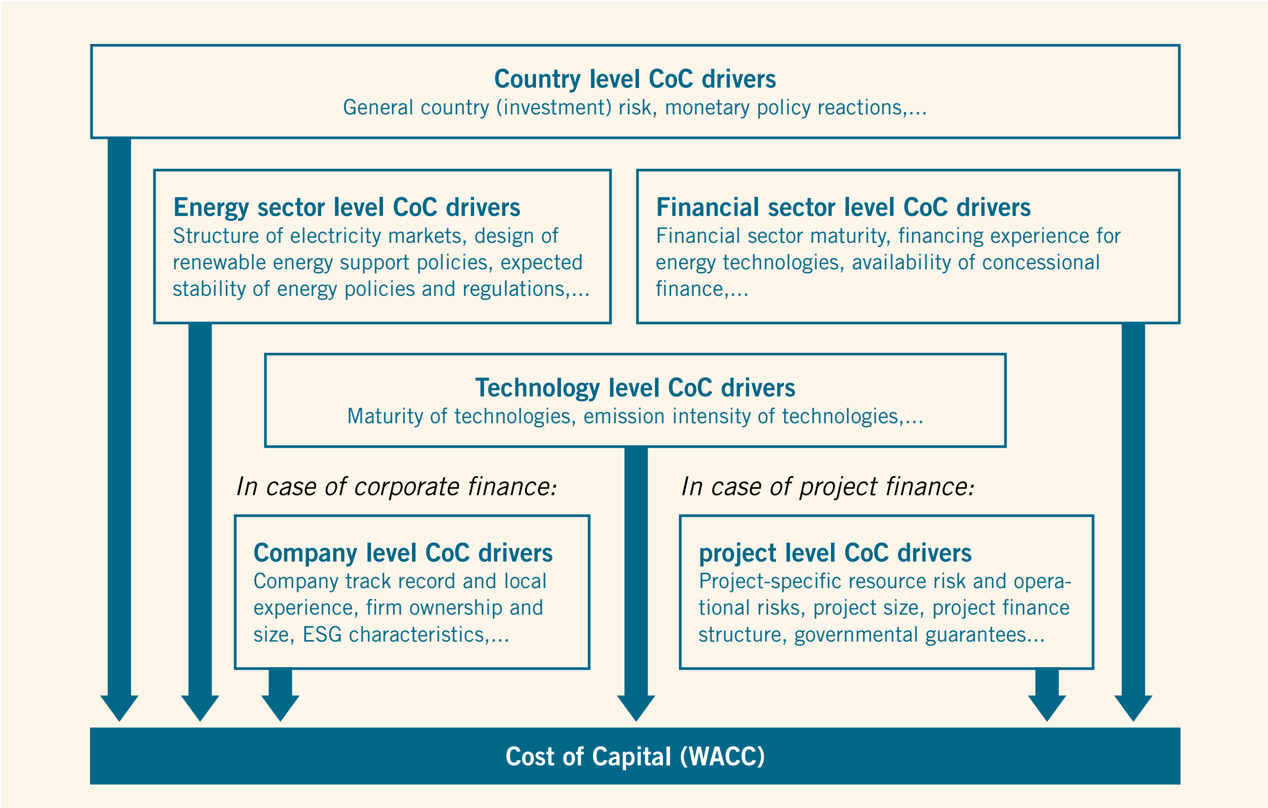
Another implication of the capital-intensity of renewables is that CoC matters, since they have a large impact on the life cycle cost of renewable energy technologies. These values can also show substantial variability due to the interest rates and perceptions of risks in different markets (Steffen and Waidelich 2022). The CoC is what capital providers demand for financing a project or company – that is, the interest rate charged for debt, the expected return on equity or the weighted average of both (weighted average cost of capital [WACC]) in case capital is sourced from both debt and equity financing (Lonergan *et al.* 2023). The CoC depends on the perceptions of investment risk, i.e. the likelihood of recouping the investment as planned.

While the investment volumes describe outcomes of renewable energy technology investment and financing decisions, the CoC represents the conditions in which financing is provided. This metric provides important information on the underlying investment risk structures, which can be a key bottleneck for scaling up investments in some regions. CoC affects not only the competitiveness of renewable energy relative to fossil fuel-based solutions, but also the overall cost of electricity. Particularly in developing and emerging economies, a high CoC affects the affordability of renewable energy-powered electricity.

Renewable energy technologies are financed in project finance structures, involving equity and debt (Steffen 2018). Accordingly, descriptors of the investor landscape can serve as a metric that captures the roles of different actors in providing capital for renewable energy assets, and a diverse landscape of investors can add to the resilience of investment flows (Polzin *et al.* 2021, Gumber, Egli and Steffen 2024). Currently, all mature renewable energy technologies are considered "bankable" by the market. This "bankability" is important for the economic viability of renewable energy technologies, as debt is generally provided at a lower cost than equity (Egli, Steffen and Schmidt 2018). The debt is typically provided by structured bank loans, with the participation of both state-owned and private banks (Waidelich and Steffen 2024). However, this may still be more challenging for countries with the financing track record and country risks too high to justify debt. Equity, in contrast, can be provided by a broader set of actors, including public or private utilities, dedicated renewable energy project developers or independent project developers, non-financial companies from sectors other than the energy sector that aim to secure electricity provision for their operations, financial companies such as institutional investors, or citizen-led structures such as cooperatives.

A large body of empirical research has evaluated determinants of CoC in the energy sector and identified drivers on different levels, with country-level conditions playing an important role (see Figure 3.1, based on Steffen and Waidelich [2022]). While some drivers at the country level (e.g. macroeconomic conditions) are not easy to change, many other drivers are a natural starting point for policy interventions trying to lower the CoC for renewable energy projects, as discussed in Section 4.3, especially since in many developing countries, these conditions can lead to prohibitively high CoC for renewables (Ameli *et al.* 2021). At the financial sector level, the general maturity of banks and other financial actors matters, as does the existence of national development banks that support renewables. At the energy sector level, it plays a role in how the electricity market structure and regulation make revenues predictable. Specific aspects of renewable energy include the design of auctions allocating power purchase agreements (PPAs), the standardization of PPAs themselves, and whether PPAs are denominated in a local or a hard currency. At the technology level, newer technologies are subject to higher risk, hence higher CoC. Countries with a track record of investment in renewable energy typically exhibit lower CoC (Egli, Steffen and Schmidt 2018; Rickman *et al.* 2023). Finally, at the company and project levels, many idiosyncratic factors play a role (see Steffen and Waidelich [2022] for a more detailed discussion).

Figure 4.1. Determinants of cost of capital in the energy sector



Source: Based on Steffen and Waidelich (2022)

4.3 FINANCIAL METRICS AND DATA FOR RENEWABLE ENERGY

In this section, we review the available data sources and how they inform the current state and trends along the key metrics for the solar PV plants, onshore wind turbines, offshore wind turbines and hydropower plants. We also evaluate how these metrics vary across technologies due to their unique characteristics and market dynamics that have implications for applicable investor types and, by extension, investment patterns more broadly. We discuss some important differences between technologies and regions, including patterns between Global North and Global South contexts. Many country-specific contextual conditions can also shed light on these relationships, which are often emphasized in the UNFCCC decisions; however, these are beyond the scope of this report. Finally, we situate these metrics within the context of just transitions, asking questions about the flows of funds and actors involved, how to connect renewable energy to broader economic development and the SDGs, and the potential for alternative investment and ownership structures.

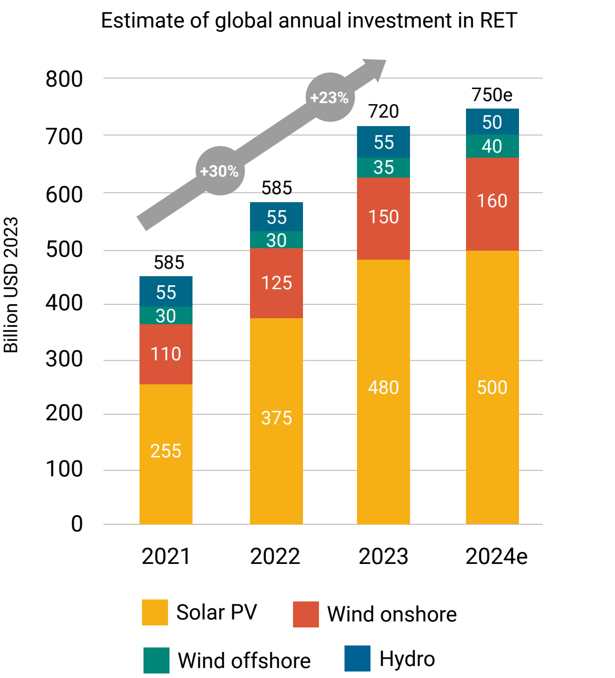
4.3.1 Investment volumes in asset finance

Accurately describing global renewable energy investment volumes is a complex task, given that equity and debt are provided from a multitude of different actors, and no central recording is available. Although some commercial data providers. such as BloombergNEF and IJGlobal, provide deal-level information on asset finance, their coverage is not exhaustive, and investment volumes are often unavailable (see, for example, the discussion in Mazzucato and Semieniuk [2018], Larosa, Rickman and Ameli [2022] and Waidelich and Steffen [2024]). Statistical data from official government offices, when available, typically lags behind by several years, with availability, granularity and format varying by country. Hence, to develop a data set that allows us to identify global patterns, we estimate volumes based on previous analyses from international organizations (IEA and IRENA) and assumptions to address gaps. The data presented here spans 2021–2024, as consistent data is unavailable for earlier years.

For these reasons, our estimates should not be taken as precise numbers, although they provide a clear picture of global trends and regional differences. According to our estimates, global investment in key renewable energy technologies has shown consistent growth, increasing from USD 450 billion in 2021 to an estimated USD 750 billion in 2024 (see Figure 4.2). This growth is primarily driven by decreasing technology costs and policy-driven deployment. While the growth in (inflation-adjusted) investment figures appears to be roughly linear, these volumes allowed a much steeper increase in capacity additions given the substantial capital cost reduction per megawatt installed, especially in solar PV (see Chapter 2) for an overview of capacity additions. Despite experiencing growth rates between 23 per cent and 30 per cent in recent years, the investment volume growth appears to have slowed latterly, with investments in 2024 projected to grow at a lower rate vis-à-vis 2023. However, global investment volume projections have been consistently underestimated in recent years and have often been corrected upwards.

At the regional level, the uneven nature of investment volumes becomes apparent. China, OECD countries and some emerging markets generally lead in financial commitments and deployment. In contrast, other developing countries face challenges related to economic stability, regulatory environments and access to capital. In 2023, investments in China (approximately USD 450 billion), Europe (approximately USD 105 billion), and the Americas (approximately USD 85 billion) collectively accounted for almost 90 per cent of the total global investment. The remaining investments were distributed among the rest of Asia (approximately USD 65 billion), Oceania (approximately USD 10 billion) and Africa (approximately USD 10 billion). Notably, the substantial increase in global investment has been primarily driven by China's strong growth, while investment levels in Europe and the Americas have increased slightly. China's investments have surged from approximately USD 200 billion in 2021 to approximately USD 440 billion in 2023, representing an increase of more than 100 per cent.

Figure 4.2. Estimates of global annual investments by renewable energy technology



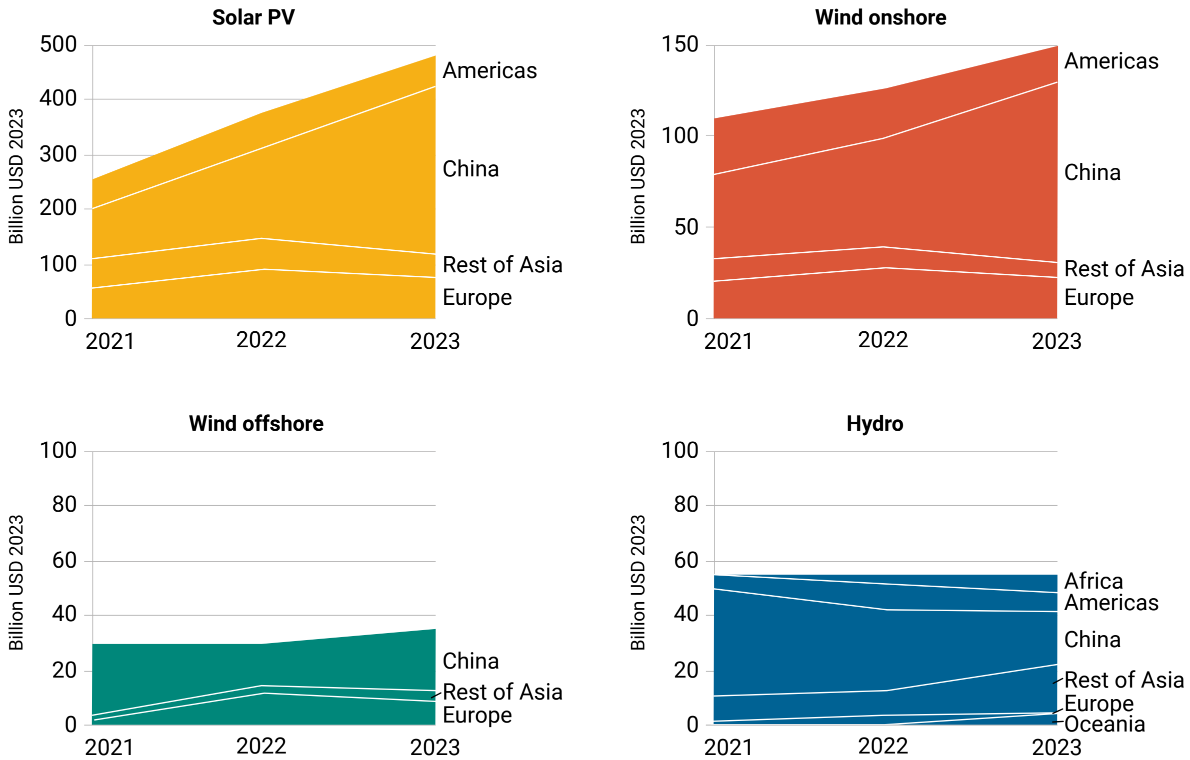
Note that 2024 are projections only. Estimates based on IEA (2024), World Energy Investment Report, for global investment, with split between onshore and offshore wind based on CPI & IRENA (2023), Global landscape of renewable energy finance 2023 report.

At the technology level, we also observe differences in investment levels by technology type (Figure 4.3). For solar PV, total investments have increased from an estimated USD 255 billion in 2021 to USD 480 billion in 2023. China dominates solar PV investments, accounting for more than 60 per cent in 2023 and driving strong growth. In comparison, investment levels in Europe (estimated at 16 per cent), the Americas (12 per cent) and the rest of Asia (8 per cent) have remained relatively stable. A similar pattern for solar PV is observed for onshore wind, with lower investment volumes and more modest overall growth, increasing from USD 110 billion in 2021 to USD 160 billion in 2023. China also leads in this sector, with more than 60 per cent of the investments in 2023, while Europe (approximately 15 per cent), the Americas (approximately 15 per cent), and the rest of Asia (approximately 5 per cent) have seen slight declines. For offshore wind, the investment landscape has been predominantly shaped by China (approximately 65 per cent in 2023) and Europe (approximately 25 per cent in 2023), maintaining a steady level in recent years. Finally, hydropower investments have remained relatively stable and more evenly distributed across regions. Although investment levels are declining in most regions, an increase has been observed in Asian countries other than China. Given the long lead times of hydrodams, however, the year-specific estimates for hydropower are likely less reliable than for the other technologies.

Economic and market conditions drive many of these differences. For example, in emerging markets, the focus may be on technologies that offer the quickest return on investment, such as solar power, which can be rapidly deployed (Polzin *et al.* 2015). However, government policies also influence these investment flows. A rise in investments for offshore wind is also expected (and likely not fully reflected in the 2022/2023 figures shown) in the Americas, as the United States of America has ambitious near-term offshore wind targets (United States Department of Energy 2023).

Within these broad technology classifications, we can also document important implications for just transitions. For example, a particular subsegment of solar PV investments is small-scale solar PV installations for off-grid electrification, such as in mini-grids, and stand-alone solutions such as solar home systems and solar-powered productive uses of energy (e.g. solar pumps). As of 2022, stand-alone systems contributed to twice the share of newly electrified households in sub-Saharan Africa compared to mini-grids (IEA 2023d), as the costs of stand-alone systems can be less expensive than the grid expansion (Egli *et al.* 2023). The off-grid sector is projected to connect close to two-thirds of sub-Saharan Africa's population by 2030, which accounts for approximately 83 per cent of the global unelectrified population (IEA *et al.* 2024). While small compared to grid-connected solar PV, this segment is crucial for cost-effective electrification, contributing to multiple SDGs in regions with large distances from existing grids or inaccessible landscapes [28]. However, despite these advantages, investments in solar PV-powered off-grid electrification remain relatively low. As of 2023, stand-alone systems had received approximately USD 3 billion in cumulative investments globally, with the highest ever recorded investment in 2023 amounting to approximately USD 750 million (GOGLA 2024; Lighting Global/Energy Sector Management Assistance Program, GOGLA, Efficiency for Access, Open Capital Advisors 2022). Cumulative investments in mini-grids have been higher, although estimates (approximately USD 30 billion in cumulative investment as of 2022 [Energy Sector Management Assistance Program 2022]) also include many diesel-powered mini-grids, especially before 2021. However, the degree of uncertainty in the data precludes showing annual trends such as those in Figure 4.3.

Figure 4.3. Estimates of region- and technology-specific annual investments in renewable energy technologies



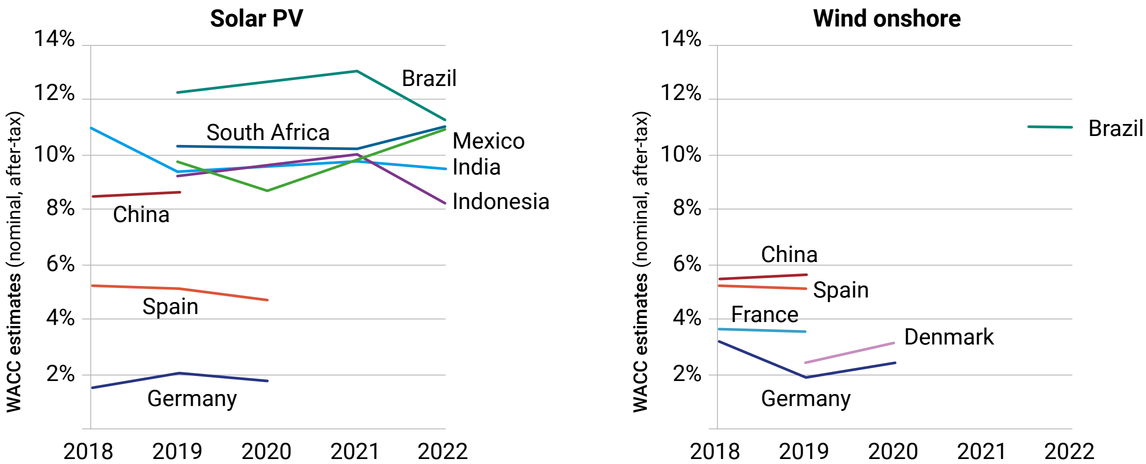
Note the different axes by technology. Estimates based on IEA (2024), World Energy Investment Report, for global investment, with split between onshore and offshore wind based on CPI & IRENA (2023), Global landscape of renewable energy finance 2023 report. Regional split is calculated based capacity additions provided by IENA (2024). Renewable Capacity Statistics 2024.

4.3.2 Cost of capital

Information on the CoC can be very difficult to obtain as it is private data, and often treated as proprietary information. Nevertheless, data availability has improved in recent years, driven by academic research (see the review by Steffen [2020]) and dedicated efforts by international organizations IEA and IRENA (IEA 2023a; IRENA 2023). Based on a forthcoming meta-analysis, Figure 4.4 shows the typical CoC for solar PV and onshore wind in major markets. We also observe a clear bifurcation of CoC estimates with OECD countries at 2–4 per cent and emerging economies at around 9–12 per cent. Political and economic contexts cause some heterogeneity between countries, with the electricity market structure and the price risk for renewable energy being important factors. Notably, data are scarce, particularly for the least developed countries (LDCs), though some studies estimate it in the same order of magnitude as in emerging economies (Steffen 2020). The persistently high CoC in developing countries is a key bottleneck to renewable energy deployment.

Comparing across technologies, we show that data availability for onshore wind is even more limited than for solar PV, with few solid studies on emerging economies. In industrialized countries, the CoC for onshore wind is now generally slightly above solar PV, reflecting the slightly higher resource risk and operational risks. This result differs from the pattern when solar PV was less mature, when it featured a higher CoC due to pertaining technology risks (Egli, Steffen and Schmidt 2018). While not shown in Figure 4.3 due to data limitations, offshore wind (which has mainly only been deployed in OECD countries and China so far), has a substantially higher CoC due to construction complexity and the very large "ticket sizes" for financing massive offshore farms (Dukan *et al.* 2023; Hansen *et al.* 2024). Overall, the persistent CoC difference between industrialized and developing countries stands out most starkly, which is both an indicator of financing challenges in the latter and a potential policy lever to address, as discussed below.

Figure 4.4. Weighted average cost of capital (in large economies by renewable energy technology)[5]



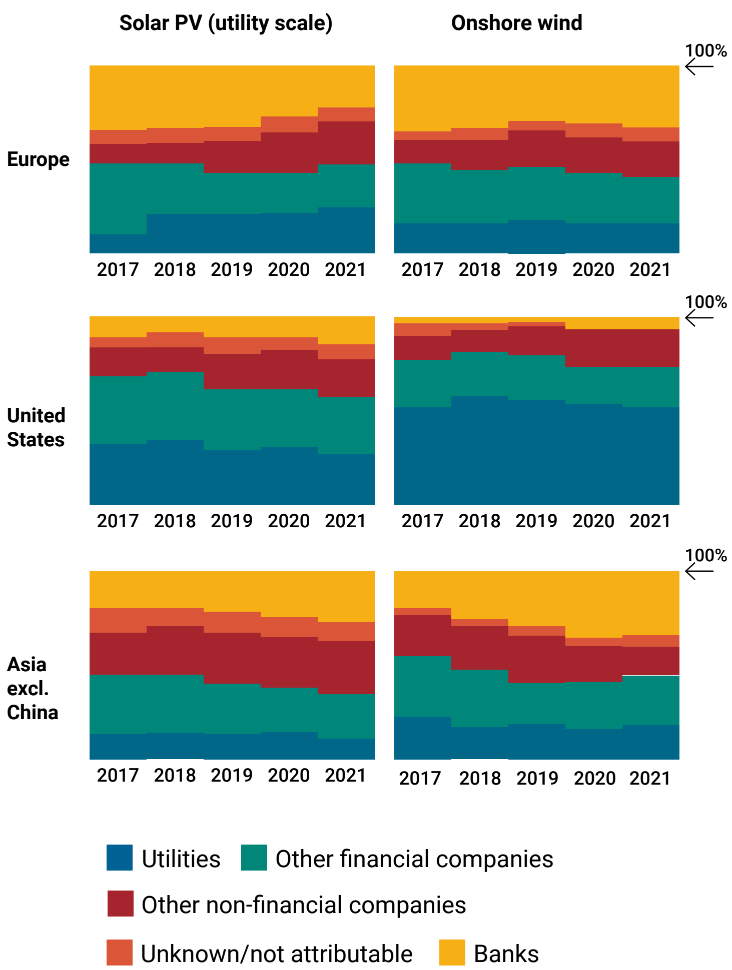
4.4 CAPITAL SOURCES AND INVESTOR LANDSCAPES

The capital sources and investor landscape provide a complementary lens through which to understand progress on renewable energy technologies by informing the robustness of the funding. Like the CoC, quantification of these aspects is not readily available, but research by academics and financial data providers endeavors to make it available, combining the piecemeal available information and imputing gaps to describe overall trends (Gumber, Egli and Steffen 2024).

Figure 4.5 shows estimated splits between different investor types for solar PV and onshore wind, for three regions selected based on data availability. It highlights that renewable energy technology, unlike fossil fuel-based power generation, generally relies on a diverse set of investors – not just utilities, but also other non-financial companies, especially dedicated renewable energy project developers. There are some distinct regional differences; for instance, utilities play a larger role in the United States of America than in Europe, especially for onshore wind. An important aspect across all regions is that financial companies, especially banks, cover a notable share of the investments. This pattern directly links to the fact that syndicated project finance plays a vital role in renewable energy technologies (Steffen 2018) and underlines the importance of a mature financial system and financial regulation to foster investments.

5 These values are broadly the same as reported in the 2023 Emissions Gap Report. Values for Brazil and Mexico are updated to the values from the IEA Cost of Capital Observatory, which are higher than those reported previously.

Figure 4.5. Investor landscape for renewable energy technologies for selected regions



Estimates based on Gumber A,, Egli F., Steffen B. (2024).

4.5 EVALUATING METRICS FOR THEIR IMPLICATIONS FOR JUST TRANSITIONS

These metrics can provide the basis for informing the achievement of the COP 28 decision on tripling current global renewable energy capacity by 2030 in terms of the magnitude and geographic distribution of the flows, the relative viability of these investments and the robustness of the investment landscape. They also provide insights into just transitions and the role that renewable energy technologies can play in these processes. For this report, we focus on discussing what these metrics and the data availability for global coverage reveal about the state and trends of fairness and inclusiveness of renewable energy technology progress. Our analysis reflects the use of the just transitions concept in various international agreements, including the Paris Agreement, which recognizes that the energy transition must be managed carefully to avoid exacerbating inequalities (Newell and Mulvaney 2013). In this vein, we also elaborate on some of the key issues around how these metrics can perpetuate the status quo. We conclude this section with the research needed to develop holistic metrics describing the investor landscape in renewable energy technologies, and other climate technologies that may complement the key metrics above (e.g. Vanegas Cantarero [2020]).

The data underlying these metrics reveal significant trends regarding the inclusiveness of renewable energy progress. For instance, while there has been substantial growth in renewable energy capacity worldwide, this growth has not been uniformly distributed. These disparities highlight the importance of designing and implementing metrics that not only track progress, but also ensure that the energy transition is inclusive. For example, the CoC can provide insight into progress where markets are well developed – or where there are expectations that reducing risks and perceptions of risks represent a critical strategy for expansion (Bachner, Mayer and Steininger 2019). This metric can represent "unfair" penalties for some developing countries, where the perception of risk hinders securement of foreign direct investment for these projects (Komendantova 2012). Furthermore, we can ask how useful this metric is as a global statistic for renewable energy technology financing when approximately 10 per cent of countries that are not covered by these metrics are countries that are more likely to rely on concessional finance (Pueyo 2018). Additionally, the available data can make it challenging to disaggregate within a technology type, which can also obscure the potential disparities that are arising, as the market generally favours larger company-led projects. For example, we highlight that stand-alone PV systems that show more favourable economics in Africa are receiving much less attention than larger projects.

It is also important to acknowledge that the very metrics used to track progress can, in some cases, perpetuate existing inequalities. Metrics that focus solely on quantitative increases in renewable energy capacity, for example, overlook the qualitative aspects of who benefits from the progress in renewable energy technologies. If not carefully considered, such metrics could inadvertently reinforce a status quo where predominantly Western countries and China continue to dominate the energy sector without fair returns or benefits being provided to local communities (Newell and Mulvaney 2013). The investor landscape matters not only as a metric for climate finance flows, but also for the governance of renewable energy projects; the ownership structure determines who has a say in investment and operating decisions. Hence, it would be helpful to have analyses, as shown in Figure 4.5, on a country/technology level for all relevant markets. However, this would require country-specific data collection.

Alternative ownership models – namely social ownership and renewable energy communities – can facilitate just transitions, especially in ensuring that the benefits of financial growth are more widely shared (Cherry 2023). Renewable energy communities are increasingly viewed as an alternative to the presumption of top-down intervention and providing a transformational process that foregrounds the priorities of the community (Gui and MacGill 2018; Hoicka *et al.* 2021). However, there are fewer examples of these initiatives in developing countries. Here, expanding the availability of and, critically, the types of finance available will determine the success of these initiatives, and as such, identifying and including these developments in the metrics along with the necessary data collection would provide additional insights into the joint progress on renewable energy technology and just transitions.

Additionally, metrics describing international – public and private – capital flows could be added to gain a comprehensive picture. One (although not the only) aspect that is especially important for many developing country contexts is the capital source, i.e., public vs. private finance, or the role of the government as investor and lender (e.g. de Aragão Fernandes *et al.* 2023). First, the energy utility landscape in many countries encompasses private and state-owned utilities, where policies and institutions play an important role in renewable energy technology investment decisions at the latter (Steffen, Karplus and Schmidt 2022). Second, state investment banks can be important for renewable energy technology investment, including co-investing with private sponsors, especially for riskier technologies such as offshore wind (Waidelich and Steffen 2024). Third, international financial institutions, such as multilateral development banks (MDBs) and the Green Climate Fund, have played a major role in financing renewable energy technologies in developing countries in the past. However, the scale of international mitigation finance falls much short of what would be needed (Steffen and Schmidt 2019; Pachauri *et al.* 2022; Semieniuk, Ghosh and Folbre 2023).

4.6 IMPROVING INVESTMENT AND FINANCE FOR RENEWABLE ENERGY TECHNOLOGIES

Despite technological maturity, investment is still very limited in many developing countries, and needs to grow in numerous emerging economies, even though there are exceptions with impressive growth. Accordingly, policy is key for global deployment of renewable energy technologies in the context of meeting the goals of the Paris Agreement. The metrics bring into focus several interventions that can enhance progress in renewable energy technologies and reduce barriers.

One key barrier is the high CoC in some country contexts – reflecting the high investment risk there, which in turn is caused by a combination of systemic issues in the energy sector, the financial sector, and with respect to the political and regulatory landscape more broadly. Thus, well-targeted interventions for countries where access to capital and CoC are hurdles to deployment are needed. This requires a clear understanding of the underlying risks from a finance and investment point of view and, accordingly, regulatory changes. "UNDP's Derisking Renewable Energy Investment" report provides a well-proven framework UNDP (2020). However, depending on the specific context, some country-wide investment risks are hard to address with energy sector-specific policy only. In these cases, more extensive development of the local financial system, including financial markets and financial intermediation, is key. While this generates revenue for renewable energy finance and economic development more broadly, these efforts require substantial and long-term engagement.

Interventions such as blended finance solutions by international financial institutions, most notably multilateral development banks that can provide low interest loans with guarantees and UNFCCC climate finance institutions, such as the Green Climate Fund, remain crucial for renewable energy technologies. For example, specific (international) public support for early plants that have not been used in a new country could kick-start deployment and financing. While well-developed programmes exist (e.g. at the World Bank), adequate financial resources for lending in high-risk countries remain a continuous struggle (Climate Policy Initiative 2024). The opportunities that renewable energy investments provide – for reaching climate goals and SDGs alike – are strong arguments for increasing international finance for these technologies, including in discussions about the multilateral development banks Capital Adequacy Frameworks and the mitigation part of the NCQG under the Paris Agreement. In many cases, public finance from these sources can be effectively used to mobilize private co-investment, by reducing risk for domestic and international private investors. One aspect in that regard is addressing foreign exchange risks, for instance, through credit guarantees that incentivize local currency financing. Identifying ways of measuring the mobilization effect of public international finance would complement the metrics discussed in this paper.

We also emphasize the need for supportive policies to accelerate the energy transition. Here, we stress the benefits of multiple and cross-cutting policies that shift the economy away from fossil fuels and towards low-carbon sources of energy (e.g. Stechemesser *et al.* 2024) within a stable regulatory context. Other support for individual technology deployment, such as subsidies and renewable energy auctions, can also help address market and non-market barriers. While the technologies selected for this chapter are mature, innovation and R&D are needed for the remaining less mature options. Notably, the benefits of these cost reductions in renewable energy technology could be freeing up investment and financing capacities for upstream and other climate actions. Identification of public investment for innovation could be facilitated by resetting the balance between the public and private sectors, as technologies and markets no longer require derisking. Additional capacity and coordination efforts can also support and create enabling environments for finance and investment, including coordination of country platforms and the support provided by UNFCCC bodies. For example, the TEC can continue to assist in establishing the collaborations among governments, private sector entities and other stakeholders needed to accelerate innovation and implementation of renewable energy solutions worldwide. The Climate Technology Centre and Network (CTCN) can also play a role in strengthening domestic enabling environments through technical assistance, capacity-building and other activities.

4.7 CONCLUSIONS

This chapter reviews the state and trends of renewable energy technology finance and points ways forward for policy. The conclusion addresses the lessons learned so far, recommendations for data and metrics to track renewable energy goals, and transferable lessons for other technology finance needs within the context of the second Global Stocktake (GST2).

Examining mature technologies such as solar, wind and hydropower reveals that the overall global picture for renewable energy progress is strong. Cost reductions have ensured that the available finance continues to lead to capacity additions. Financial markets consider them to be mature from both a technological and financing point of view, and efficient financing structures and instruments are well established. These include classical corporate finance by utilities, but also project finance with high debt shares, tapping into financial markets via green bonds, and various types of public finance. Global investment flows have risen consistently and considerably over the years. In this regard, renewable energy technologies are among the most advanced climate technologies, and their financial development can serve as an example for many other asset-heavy technologies.

Moving forward for the CTPR and within the context of the GSTs, these findings have implications for tracking climate technology progress for and beyond renewable energy technologies. First, it is necessary to collect investment volumes by region, as they are an important early indicator for climate technology deployment. Countries may also consider how to collect this information in relevant subnational classifications – e.g. urban/rural or at the sectoral level – to look for additional patterns of investment that may require policy alignments. It is also necessary to improve information for the CoC. As these data are held by various players in the financial industry, they can be challenging to collect and validate, especially in smaller markets and many developing countries. As the CoC captures the market maturity, as well as the state and trends of other key enabling conditions for these investments, having accurate and complete data is important for evaluating the near-term expectations for translating financial flows into capacity expansion. We also highlight the importance of market structure and investor type, as understanding the diversity of actors speaks to the maturity of the markets as well as the choices around policy interventions. However, significant gaps remain, particularly in tracking private sector investments and understanding the long-term impacts of financial flows. Improved data collection and transparency are essential for more effective financial planning and policymaking. The main issue is that private and commercial finance can be more difficult to access and to track compared to public finance.

Finally, there is still a need to improve the evaluation of renewable energy technology finance and investment and its links to just transitions. These metrics reveal many aspects of the inequities within the current systems, namely the high CoC. However, these metrics can also obscure important aspects of just transitions, such as potential alternative ownership models. A just transition lens also opens opportunities for metrics that capture the effectiveness of these investments beyond flows into their impacts, such as aligning renewable energy investments with the SDGs (see Chapter 3 on FA) as well as tracking broader social, economic and environmental benefits (Karytsas, Mendrinos and Karytsas 2020). While this falls outside of the scope of this initial consideration on key metrics for the COP 28 decisions, measures of effectiveness that are especially tailored to just transitions warrant more attention.

5.

Digital innovation and governance

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KEY MESSAGES

- Innovative solutions for integrating renewable energy into existing grids help manage variability and ensure stability. This includes smart grids and advanced energy management systems. Supported by responsible governance, this can accelerate renewable energy diffusion, enhance mitigation efforts, and create cross-sectoral benefits. However, strong governance mechanisms and circular economy strategies at the national level are needed to mitigate the increased demand for ICT hardware and infrastructure, which could offset potential gains.

- Context-specific understanding of digitalization's role in decarbonization pathways, especially at regional levels, remains inadequate and demands further study from various perspectives.

- Digital technologies are increasingly important for mapping renewable energy potential, improving efficiency, and enabling interconnections with other sectors like water and agriculture. However, they cannot replace the physical infrastructure and governance systems needed for energy transition.

- Robust governance frameworks are necessary to ensure the responsible use of AI in renewable energy projects, including setting national standards for data privacy and equitable access. Accessible AI-enabled platforms for all socio-economic groups, including marginalized communities, are crucial and can be facilitated through subsidies and a global AI fund promoting digital literacy.

- National policies should focus on building digital literacy and skills to generate evidence on energy and digitalization, promoting country ownership and mobilizing international funding for digital education and clean energy development in low and middle-income countries.

5.1 INTRODUCTION

Understanding the role of innovation and governance in creating the enabling conditions for climate technology progress is essential to delivering responsible solutions for low-carbon and climate-resilient development (IPCC 2022). The 2024 CTPR highlights the critical importance of mobilizing climate technology solutions to accelerate the uptake of renewable energy in line with pledges to triple global renewable energy capacity by 2030 (IEA 2023). This chapter examines the role of digitalization in the context of the global energy transition and applies a responsible innovation governance approach to explore the interlinkages between digitalization and energy.

Digital technologies resulting from innovations have distinctive features that enable radically disruptive transitions in the energy sector. They offer opportunities to develop new production and consumption models reshaping conventional approaches of energy generation and consumption (Nwaiwu 2021). Digital innovations, with responsible governance, can accelerate renewable energy adoption, enhance mitigation efforts and create new opportunities for the energy transition. Chapter 6 explores the rationale behind digital innovation and governance, focusing on their energy system applications and possible cross-sector benefits.

Digital innovation refers to the creation and adoption of new and value-adding novelties in products, processes, services or business models through the incorporation of digital technology (Hund *et al.* 2021). Digital innovations span both hardware-based technologies, such as information and communications technology (ICT), data centres, robotics and the Internet of things, and software-based innovations, including applications, cloud computing and AI. The rapid adoption of digital technologies requires a global understanding of their effects on energy demand, socioeconomic development and climate impacts (Di Salvo *et al.* 2017; Samuel, Lucivero and Somavilla 2022). While the rate of digitalization varies from country to country, it is a key trend in climate change mitigation, and it is crucial to assess the potential of digital technologies and establish responsible governance mechanisms to manage associated risks (Stilgoe, Owen and Macnaghten 2013; Winfield and Jirotka 2018; Schulz and Feist 2021; Widdicks *et al.* 2023).

Digital innovations are recognized for their potential to address climate-related challenges and are often highlighted for their ability to accelerate the implementation of the Paris Agreement and the SDGs (ITU and UNDP 2023; IEA 2024). For example, software-based tools such as ML can predict energy demand and adjust supply accordingly, thereby reducing costs and improving the efficiency and resilience of energy systems through advanced monitoring (Pallonetto, Jin and Mangina 2022). Without proper governance, however, digital change can increase the demand for energy and materials, exacerbate harmful consumption and production patterns, and offset potential benefits (Dauvergne 2022; Widdicks *et al.* 2023). Digital innovation alone cannot replace the physical infrastructure needed for the global energy transition. Scaling both digital and renewables requires investment and governance systems that can significantly increase their potential, improve efficiency, increase energy access and connect with sectors such as the water and agriculture nexus (Sanchez Santillano *et al.* 2022).

A key starting point is recognizing that there are differing approaches to assessing the benefits and risks associated with the energy transition and the deployment of digital technologies. For example, the World Economic Forum (WEF) estimates a potential 20 per cent reduction in GHG emissions (metric tons of carbon dioxide equivalent [$MtCO_2e$]) by 2050 using digital tools in energy, materials and transport, based on scenarios from IEA Net Zero by 2050 and the OECD Environmental Outlook, and data from WEF, the United Nations and the Government of the United States of America (Vestberg 2024). In contrast, the peer-reviewed scientific literature projects an exponential increase in energy consumption and global GHG emissions due to the expansion of ICT infrastructure and use (Freitag *et al.* 2021; Samuel, Lucivero and Somavilla 2022). This inherent contradiction underscores the need to closely examine the relationship between digitalization and energy systems. While the ecosystem of digital innovations is complex and rapidly expanding, it is essential to understand how digital technology solutions can advance renewable energy deployment and adoption. Consequently, this chapter focuses on two specific examples. The first case (global scope) explores the emerging role of AI, particularly ML, combined with geographic information system (GIS) tools to map global rooftop solar capacity expansion. The second case investigates the implementation of pay-as-you-go (PAYG) solar technology in Burkina Faso. Both examples of digitalization in energy are highly relevant for enhancing global solar capacity and improving electricity access in Africa. The following section outlines the main challenges and risks associated with developing digital innovations in the energy transition, providing a rationale for assessing their potential and offering policy recommendations.

5.2 OPPORTUNITIES AND CHALLENGES IN GOVERNING DIGITAL INNOVATION FOR THE ENERGY TRANSITION

Digitalization is emerging as a key driver of energy transitions, reshaping the way energy capacity is assessed, produced, distributed and consumed. Currently, much of the progress driven by the rapid advancement of digital technologies in the context of renewable energy transitions remains concentrated in high-income countries, highlighting the need for greater efforts from both the public and private sectors to mobilize investments in digital infrastructure in low- and middle-income countries (IEA 2024; World Bank 2024).

As countries develop their low-emission development strategies and update their NDCs, significant opportunities and policy momentum could enable appropriate national and regional pathways that address digitalization as a multisectoral strategy for transforming energy systems. Yet, while digital innovation holds the promise of facilitating the wider deployment and uptake of renewable energy systems, it also presents significant challenges and risks (European Commission 2024). These challenges are particularly pronounced in contexts where governance frameworks, socioeconomic conditions and investment in infrastructure are insufficient to meet the diverse needs of various low- and middle-income countries. Many countries in sub-Saharan Africa face severe energy shortages, resulting in widespread energy poverty, a problem worsened by rapid population growth. The urgent need to expand electricity access has sparked growing research interest in innovative ways to accelerate the energy transition in the region (Mulugetta *et al.* 2022). These challenges present a unique opportunity for the continent to harness digital transformation in its energy systems to meet development needs. However, it is crucial to weigh up both the benefits and the risks involved.

Firstly, digitalization in energy systems raises the energy demand for software and infrastructure such as data centres, which in turn leads to an increase in carbon emissions and resource consumption. Large-scale digital projects drive environmental impacts such as water and energy use, mining expansion, toxic waste generation and carbon emissions (Dauvergne 2022; Schütze 2024). Furthermore, uneven access to digital tools worsens the global digital divide (Nyahodza and Higgs 2017), with 2.6 billion people still lacking access to the Internet, thus posing an obstacle to achieving many SDGs, particularly SDG 9 and SDG 7 (United Nations Conference on Trade and Development 2024; Vestberg 2024). Secondly, digital technologies such and AI and ML can be prone to algorithmic biases, arising from inaccurate training data, poorly suited models, or differences between training and application contexts (Arora *et al.* 2023). These biases can lead to skewed outcomes and reduce the effectiveness of models in real-world situations. Thirdly, information asymmetry poses a significant risk for decision makers who wish to use digital innovations in energy transitions (Meunier 2023; IMF 2024). Disparities in data access can exacerbate power imbalances and undermine trust between stakeholders, thus hindering collaboration. In the context of AI models, data is mainly available in high-income countries, giving them an advantage and leaving lower-income countries behind. While some lessons can be transferred, significant contextual differences can lead to negative outcomes if not addressed in robust national governance strategies.

Given existing opportunities and risks, effectively harnessing digital innovations to improve access to renewable energy and expand its capacity requires responsible innovation governance tailored to the specific national or regional context in which digital technologies are deployed (Stahl 2022). It is crucial to assess how responsible innovation governance can help identify the most valuable options for supporting energy system transformations, while simultaneously mitigating and managing related risks. The following section outlines the key dimensions of responsible innovation governance in the context of the energy transition, which are then applied to both case studies to identify relevant lessons and policy recommendations.

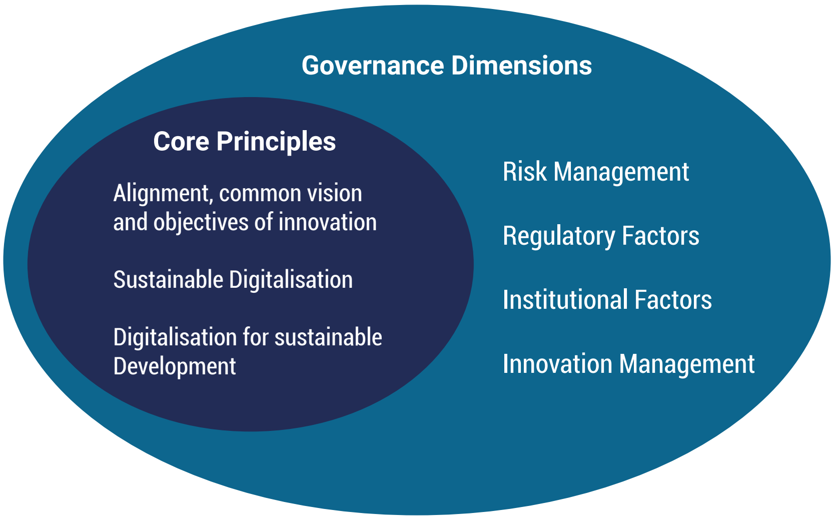
5.2.1 Key dimensions for responsible innovation governance in the context of digitalization and the energy transition

Digital innovations have the potential to accelerate and scale up energy system transformations, provided that robust governance mechanisms are put in place. There are two critical governance aspects at the intersection of digital innovation and energy systems. The first is sustainable digitalization, which highlights the need to ensure the sustainability of digital innovation processes. The second is digitalization for sustainable development, which involves the deliberate design of digital solutions to promote sustainable development.

The potential of digital innovations to support the mobilization and deployment of renewable energy systems is increasingly being recognized. This includes co-benefits and complementarities with other sectors (IPCC 2022; Muench *et al.* 2022). Digital technologies offer synergies with the SDGs (Vinuesa *et al.* 2020) and can facilitate more ambitious and transparent NDCs under the UNFCCC process (GESI 2020).

In the context of this report, this means improving renewable energy systems and services in line with SDG 7 to ensure universal access to affordable, reliable and sustainable energy. To address sustainable digitalization and digitalization for sustainable development, we provide a set of governance dimensions for understanding and developing a framework for responsible innovation at the nexus of digital and energy transitions at the national level. The four governance dimensions are: risk management, regulatory factors, institutional factors and innovation management (see glossary in this report). These principles have been extracted and interpreted from the Sixth Assessment Report (AR6) of the IPCC (2022) and correspond to key criteria for evaluating digitally enabled energy system transitions.

Figure 5.1 Responsible innovation governance for digitally enabled energy system transitions



Source: Authors own elaboration.

Figure 5.1 highlights key areas necessary to maximize the potential of digital technological solutions while mitigating negative socioeconomic and environmental impacts. The diagram emphasizes the need for aligning visions, values and objectives when creating digital technology strategies and policies by considering regulatory factors, innovation management, institutional aspects and risk management.

While the framework is of a general nature, each dimension will need to be adapted to the specific needs and context of the country in which it is being applied. The authors have developed guiding questions for each problem area, which serve as entry points for policymakers to address context-specific challenges related to digitalization and energy system transitions.

Table 5.1 Guiding questions for assessing opportunities/risks and improving governance

Problem area	Guiding questions for assessing opportunities/risks and improving governance
Digitalization and sustainable development	Which aspects of the technology in question promote sustainable digitalization? If sustainability considerations are missing, how can they be integrated to drive digital innovation towards sustainable development objectives?
Regulatory factors and governance	What are the context-specific requirements, including policy, for the effective governance of this technology? What key regulatory factors and capacities are needed for proper regulation?
Risk management	What are the main social (diversity, equity and inclusion) and environmental risks associated with the technology in question? Are adequate risk management strategies in place to address these issues?
Institutional factors and innovation management	Which institutional factors can act as barriers or enablers for the mobilization, deployment and implementation of the technology? What processes and resources are needed for effective short- and long-term technology management? Who are the key stakeholders and how are they informed, involved or affected by these innovations?

The following section presents two cases that illustrate how this framework can be used to identify potential opportunities and risks for the responsible governance of digital innovation in the energy transition. The first case (global scope) investigates the use of AI, particularly ML, combined with GIS tools to map the global expansion of rooftop solar capacity. The second case focuses on established PAYG solar technology and its implementation in Burkina Faso. Together, these examples demonstrate how digitalization can accelerate solar capacity growth and improve electricity access across Africa. Both case studies also address key aspects of digitalization, including challenges and risks related to regulatory and institutional factors, risk management and the forward-looking governance of innovation.

5.3 CASE STUDIES

5.3.1 Case study 1: Using artificial intelligence for rooftop solar capacity expansion

Solar PV energy is an important source of renewable energy. Currently, about 6 per cent of the world's energy is produced by solar PV (IEA 2019). Raw materials to produce solar PV cells are widely available, and solar cell production is standardized, allowing for low-cost scale-up. Significant cost reductions in solar PV over the past decade (IEA 2019) have led to an increase in global solar PV capacity of about 41 per cent since 2009 (BP 2018); a further tenfold increase in global solar PV is expected over the next decade (IRENA 2019), which would make solar PV the largest primary energy source by 2040 (IEA 2024).

Several complementary advances using ML and AI have been developed in recent years to support global solar PV capacity assessment (see Kruitwagen *et al.* 2021; Joshi *et al.* 2021) and solar PV maintenance efficiency (Oviedo *et al.* 2023). In addition to large-scale industrial solar PV installations, small-scale rooftop PV accounts for about 40 per cent of global solar PV capacity (Joshi *et al.* 2021), and thus represents an additional important route for increasing solar PV capacity rapidly and at low cost in both rural and urban areas. Encouraging the deployment of rooftop PV thus represents a viable policy pathway for increasing renewable energy capacity at the global scale. However, factors such as rooftop area, solar radiation and roof angle affect how much stored energy can be generated from sunlight. Differences in these factors make certain rooftops much more efficient at producing solar PV than others. Recent AI-based approaches have shed light on the assessment of rooftop potential by predicting the expected solar PV capacity for individual houses, thus making it possible to assess which houses are particularly effective in generating solar PV energy in the built environment. Understanding rooftop solar PV potential can be particularly important for individuals or businesses when deciding whether it is financially viable to install solar PV; therefore, AI-based insights help to reduce the uncertainty associated with the generation and cost of solar PV, and can thus significantly facilitate the further adoption and expansion of solar PV in both urban and rural areas around the world.

Under the name Project Sunroof, Google created actionable insights by developing an AI algorithm based on satellite imagery to predict the rooftop PV potential of individual hous-

Figure 5.2 How artificial intelligence and machine learning can support insight and uptake of solar photovoltaic energy

Predicted rooftop solar potential over buildings of São Paulo.

Source: https://developers.google.com/maps/documentation/solar/overview es in cities. Users can query the PV potential of their own homes on Google's platform, based on a model that analyses rooftop exposure to sunlight, meteorological data and local electricity prices, among other factors. Similar information is also provided for entire geographic regions, potentially giving policymakers new insights into the amount of solar power that could be generated through regional rooftop solar PV programmes. Building on Google's platform, Monalee, a climate technology company based in the United States of America and launched in 2022, provides users with individual real-time price quotes and customized offers based on a homeowner's specific rooftop solar PV potential. By using the precision solar PV estimates described above, Monalee has been able to offer customers solar PV installations at a lower cost and with much greater price transparency. This example shows how precision information provided by AI-based analytics, and synergies between large technology companies and renewable energy providers, can significantly increase the uptake of existing renewable energy sources.

The risk of asymmetry of AI capacity and regulatory responsibility

Generating large algorithms requires huge amounts of data and server capacity. Both are predominantly in the hands of the private sector. This creates a conundrum where the resources to drive AI's contribution to the adoption of renewable energy are in the private sector, while governments and the public sector are the regulators, who generally do not have access to the algorithms generated. These discussions on appropriate AI policy and public regulation of the AI sector are broader than those applying solely to algorithms produced in the context of energy (see, for example, Centre for the Governance of AI [2024]). Furthermore, in the context of AI algorithms for energy, the entities that produce algorithmic insights are typically technology companies, while energy producers are those that benefit from the insights. Therefore, both the asymmetry between private sector AI capacity and public sector regulation, and the sectoral separation between technology companies producing algorithmic insights and energy companies with the capacity to physically scale up renewables, highlight the importance of collaboration between the public and private sectors, and between entities across different private sectors, to ensure the efficient and frictionless adoption of AI-based innovations in solar PV (or other technologies).

The importance of ground truthing algorithms to reduce global inequities of algorithmic benefits

Large AI models require data that are available in large quantities and exhibit low (measurement) biases. Developing countries generally have low statistical capacity, resulting in low to no data. While AI-based insight can be used to infer insight for a low-data context from algorithms trained on high-data contexts, if large heterogeneity exists between the contexts, this can lead to unrealistic, biased and harmful predictions for low-data contexts. For the prediction of rooftop potential, ground truth information on physical parameters of houses' rooftops, and associated existing solar PV capacity is required to infer the former from imagery and subsequently the latter from the former.

This will be absent or only available in limited amounts for certain countries (especially developing countries), where the low availability of both data and energy are crucial issues. Hence, while AI-based algorithms can be produced in any location with cloud and server infrastructure no longer required to be local, responsible (solar PV) algorithms require both collection of ground truth information also across low-data contexts and validation of the produced algorithm across low-data contexts, especially given vast differences in physical houses' morphology, which influences rooftop solar PV potential across countries.

Fragmentation of multisectoral stakeholders as a risk

As outlined above, in this context of algorithmic insights on rooftop solar PV, AI-based insights cannot replace physical expansion of energy capacity. However, it can directly assist in reducing the uncertainty of the produced capacity and support a more efficient expansion of solar PV. Therefore, efficient adoption of algorithmic insights for solar PV capacity requires both insights from the technology sector and action from the energy sector. Where partnerships exist, or where entities within the energy sector have in-house AI capabilities, a more rapid synergy between AI insights and physical energy capacity expansion can be achieved. In developing countries, more transparent insight into rooftop solar PV potential offers a great opportunity to attract funding for further solar PV projects with less uncertainty, but with the caveat of the importance of algorithmic validation outlined above.

In conclusion, while algorithmic insights cannot replace the physical deployment of solar PV, they can significantly reduce uncertainty and attract more investment from both the private and public sectors into rooftop solar PV development. As the capabilities of algorithmic modelling rapidly advance, the efficient use of these insights for renewable energy capacity will require strong collaboration and coordination between private sector entities and with the public sector.

5.3.2 Case study 2: Developing last-mile pay-as-you-go energy access innovations in Burkina Faso

Sahelia Solar, a Burkina Faso-based company, focuses on integrating solar PV systems to harness the country's solar potential, reduce energy costs and contribute to climate change mitigation (Sahelia Solar 2023). Through a PAYG model, Sahelia Solar has launched several projects targeting rural agro-industrial facilities (IRENA 2022). However, challenges related to powering agricultural machinery, identifying the appropriate business models for climate- and economically vulnerable populations, delivering solutions efficiently in remote areas where infrastructure and resource access are often limited, and identifying specific energy needs have slowed progress (World Bank 2021).

To overcome these barriers, technical assistance from the CTCN's national entity in Burkina Faso aims to enhance technological solutions and payment systems for productive uses in agri-processing applications (CTCN 2023). This includes, on the one hand, identifying locally led agricultural solutions for implementation and, on the other, analysing existing payment challenges, developing a new "pay-as-you-use" system and improving system management. The technical support will also address issues such as energy access disparities, equipment quality and after-sales services, while strengthening stakeholder engagement, revising payment models and establishing quality standards. These efforts will enable Sahelia Solar to promote renewable energy more effectively and sustainably in the country (IRENA 2022).

Digitalization: Exploring technology's role and relevance to digitalization

Initial aspects of the technology related to digitalization in the project include using mobile payment platforms and smart metres within the PAYG model. These tools enable flexible payment and energy usage monitoring, enhancing access to energy services for low-income populations (Balfour 2018).

The innovative element in this project includes the contextual adaptation of the PAYG model, which aligns payment structures with the income patterns of Burkina Faso's rural populations, ensuring affordability and accessibility for economically vulnerable groups; community-centric digital engagement tools; and the integration of revenue-generating activities that further facilitate affordability and accessibility for these economically vulnerable populations (IRENA 2022).

Governance and enabling environment: Specific requirements for effective implementation of technology in Burkina Faso

To effectively implement PAYG solar technology in Burkina Faso, a supportive regulatory framework for renewable energy was essential, with clear policies for off-grid systems, licensing and consumer protection (Burkina Faso, Ministry of Energy and Water 2022). Streamlined procedures for permits, integration of mobile banking for payments and grid connection standards are crucial (IRENA 2022). Additionally, building the capacity of local authorities and prioritizing rural electrification policies will help to manage and regulate the technology effectively (World Bank 2021).

In this case, several governance and regulatory factors are essential. First, efficient licensing and permitting processes are crucial. This involves simplifying procedures to reduce bureaucratic delays and ensuring that the criteria for granting licenses are transparent and fair, as outlined by the Ministry of Energy and Water, Burkina Faso (2022).

Consumer protection is another key factor. It requires mandating quality standards for equipment and services while establishing mechanisms for consumer grievance redressal, as recommended by UNICEF (2020). Financial integration also plays a vital role. It includes enabling seamless mobile payment integration for PAYG systems and supporting flexible microfinancing products tailored to rural communities, as suggested by Balfour (2018).

Institutional capacity-building is necessary to support these initiatives. This involves providing training for regulatory bodies and enhancing technical expertise within institutions to effectively oversee renewable energy projects (Burkina Faso, Ministry of Energy and Water 2022). Monitoring and evaluation systems should be implemented to collect and analyse data on project performance, which will inform necessary policy adjustments. Lastly, stakeholder coordination is essential, which includes promoting interministerial collaboration and encouraging PPPs to leverage diverse resources and expertise.

Risks and stakeholders: Key social and environmental risks and management strategies for technology roll-out

The key social risks associated with PAYG solar technology in Burkina Faso include unequal access, particularly for marginalized groups such as women, low-income households and people in remote areas, who may face affordability or accessibility challenges. Additionally, limited digital literacy could prevent some users from effectively utilizing mobile payment platforms. On the environmental side, improper disposal of solar batteries poses a risk of pollution and soil contamination.

To mitigate these risks, promoting inclusivity through flexible payment plans for underserved groups and providing digital literacy training is essential. Environmentally, establishing safe disposal and recycling programmes for solar components should be prioritized. Engaging local communities through education on sustainable energy practices is also crucial.

Currently, key actors include UNFCCC's CTCN, Sahelia Solaire, Burkina Faso's nationally designated entity (NDE), and international partners such as the French Development Agency (AFD). Further involvement from local NGOs, women's groups and environmental organizations would enhance inclusivity and sustainability efforts. This technology assistance TA is implemented in collaboration with a private company. The exit strategy involves ensuring the technology is sustainable, allowing the private company to continue operating it independently.

Barriers: Institutional factors affecting financing, deployment and implementation of the technology

Key barriers include digital literacy and technological adoption. Despite the importance of digital payment systems in the PAYG model, low levels of digital literacy in rural areas prevent some users from effectively utilizing mobile platforms. This issue is particularly acute for marginalized groups, such as women and older populations, limiting their participation in the system. In addition, policy and regulatory gaps include the regulatory framework for renewable energy in Burkina Faso, particularly for off-grid solar systems, which remains underdeveloped. Licensing, consumer protection and the integration of mobile payment systems face significant gaps, creating obstacles to the widespread adoption and scaling of this technology.

Strategies to achieve digital literacy

To achieve its digital literacy objectives, Sahelia Solar implements a comprehensive set of strategies aimed at enhancing users' digital skills. The first strategy involves initial onboarding sessions during the deployment of the PAYG system. Sahelia Solar conducts hands-on workshops and live demonstrations to familiarize users with digital tools and platforms. These sessions teach users how to operate mobile applications, make payments and access marketplaces.

In addition to onboarding, Sahelia Solar establishes peer support networks. These user groups and forums provide a space for individuals to share experiences, exchange tips and support each other in using the PAYG system. Mentorship programmes pair digitally proficient users with those requiring additional assistance, fostering mutual learning and community solidarity (UNDP 2021).

Another key strategy is the implementation of feedback mechanisms. Users are encouraged to offer feedback on training programmes and digital tools through surveys, suggestion boxes and interactive sessions. This feedback is crucial in identifying areas for improvement and customizing educational content to better meet users' needs (Mulu 2020). Sahelia Solar's long-term goal is to integrate localized content and language support into its digital literacy programmes. By developing training materials in local languages and using culturally relevant examples, the content becomes more accessible, inclusive and relatable to all users (UN-Women 2021).

To conclude, based on this case study, the following recommendations can be highlighted: it is crucial to strengthen local capacity and after-sales support by establishing local service centres that offer technical support, maintenance and after-sales services, especially in rural areas. Additionally, enhancing digital literacy and access to technology is vital. This effort would empower marginalized groups, including women and the elderly, to better understand and use mobile platforms associated with PAYG systems, thereby improving their participation in and access to renewable energy.

5.4 CONCLUSIONS

This chapter has explored some of the key challenges and opportunities of deploying digital climate technologies, providing examples and lessons learned to inform the governance of digital innovation in the context of energy transition. Digital innovation is expected to remain a disruptive force across sectors, particularly at the intersection of energy and digitalization. The diverse contexts in which these digital technologies are applied require tailored approaches to their design and governance. Technological change is influenced either positively or negatively by several non-technological barriers, which would generally fall under the category of socioeconomic and institutional dynamics and will require appropriate governance mechanisms to maximize benefits and minimize potential harm (Knobloch and Mercure 2016).

This chapter has identified numerous barriers and enablers that are critical to advancing low-carbon and climate-resilient development through digitalization.

To accelerate renewable energy deployment in line with global commitments to triple renewable energy capacity, countries need strong institutional and governance frameworks that integrate energy and digital strategies. Collaboration between different actors and sectors, each with different mandates, preferences or expectations, is currently fragmented. It is therefore essential to address the wider implications of digital technologies for energy systems and other sectors. It is equally important to recognize and address institutional and governance gaps, as these will have a significant impact on the successful implementation of cross-sector digital capabilities for effective digital innovations.

In addition, as digital innovation drives new demand for digital products and services, the need for improved connectivity, faster data transmission, investment in ICT infrastructure, and better applications and digital platforms becomes critical. These elements are critical to the transition, which in turn accelerates material and energy production and consumption – an urgent issue that must be addressed. A context-specific understanding of the role of digitalization in decarbonization pathways, especially at the regional level, remains lacking and requires further research from different perspectives.

In the global energy transition, understanding the digital aspects of new technologies, while fostering an enabling environment for effective regulation and risk management, is critical to assessing their contributions. Digital tools, from Internet connectivity to smartphone apps, data sensors and complex ML, offer significant potential for forecasting energy demand, optimizing energy supply, and improving system efficiency and resilience. However, without appropriate governance, digitalization could exacerbate unsustainable consumption patterns and negate potential efficiency gains by increasing demand for energy and materials. Current research does not adequately consider the energy implications of digital technologies, particularly regarding the energy demand of digital devices throughout their life cycles (i.e. manufacturing, use, end-of-life and circularity). Additional research is needed to understand the role of critical minerals and other raw materials in the global energy transition.

While digital innovations cannot replace the need for physical infrastructure and governance systems, they will continue to play an important role in mapping renewable energy potential, improving generation efficiency and fostering linkages with other sectors such as water and agriculture. Policies that encourage investment in clean energy are essential to support the infrastructure needed for a green digital economy.

In addition, scaling up AI-based technologies, such as using ML for advanced solar capacity mapping, requires fostering public-private partnership models, promoting transparent and accessible data, and integrating AI tools, skills and capabilities into national energy strategies. Robust governance frameworks are essential to ensure the responsible use of AI tools in renewable energy projects. These frameworks should include national standards for data protection and equitable access to data. In addition, it is crucial to make AI-enabled platforms accessible to a wide range of socioeconomic groups, including marginalized communities. This can be achieved through subsidies and the creation of a global AI fund to promote digital literacy and access to digital technologies. Such measures will facilitate the responsible and widespread adoption of AI and ensure that its impact is managed more effectively and equitably across different regions and countries.

Thus, while public and private entities focus on greater innovation and investment in digital solutions (ranging from sensors to smart energy grids and the use of AI tools for better mapping and resource management), it is essential for each national research and policy sector to focus on creating digital skills to build robust evidence on energy and digitalization, promote country ownership, and significantly mobilize digital literacy programmes at the national and global levels. At the same time, the international community of donors and technology companies must promote coordinated funding for digital literacy and clean energy development in low- and middle-income countries. These concerted efforts will enhance the skills, awareness and governance perspectives that will guide more informed and responsible digital innovation across the digital and energy value chains in low- and middle-income countries, both in the short and long term.

Digital innovation, supported by responsible governance, can accelerate the deployment of renewable energy, enhance mitigation and adaptation efforts, and generate cross- sectoral benefits. However, strong governance mechanisms and robust planning at the country level are needed to avoid increasing energy and material demand for ICT hardware, software and infrastructure, which could undermine potential efficiency gains. Additional linkages with circular economy planning at the country level are therefore needed.

Careful country assessments and advocacy are also necessary to embed responsible governance in national innovation and energy policies, with a focus on raising awareness and strengthening linkages between the digital and energy sectors. This can be achieved through nationally owned, actionable principles and policies that drive cross-sectoral governance arrangements and help mobilize investment opportunities in climate technology solutions.

Lastly, supporting an enabling environment that embraces broader systems thinking and emphasizes context-specific innovation and governance processes in pursuit of the SDGs and more ambitious NDCs will be beneficial. Future actions and decisions should address the specific risks and uncertainties of digital innovation, and address national regulatory concerns, while promoting the creation of stronger capabilities and institutions that support a responsible enabling environment for the governance and promotion of digital technology to drive responsible energy transitions and climate action.

Jakarta, indonesia. Bus rapid transit (BRT). The Transjakarta bus system enjoys its own traffic lane to avoid congestion ©Shutterstock

ANNEX 1 - Interlinkages between key technologies and SDGs

Adaptation technologies			
Technology	**Mitigation**	**Adaptation**	**SDGs**
Resilient power infrastructure (Ahad *et al.* 2020; Guerrero Delgado, Sánchez Ramos and wÁlvarez Domínguez 2020)	Support a reduction in the emission of all pollutants and CO_2, provided that renewable energy is used.	Power system remains functional during emergency and disaster situations, reducing the vulnerability of the urban system.	Resilient power infrastructure technologies, particularly in combination with reliable power system technologies, contribute directly to SDG 7 (affordable and clean energy) and SDG 13 (climate action). They can also contribute to SDG 3 (good health and well being) and SDG 6 (clean water and sanitation), by guaranteeing the functioning of other infrastructures and urban facilities and services, in addition to domestic supply. As a result, these technologies contribute to a more sustainable urban system, helping to achieve SDG 11 (sustainable cities and communities). Depending on the economic, political and institutional conditions, such technologies can not only benefit vulnerable and poorer populations in terms of domestic consumption, but also provide reliable energy to health centres, shelters, early-warning systems or general communication systems, thus helping to achieve SDG 1 (no poverty). These technologies also support SDG 6 (clean water and sanitation) by using it more efficiently.
Reliable power system (Ahad *et al.* 2020; Guerrero Delgado, Sánchez Ramos and Álvarez Domínguez 2020)		Can provide reliable electricity to the urban system, including the many sectors and potentially also vulnerable populations and informal areas that are usually unable to access reliable sources.	
Water use efficiency (Padilha Campos Lopes *et al.* 2020; Zhou *et al.* 2020)	Support more efficient electricity generation processes.	Improves water use and management of the generation plant, but could also improve the management of watersheds.	
Smart grids/digitalization (Mondejar *et al.* 2021; Babazadeh *et al.* 2022; Judge *et al.* 2022; Kaur *et al.* 2022; Meenal *et al.* 2022; Durillon and Bossu 2024; Kumar *et al.* 2024; Nyangon 2024)	Support a reduction in the emission of all pollutants and CO_2, provided that renewable energy is used. Synergies with mitigation should therefore be considered in the context of other enabling technologies, such as distributed energy resources, advanced metering infrastructure, communication networks and electric vehicle infrastructure.	Can support the provision of reliable electricity to the urban system and grid connected areas.	SDG 7 (affordable and clean energy), SDG 9 (industry, innovation and infrastructure), SDG 11 (sustainable cities and communities) and SDG 13 (climate action) can all be supported through smart grids, as they enable the integration of renewable energy sources, improve the energy efficiency of electricity transmission and reduce peak demand.

Mitigation technologies			
Technology	**Mitigation**	**Adaptation**	**SDGs**
Solar energy (Albatayneh et al. 2021; Bhuvad and Udayraj 2022; López Prol *et al*. 2024)	Reduce the national emissions intensity and the environmental impact of cities. Increase sustainable management and the efficient use of natural resources. Enable end users to produce their own electricity, whether online or offline.	Rooftop solar panels could be used as a shading device in uninsulated buildings, which would help to increase thermal comfort and reduce the summer cooling load.	In addition to synergies with SDG 11 (sustainable cities and communities) and SDG 13 (climate action), clean and renewable solutions for the generation and distribution of energy, such as small scale distributed energy resources, will have a positive impact on the reduction of air pollution and the pollution of water resources, in turn supporting SDG 3 (good health and well being) and SDG 6 (clean water and sanitation). Furthermore, following an initial individual investment, renewable solutions can make the cost of energy much lower for the consumer, thus helping to achieve SDG 7 (affordable and clean energy) and SDG 1 (no poverty). Renewable technologies are less polluting than other sources, leading to synergies with SDG 15 (life on land). Thanks to their low cost, both solar and wind technologies enhance SDG 8 (decent work and economic growth) and can support important applications related to agriculture and livestock. However, available and desirable sites for solar and wind generation can also result in harm to ecosystems, as well as damage to local biodiversity, landscapes and economic activities, such as tourism and traditional subsistence activities. In turn, the use of such sites can have a negative impact on SDG 15 (life on land), SDG 8 (decent work and economic growth) and SDG 3 (good health and well-being). Possible sites for large scale solar power generation can face challenges due to competition with land use and trade-offs with biodiversity in locations that, despite providing the ideal conditions for solar energy production, are home to endangered species or present other environmental weaknesses. Moreover, the production of solar panels and turbines has a higher environmental impact, due to the mining of raw materials and minerals and manufacturing processes. In the case of wind energy, there have been reports of noise emissions, in addition to risks to migratory birds and biodiversity, depending on the conditions of the local ecosystem.
Wind energy (Olabi et al. 2023; López Prol *et al*. 2024)	Reduce GHG emissions when displacing fossil fuels. Increase sustainable management and the efficient use of natural resources. Enable local communities to produce electricity.	Provides co benefits associated with the reduced use of fossil fuels, as well as benefits to rural populations when used as a stand alone system or a distributed generation system within communities to provide light to homes, community centres, shelters and health facilities, as well as other productive use applications.	
Geothermal energy (Gonzales Zuñiga *et al.* 2018)	Reduce the national emissions intensity and the environmental impact of cities. Increase sustainable management and the efficient use of natural resources.	Increases energy security by reducing reliance on energy imports.	Besides synergies with SDG 7 (affordable and clean energy), SDG 11 (sustainable cities and communities) and SDG 13 (climate action), the technology can support sustained economic growth and reduced energy poverty through green job creation, helping to achieve SDG 1 (no poverty), SDG 8 (decent work and economic growth) and SDG 12 (responsible consumption and production). However, the costs involved in the initial implementation are high. There are also possible environmental trade offs relating to the risk of polluting water sources, the need for high volumes of water to produce the energy and the risk of warming the surroundings.

Mitigation technologies			
Technology	**Mitigation**	**Adaptation**	**SDGs**
Hydroelectric power (Fan *et al.* 2022; Gemechu and Kumar 2022; Kuriqi and Jurasz 2022; Rahman, Farrok and Haque 2022; Schulz and Skinner 2022; Ubierna, Santos and Mercier Blais 2022; Wang *et al.* 2022)	Reduce GHG emissions when displacing fossil fuels (especially when using existing water infrastructure and run-of-river schemes). Use revenue from generation to fund improvements to meet a variety of objectives, such as environmental enhancements and improved safety.	A multipurpose infrastructure provides safety (i.e. flood control) and socioeconomic benefits (i.e. water supply security) which are critical to increasing community resilience.	Hydropower technologies contribute directly to SDG 7 (affordable and clean energy) and SDG 13 (climate action). Dam based hydropower plants are more resilient to the impacts of droughts which may worsen with climate change, while run-of-river solutions are extremely affected by rainfall patterns. However, dam based plants have specific negative environmental and cultural impacts with GHG emissions resulting from the drowning of forests, impacts on local ecosystems and aquatic species, and the displacement of local populations, with several negative impacts on SDG 3 (good health and well-being), SDG 8 (decent work and economic growth) and SDG 14 (life below water). At the regional and national level, the same SDG can be positively affected by synergies with SDG 7 (affordable and clean energy), SDG 8 (decent work and economic growth) and SDG 11 (sustainable cities and communities). Small power generation structures can be combined for multiple coordinated purposes, such as flood control and recreation, helping to achieve SDG 6 (clean water and sanitation), but also SDG 3 and SDG 11.
Energy storage (Arshad *et al.* 2022; McNamara *et al.* 2022; Xue *et al.* 2022; Amir *et al.* 2023; Mousavinezhad *et al.* 2024; Wang and Zhang 2024)	Enable the use of electricity asynchronously, generated by non dispatchable renewable resources.	Can be used to increase resilience in island communities during disaster situations.	In addition to the direct synergies with SDG 7 (affordable and clean energy), SDG 12 (responsible consumption and production) and SDG 13 (climate action), these technologies can help to achieve SDG 3 (good health and well being) and SDG 11 (sustainable cities and communities), ensuring access to energy even in disaster situations and scenarios where energy resources are scarce. However, the negative environmental impacts must be addressed so that these benefits can be fully achieved. In the case of PSH, these impacts are relevant at the site where the storage structure is installed, because it modifies the environment in which the reservoirs are built, affecting the local ecosystem and, ultimately, local populations. In the case of BES, the problem lies in obtaining lithium from mining (when this material is used) and disposing of the residual material. Mining can have a negative effect on the environment and on the miners themselves. If these impacts are minimized, PSH can potentially help to achieve SDG 8 (decent work and economic growth), but both technologies still face either high up front or production costs.
Demand mitigation (Nahlik and Chester 2014; Alawneh *et al.* 2018; Di Foggia 2018; Sharifi 2021; Bertoldi 2022; Zakari *et al.* 2022; Naimoli and Wilcox 2023; Anciaes and Alhassan 2024; Monteiro *et al.* 2024; Siddiqui *et al.* 2024; Vecchio *et al.* 2024)	Reduce energy consumption and the associated emissions of all pollutants and CO_2. There are several co benefits to this: improvement of indoor air comfort, creating local jobs and reducing energy poverty.	Can help to reduce the impact of heatwaves. Can increase resilience to storms. Can improve territorial justice. If on site PV and batteries are installed in buildings, they can provide electricity during blackouts.	Resilient technologies for buildings construction and retrofitting, as well as public transport, can contribute directly to SDG 3 (good health and well-being), SDG 7 (affordable and clean energy), SDG 11 (sustainable cities and communities), SDG 12 (responsible consumption and production) and SDG 13 (climate action). However, these technologies can also help to reduce energy poverty (buildings) and improve territorial justice (public transport), thus helping to achieve SDG 1 (no poverty). They also help to create jobs in the construction sector (buildings) and support SDG 8 (decent work and economic growth). By employing retrofitting strategies for buildings or through the adaptation of public transport, heat islands and the impact of heatwaves can be reduced, air quality can be improved, and high indoor and outdoor temperatures can be alleviated. Depending on the autonomous energy generation technologies adopted, retrofitting buildings can also increase energy autonomy, reducing the risk of supply failure during extreme weather events, as well as individual energy costs.

Solar Power at lighthouse on cliffs ©Pexels, Gündüz Deniz Fotoğrafi

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