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ENERGY OPTIONS FOR WATER DESALINATION IN SELECTED ESCWA MEMBER COUNTRIES

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The photographs on the cover of this publication have been taken from the following publications:

- Ras Abu Fontas power and water station, Qatar
  SolarPACES, Concentrating Solar Power in 2001: An IEA/SolarPACES Summary of Present Status and Future Prospects.

- Jebel Ali power and desalination station, Dubai, United Arab Emirates
  A Success Story of Dubai. Dubai Electricity and Water Authority (DEWA) 1997, United Arab Emirates.

- Ghoubra desalination plant, Sultanate of Oman
  Annual Statistical Report for the Electrical Sector, 1999. Ministry of Electricity and Water; Muscat, Sultanate of Oman.

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Preface

Water desalination, the availability of abundant energy resources and the advanced technology required for these processes, are important issues for the region. With this in mind, *Energy Options for Water Desalination in Selected ESCWA Member Countries* was prepared by the Energy Issues Section (EIS) of the Energy Natural Resources and Environment division (ENRED) at the request of the secretariat of the Economic and Social Commission for Western Asia (ESCWA) for 2000-2001.

This report was largely based on input from ESCWA consultant Mahmoud Abdel-Jawad, Senior Research Scientist at the Water Desalination Department of Kuwait Institute for Scientific Research (KISR).

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ABBREVIATIONS AND EXPLANATORY NOTES

BIG/GT	Biomass gasifier gas turbine
bm^3	billion cubic metres
Celsius	C
CHP	combined heat and power
Cr	Chromium
CSP	Concentrating solar power
Cu	Copper
ED	electrodialysis
ER	energy recovery
FDA	Food and Drug Administration, United States of America
Fe	Iron
G	genarator
GCC	Gulf Cooperation Council
GDP	gross domestic product
GW	gigawatt
GOR	gain output ratio
GT	gas turbine
HE	heat exchange
HP	high pressure
HRSG	heat recovery steam generator
IDA	International Desalination Association
Kboe/d	Kilo barrels oil equivalent per day
Kg/kg	Kilogram per kilogram
kg/mJ	kilograms per mega joule
kWh/m^2	kilo watt hour per square metre
kWh/m^3	kilo watt hour per cubic metre
LP	low pressure
m^3	cubic metres
MED	multiple effect distillation
MIGD	million imperial gallons per day
MP	medium pressure
Mpa	metric barometric pressure
MSF	multistage flash distillation
MSE	multistage flash evaporation
Mtoe	million tonnes oil equivalent
MVC	mechanical vapour compression
MW	megawatt
NF	nano filtration
NG	natural gas
Ni	Nickel
OM	operations and maintenance
OSW	Office of Saline Water, United States of America
PCS	process computer system
pH	measure of acidity
ppm	parts per million
PR	performance ratio
PSI	pounds per square inch
PV	photovoltaic
RE	renewable energy
RO	reverse osmosis
TVC	thermal vapour compression
VC	vapour compression

ABBREVIATIONS AND EXPLANATORY NOTES (*continued*)

The following symbols have been used throughout this publication:

References to dollars ($) and cents indicate United States dollars and cents unless otherwise indicated.

The symbol < means less than.
The symbol > means greater than.

The following symbols have been used in the tables throughout the publication:

Two dots (..) indicate that data are not available or are not separately reported.

A dash (—) indicates that the amount is nil or negligible.

A hyphen (-) indicates that the item is not applicable.

Parentheses ( ) indicate a deficit or decrease, except as otherwise stated.

A slash (/) indicates a school year or a financial year (e.g., 1981/82).

Use of a hyphen (-) between dates representing years, for example, 1981-1983, signifies the full period involved, including the beginning and end years.

Details and percentages do not necessarily add up to totals, because of rounding.

INTRODUCTION

A. Background

Most ESCWA member countries have abundant fossil and renewable energy resources. However there is a scarcity of freshwater resources in the region. This is a particular problem for the Gulf Cooperation Council (GCC) countries, which have abundant seawater resources but limited ground water supplies. Their fresh water resources are below the poverty level of 500 cubic metres (m^3) per head per year.

This situation means that national plans for urban development in GCC countries, including the social, economic, industrial and agricultural spheres rely heavily on water desalination. Owing to extensive urbanization, rapid population growth and improved standards of living, the number of desalination projects in the area has multiplied since the 1950s and is expected to continue to expand in the future. This demand will most probably be satisfied by seawater desalination. However onsite water and energy resources could also serve the fresh water needs of rural populations, which comprise approximately 16 per cent of the total population of GCC countries.

The GCC region accounts for approximately 45 per cent of total desalination capacity, including all types of technology, in the world. This is some 96 per cent of the total capacity in the ESCWA region. However, the GCC countries have approximately 80 per cent of the world's multistage flash desalination systems (MSF). Water desalination will play an important role in the realization of a sustainable energy development and integrated resource plan. Energy is a basic ingredient in all desalination processes. It is also a major cost component for the freshwater production of these processes. It must therefore be afforded special attention when freshwater production by a process of desalination is under consideration.[1]

B. Objectives and content

This study aims:

(a) To assess and identify appropriate energy supply options that would be capable of responding to the acute need for water desalination in the GCC countries;

(b) To conduct a survey of existing energy supply systems coupled with desalination plants and evaluate their energy consumption;

(c) To perform a preliminary cost analysis of desalinated water using relevant energy supply options.

Chapter I reviews the availability of water and energy resources in the GCC countries and their possible integration. Furthermore, it presents an evaluation of desalination capacities in the GCC countries for 1975 to 2000.

Desalination classification, energy requirements and the factors affecting the selection of desalination processes for a specific application, with emphasis on energy requirements, are examined in chapter II. This chapter also analyses the energy consumption and performance of these processes.

Chapter III reviews the existing energy supply systems for desalination processes in the GCC countries, operating principles and comparative evaluation, with a focus on dual-purpose cogeneration systems. In addition, it highlights potential renewable energy systems for desalination within the next five to ten years. The environmental impacts of power/water desalination systems on the marine environment of the Gulf are discussed.

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[1] According to Mahmoud Abdel-Jawad, "Energy sources for coupling with desalination plants in the GCC countries", consultancy report prepared for ESCWA, (September 2001).

The implementation status of water desalination systems in GCC countries by 2000, comparative cost evaluation methodology, results and identifying means for cost reduction of desalinated water are studied in chapter IV.

A summary of the study, conclusions and recommendations for the facilitation of the future development of appropriate energy supply options for desalination systems that will serve the development objectives of different communities in the GCC countries are presented in chapter V.

I. WATER DESALINATION, THE INTEGRATION OF WATER AND ENERGY RESOURCES IN THE GULF COOPERATION COUNCIL COUNTRIES

A. ENERGY AND WATER INTEGRATION CHALLENGES

1. *Geographic conditions and resources base*

(a) *Geographic and climatic conditions*

GCC countries have extremely dry climates, delicate soil conditions and limited natural vegetation. With the exception of the coastal strips and mountain ranges, they are largely desert. Interior regions have cool winters and long, dry summers. The winter is milder and the summer hotter and more humid, for coastal regions. Seasonal temperatures in the interior range between –5º and 46º C, and between 5º and 25º C in the coastal areas and mountainous highlands. Humidity is generally low in the interior, ranging from 10 to 30 per cent, while in the coastal areas it ranges between 60 and 95 per cent. As a result of high solar radiation, the total annual evaporation is high, ranging between 2,500 mm in the coastal areas to more than 4,500 mm inland. Rainfall is low and erratic. Although the average annual rainfall is 100 mm, it is often the case that large areas do not experience rainfall for several years.[2]

(b) *Water and energy resources*

GCC countries are some of the richest nations in the world in terms of petroleum, oil and natural gas (NG). They held more than 45 per cent of the world's total of these resources in 1999. These countries have some of the longest coastlines in the world. Nevertheless, they are amongst the most arid regions on earth. However, despite the fact that GCC countries suffer from a serious lack of freshwater resources, they have enough supplies to solve the problem.[3]

2. *Demographic features and needs*

The total population of the GCC countries was estimated at 29.8 million in 2000. This constitutes 17.7 per cent of the population in the ESCWA region. Table 1 indicates that there are marked differences in the population size of various countries in the GCC region, from as low as 617 thousand in Bahrain to 21.61 million in Saudi Arabia.

TABLE 1. TOTAL AND RURAL POPULATION OF GCC COUNTRIES, 2000
(*Thousands*)

Country	Total	Rural	Rural percentage
Bahrain	617	56.8	9.2 a/
Kuwait	1 971	49.3	2.5 a/
Oman	2 541	566.6	22.3 a/
Qatar	599	50.3	8.4 a/
Saudi Arabia	21 607	3 565.2	16.5 a/
United Arab Emirates	2 441	383.2	15.7 a/
Total GCC	29 776	4 671.4	15.68
Total ESCWA	167 068	86 182	43.5 b/
GCC (percentage)	17.8	5.42	

Source: ESCWA, *Statistical Abstract of the ESCWA Region,* twentieth issue, (New York, 2000) (E/ESCWA/STAT/2000/6) (Sales No. A/E/00.II.L.12).

a/ 1996 statistics.
b/ Percentage of GCC rural population to the total rural population in the ESCWA region.

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[2] Mahmoud Abdel-Jawad, "Energy sources for coupling with desalination plants in the GCC countries", a consultancy report prepared for ESCWA, (September 2001) and Ali M. El-Nashar, "The role of desalination in water management in the Gulf region", Abu Dhabi Water and Electricity Authority, (Abu Dhabi, 2000).

[3] Ibid.

The majority of the population in GCC countries is concentrated in urban areas. However, approximately 15.7 per cent of people in the region inhabit rural areas with no access or very limited access to suitable water and energy resources, in particular electricity. However, diesel generators are used in some cases. The percentage of rural to total population varies from 22.3 per cent and 16.5 per cent respectively in Oman and Saudi Arabia, to as low as 8.4 per cent in Qatar and 2.5 per cent in Kuwait.

This type of population distribution indicates the difference in scope of water desalination capabilities between countries and between urban and rural areas of the same nation. Furthermore, it highlights the fact that the development of small- to medium-sized desalination systems, that are capable of satisfying the needs of rural populations, is a priority. Countries must, therefore, develop suitable energy resources for rural and remote areas, particularly onsite energy resources, namely, renewable resources.

3. *Integration challenges*

Although GCC countries suffer from severe water shortage problems, which will be reviewed in more detail below, they have tremendous fossil and renewable energy resources. Since energy supplies power large desalination plants in urban areas, these resources do not always benefit people living in rural areas. Therefore the problems that must be tackled include: the rapidly growing demand for fresh water in general and water scarcity in rural and remote areas, in particular. An integrated plan based on available water and energy resources will help to meet these challenges.

B. THE NEED FOR WATER DESALINATION

1. *Water scarcity*

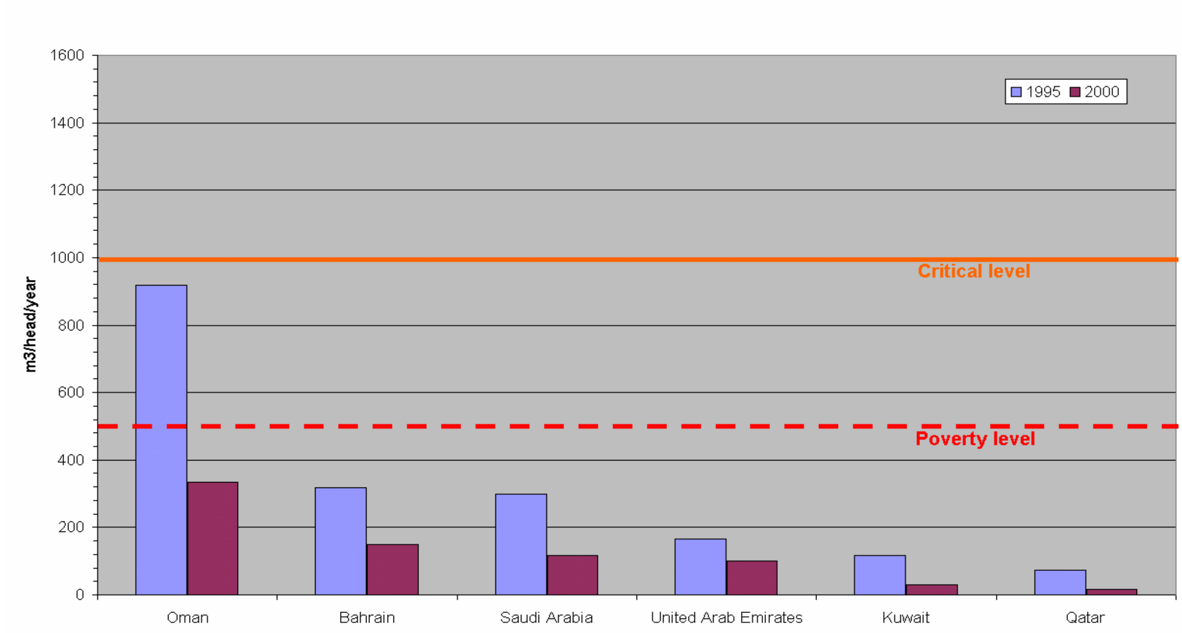
The Arabian Peninsula is devoid of rivers and natural freshwater lakes. Annual rainfall does not exceed an average of 200 mm in any country, with the exception of some areas in the southwest of Saudi Arabia and certain mountainous areas of Oman. Aquifer waters, which are non-renewable and tend to be very limited, can be found at large depths. Over-exploitation of aquifer waters is expected to cause irreversible damage to these crucial freshwater reserves. Renewable surface waters are dependent on sporadic seasonal flash floods, which feed the subsurface basins. However, these are also limited and at risk from human contamination.

Figure I highlights the availability of per capita renewable water resources in these countries from 1995 to 2000. It reveals that all GCC countries are below the poverty level of renewable water resources—500 m^3 per year per capita—and that five of them are as much as 40 to 50 per cent below this benchmark.

Freshwater scarcity has been a serious challenge for GCC countries in the past and will continue to pose a severe problem in the future. Since the 1950s, it has become increasingly apparent to some of these countries, in particular Kuwait, that fresh water supplies from conventional sources would be unable to meet very basic demands, let alone be capable of sustaining national plans for social, economic, industrial, agricultural or urban developments.

It was acknowledged that the only solution to this problem would be the discovery and establishment of reliable non-conventional freshwater resources. Post World War II technological progress in the industrialized countries in addition to scientific efforts and advances, especially by the Office of Saline Water (OSW) in the United States of America, favoured the desalination option as opposed to alternative non-conventional water resources for countries suffering from a lack of freshwater resources, particularly the GCC countries.

Figure I. Renewable water resources available per capita in the GCC countries



Source: Taysir Ali Dabbagh, "The role of desalination and water management in sustaining economic growth in the Gulf", International Desalination Association (IDA), World Congress on Desalination and Water Sciences, (Abu Dhabi, 18-24 November, 1995).

2. *Development of water demand*

The projections for future total freshwater demand shown in table 2 may appear to be some 20 per cent higher than other projections. This is based on the assumption that consumer attitudes will remain the same as attitudes during the oil boom years. The region has a very high standard of living compared to other countries in the developed world and the projected increase in per capita demand may not be justifiable. Nevertheless, the gap between available freshwater resources, including the existing desalination capacities, and the least conservative demand forecasts is growing enormously.

TABLE 2. THE FORECAST FOR WATER DEMAND IN DIFFERENT SECTORS IN THE GCC COUNTRIES
(*Billions of cubic metres*)

Year / Sector	1980	1990	2000	2010	2020	2025
Domestic	0.91	2.58	4.24	5.72	7.42	8.30
Industrial	0.08	0.24	0.44	0.72	1.09	1.31
Agricultural	3.26	15.96	24.54	29.75	36.35	39.78
Total	4.25	18.78	29.22	36.19	44.86	49.38

Source: GCC Secretariat General, "Current status of water resources in the GCC countries and the role of water desalination in securing current and future demands", Directorate of Commerce and Agriculture, (2000) (in Arabic).

(a) *Total demand*

The continuing rapid increase in population, estimated at an annual average rate of some 3 per cent according to the GCC Secretariat General,[4] combined with the need for sustainable comparable levels of

[4] GCC Secretariat General, "Current status of water resources in the GCC countries and the role of water desalination in securing current and future demands", "الوضع الحالي لمصادر المياه في دول مجلس التعاون لدول الخليج العربية وأهمية تحلية المياه المالحة بالنسبة للاحتياجات الحالية والمستقبلية", Directorate of Commerce and Agriculture, (2000) (in Arabic).

development on various economic fronts has had an acute impact on the utilization of freshwater resources in the GCC countries. Freshwater demand climbed from 4.25 billion cubic metres (bm^3) in 1980 to 18.78 bm^3 in 1990, reaching 29.3 bm^3 in 2000. Table 2 shows the estimated leap in demand for freshwater resources for the first quarter of the twenty-first century. These demands have been calculated for the domestic, industrial and agricultural sectors. It is important to bear in mind that consumption patterns within these sectors vary within the GCC.

(b) *Per capita demand*

Table 3 represents the annual sectoral consumption and per capita demand for each of the GCC countries.

TABLE 3. ANNUAL PER CAPITA SECTORAL WATER CONSUMPTION AND PROJECTED DEMANDS FOR THE GCC COUNTRIES
(*Cubic metres*)

	Domestic and industrial			Agricultural			Total demand		
Country	1990	2000	2010	1990	2000	2010	1990	2000	2010
Bahrain	205	237	279	225	199	215	430	436	494
Kuwait	141	308	302	37	64	60	178	372	362
Oman	56	54	76	72	467	417	128	521	493
Qatar	199	258	296	255	341	349	454	599	645
Saudi Arabia	114	140	137	982	978	880	1096	1118	1017
United Arab Emirates	340	340	352	598	573	638	938	913	990
Total	1 055	1 337	1 442	2 169	2 622	2 559	3 224	3 959	4 001

Source: Taysir Ali Dabbagh, "The role of desalination and water management in sustaining economic growth in the Gulf", International Desalination Association (IDA), World Congress on Desalination and Water Sciences, (Abu Dhabi, 18-24 November 1995).

(c) *Sectoral demand*

In 1990, the agricultural sector in Saudi Arabia, United Arab Emirates and Qatar and, in 2000, in Oman, was the major consumer of water. The combined demand for water from domestic and industrial sectors was much less. In the same year, water consumption was divided almost equally between agricultural, domestic and industrial sectors in Bahrain and Oman, with the agricultural sector consuming slightly more water. However, Kuwait was the only country where water consumption in the domestic and industrial sectors combined far outweighed that of the agricultural sector. Both Kuwait and Bahrain have maintained their respective patterns in 2000, despite the fact that demand has shifted even more towards the domestic and industrial sectors. The per capita demand for water from the domestic and industrial sectors in Oman in 2000 appeared to be almost unchanged, while demand from the agricultural sector has increased significantly. However, overall, the agricultural sector is the main consumer of water by approximately 85 per cent. Most of this demand is supplied from ground water through over-exploitation of deep aquifers.

According to table 3, more than 80 per cent of the demand for water from the domestic and industrial sectors in Kuwait, Bahrain, Qatar and United Arab Emirates, was supplied by desalinated water in 2000. In Saudi Arabia and Oman, water production from desalination, supplies some 45 per cent of the demand for these sectors; ground water resources supply the remaining 55 per cent.[5]

[5] Taysir Ali Dabbagh, "The role of desalination and water management in sustaining economic growth in the Gulf", IDA, World Congress on Desalination and Water Sciences, (Abu Dhabi, 18-24 November 1995) and GCC Secretariat General, "Current status of water resources in the GCC countries and the role of water desalination in securing current and future demands", Directorate of Commerce and Agriculture, (2000) (in Arabic).

C. Energy resources, consumption and production

1. *Energy resources and production*

Energy is essential for the development of water desalination projects. The energy requirements for a desalination plant depend on plant design and water salinity, while energy accounts for some 20 to 30 per cent of water production costs. The availability of appropriate energy resources at reasonable prices would facilitate the planning and implementation of water desalination projects. Given that GCC countries have considerable fossil and renewable energy resources, they are in a good position to capitalise on this. However, primary energy consumption in the GCC countries is still dominated by oil and gas, with almost no contribution from renewable resources, even in remote areas.

In view of this situation, this section reviews the energy resources, energy production and consumption features of the GCC countries. It also examines the main facets of electricity generation systems in GCC countries, as the majority of existing desalination plants are linked to electric power plants.

(a) *Oil and gas reserves and production*

Since oil revenues are a major contributor to the gross domestic product (GDP) of most of the GCC countries, the oil and gas industries of those countries make valuable contributions to development programmes and satisfy the energy needs of various sectors, including fresh water production.

According to table 4, the total proven oil reserves of the GCC countries were estimated at 468.2 billion barrels in 1999. This accounted for more than 79.23 per cent of the total reserves in the ESCWA region and 45 per cent of the world's total proven reserves for that year. GCC countries produced an average of 17.75 million barrels per day of crude oil in 1999, accounting for 75.8 per cent of total oil production in the ESCWA region.[6]

Natural gas (NG) reserves totalled 22,675 bm^3 in 1999, representing some 82 per cent of the total NG reserves in the region. The main gas reserves are in Qatar, Saudi Arabia and the United Arab Emirates. NG production in GCC countries, while lower than oil production, is increasing with an average annual growth rate of 4.5 per cent compared to 0.6 per cent growth in oil production. Total gas production reached 167.5 bm^3 in 1999. This accounted for 78.6 per cent of production in the ESCWA region.[7]

Table 4. Oil and natural gas reserves and production in the GCC countries, 1999

Country	Reserves		Production		Total energy products (Kboe/d)[b/]
	Oil (billion barrels)	NG (bm^3)	Crude oil (Kbl/d)[a/]	NG (bm^3 per year)	
Bahrain	0.2	110	176	11.1	392
Kuwait	96.5	1 480	1883	10.9	2 211
Oman	5.4	805	895	10.5	1 113
Qatar	4.5	8 500	633	26.2	1 228
Saudi Arabia	263.5	5 777	7 700	49.8	9 552
United Arab Emirates	98.1	6003	2 060	49.0	3 253
Total GCC	468.2	22 675	13 347	167.5	17 749
Total ESCWA	590.9	27 728	17.750	213.0	23 306
(%) GCC/ESCWA	79.23	81.78	75.79	78.64	76.16

Source: OAPEC, *Annual Statistical Report 2000*.

a/ Thousands of barrels per day.

b/ Thousands of barrels oil equivalent per day.

[6] Organization of Arab Petroleum Exporting Countries (OAPEC), *Annual Statistical Report 2000*.

[7] Ibid.

(b) *Renewable energy resources and production*

Indigenous, clean and non-depletable renewable energy (RE) resources, namely solar, wind, and biomass, are abundant in GCC countries (see table 5).[8]

(i) *Solar resources*

All GCC countries have high quality solar resources with an annual average of global solar radiation varying from 4 to 8 kilowatt hours per square metre (KWh/m^2) per day, however this is very site-specific.[9] They also have high direct normal radiation varying between 1700 to 2800 KWh/m^2 per year. The annual average total cloud cover in the region is often less than 10 per cent in Saudi Arabia and Oman.

TABLE 5. RENEWABLE ENERGY RESOURCES IN THE GCC COUNTRIES

Country	Global solar radiation[a/] (kWh/m^2/day)[e/]	Direct normal solar radiation[b/] (kWh/m^2/day)[f/]	Wind energy[c/] (m/s)[g]	Biomass and fuel wood[d/] (mtoe/year)
Bahrain	6.4	6-7	5-6	0.14
Kuwait	6.2	6-7	5-6.5	0.37
Oman	-	5-7	4-6	0.47
Qatar	5-6	5-6	5-7	0.07
Saudi Arabia	6-8	5-8	4.5-6.5	3.0
United Arab Emirates	5-7	5-7	3.5-4.5	0.33
Yemen	4-6	5-8	4-6.6	3.5

a/ A. Hegazi, "Status of photovoltaic applications and the renewable energy promotion mechanism in the ESCWA region", ICS Expert Group Meeting on Networking of Photovoltaic Systems and Applications, (Cairo, 26-28 April 2000).

b/ Web site of the Department of Energy. www.eia.doe.goc/index.html.

c/ Data compiled from national reports and authorities.

d/ A. Hegazi, "Renewable energy: an option for sustainable development in the Arab states", a paper presented at the Middle East and North Africa International Energy Congress, (Cairo, 16-18 February 1999).

e/ The annual average of the global radiation range on the horizontal surface of different areas.

f/ Estimates of annual average direct normal solar radiation using inputs derived from satellite and/or surface observations of cloud cover, aerosol optical depth, perceptible water vapour, albedo, atmospheric pressure and ozone sampled at a 40 km resolution.

g/ Average annual wind speeds at designated sites. Data compiled from national reports and relevant authorities.

(ii) *Wind resources*

Wind resources are insufficient according to GCC estimates. Therefore, appropriate wind resource assessment is recommended.

(iii) *Biomass resources*

These are related to wood and agriculture residues, animal waste and municipal solid waste. This type of energy has been used in different countries in the past and is used for power generation with modern conversion technologies. However, apart from several biomass resource assessments in GCC countries, an appropriate quantitative or qualitative information base on this subject has not been developed.

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[8] ESCWA, *Regional Approach for Disseminating Renewable Energy Technologies*, Part I, (New York 2001) (E/ESCWA/ENR/2001/10/(Part I)).

[9] Taysir Ali Dabbagh, "The role of desalination and water management in sustaining economic growth in the Gulf", International Desalination Association (IDA), World Congress on Desalination and Water Sciences, (Abu Dhabi, 18-24 November 1995).

2. *Energy consumption trends*

(a) *Primary and per capita energy consumption*

The primary energy consumption in GCC countries is mainly in the form of commercial energy, particularly crude oil, natural gas and hydropower. From 1973 to 1998, this source of energy consumption increased nine fold in GCC countries, with an average growth rate of 10.9 per cent**.** Table 6 shows that in 1999, this consumption reached 149.56 million tonnes of oil equivalent (mtoe), of which 73,963 mtoe was crude oil and 75.6 mtoe was NG. There was a tendency to move towards more NG consumption at 50.6 per cent according to the OAPEC *Annual Statistical Report 2000*. Compared to primary energy consumption in the ESCWA region, GCC consumption is 60.4 per cent of the total region's consumption, while the population constitutes only 17.6 per cent of the region's population. This is emphasized by the average per capita consumption, which reached 5023 kilograms of oil equivalent (kgoe) per year, some 3.4 times the average in the region.

TABLE 6. PRIMARY ENERGY CONSUMPTION IN THE GCC COUNTRIES, 1999
(*Thousands of tonnes of oil equivalent per year*)

Country	Crude oil (ktoe/y)	Natural gas (Ktoe/y)	Total (Ktoe/y)	Per capita (kgoe/y)
Bahrain	993	7 843	8 836	13 286
Kuwait	6 950	7 694	14 644	6 474
Oman	2 135	2 482	4 617	1 865
Qatar	1 092	7 198	8 290	14 804
Saudi Arabia	49 640	37 230	86 870	4 290
United Arab Emirates	13 353	13 155	26 508	9 059
Total GCC	73 963	75 602	149 565	5 023
Total ESCWA	141 120	98 572	247 600	1 483
GCC/ESCWA (percentage)	52.4	76.7	60.4	3.387[a/]

Source: OAPEC, *Annual Statistical Report*, (2000).

a/ The ratio of per capita consumption GCC/ESCWA.

(b) *Installed electric capacity and electricity generation*

The electric power sector in the GCC countries has developed exceptionally during the past two decades. Table 7 shows that the total installed capacity of electric power plants in the GCC countries reached 44,645 megawatts (MW) of thermal generated in 1999, accounting for 74,832 MW or approximately 59.7 per cent of the total installed capacity in the ESCWA region. Figure II illustrates that this type of thermal generation capacity incorporates 17,007 MW and 22,095 MW from steam and gas power plants respectively in addition to 1,749 MW of combined cycle power plants and 1,523 MW of diesel generation technologies in 1999. A further 2,271 MW were imported to the Saudi Arabian grid from desalination plants.[10]

The GCC countries generated 189,261 gigawatts (GWh) of electric energy in the same year. This was distributed as shown in table 7. This figure accounted for 57.7 per cent of electricity generated in all ESCWA member countries. The growth rate of power demand in GCC countries during the past decade averaged 5 per cent.[11]

[10] Ali M. El-Nashar, "The role of desalination in water management in the Gulf region", Abu Dhabi Water and Electricity Authority (Abu Dhabi, 2000).

[11] M. Badawi, "Arab cooperation in the sphere of electricity", التعاون العربي في مجـال الكهربـاء, paper presented at the Sixth Arab Energy Conference, (Damascus, 10-13 May 1998) (in Arabic).

TABLE 7. THE GCC ELECTRIC INSTALLED CAPACITY, GENERATED ELECTRICITY AND THE CAPACITY DISTRIBUTION BY TYPE OF GENERATION, 1999

	Capacity distribution by type of generation						
Country	Steam	Gas	Combined cycle	Diesel	Wind and other	Total installed capacity (MW)	Generated electricity (GW)
Bahrain	100	1 360	—	39	—	1 499	5 800
Kuwait	8 154	219	—	—	—	8 373	31 576
Oman	140	1 412	47	412	—	2 011	8 419
Qatar	60	1 794	—	10	—	1 864	8 505
Saudi Arabia	5 572	12 907	1 410	758	2 271	22 918	105 612
United Arab Emirates	2 981	4 403	292	304	—	7 980	29 349
Total GCC	17 007	22 095	1 749	1 523	2 271	44 645	189 261
Total ESCWA	32 823	25 266	6 268	1 695	2 272	74 832	327 654
GCC (percentage)	51.81	87.45	27.90	89.85	99.96	59.66	57.76

Source: M. Badawi, "Arab cooperation in the sphere of electricity", paper presented at the Sixth Arab Energy Conference, (Damascus, 10-13 May 1998) (in Arabic).

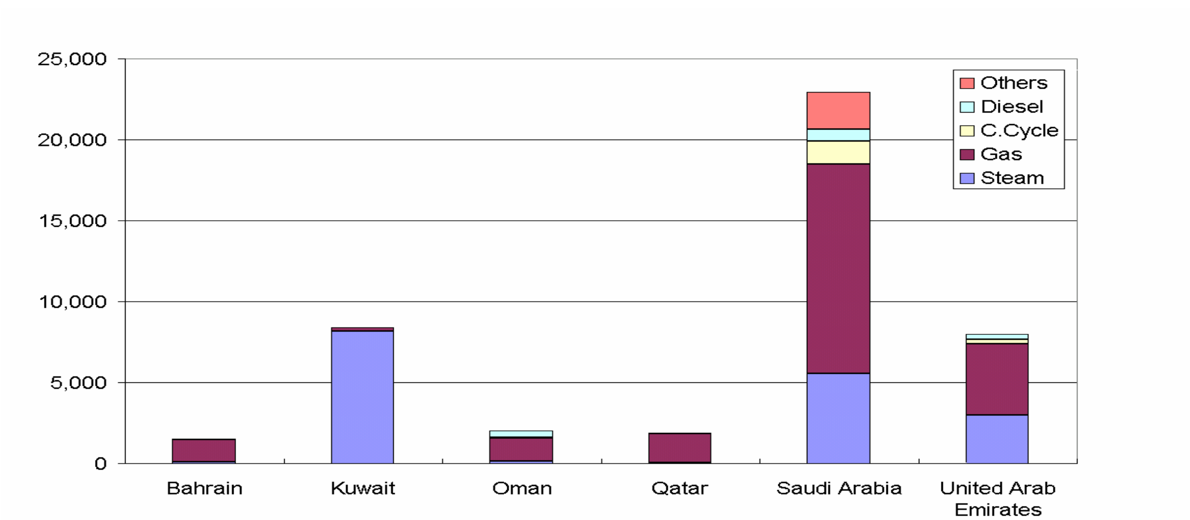
Table 8 shows the estimated development of the electric installed capacities in the GCC countries up to 2015. This is expected to reach 103.654, 127.272 and 148.053 GW in 2005, 2010, and 2015, respectively, to cover requirements for both electric energy and desalinated water.

TABLE 8. DEVELOPMENT AND FORECAST OF INSTALLED ELECTRIC CAPACITY IN THE GCC COUNTRIES, 1995-2015

	Installed capacity (MW)			Forecast of installed capacity (MW)		
Country	1995	1999	Average growth rate (%)	2005	2010	2015
Bahrain	990	1 499	10	1 421	1 696	2 023
Kuwait	6 898	8 373	5	11 725	14 662	15 893
Oman	1 661	2 011	5	2 539	2 959	3 247
Qatar	1 288	1 864	10	2 484	2 784	3 300
Saudi Arabia	19 865	22 918	3.65	34 704	42 643	51 260
United Arab Emirates	6 494	7 980	5.3	5 720	6 663	7 140
Total	39 191	44 645	4.45	103 654	127 272	148 053

Source: M. Badawi, "Arab cooperation in the sphere of electricity", paper presented at the Sixth Arab Energy Conference, (Damascus, 10-13 May 1998) (in Arabic).

Figure II. Distribution of installed electric capacity by type of generation in the GCC countries, 1999



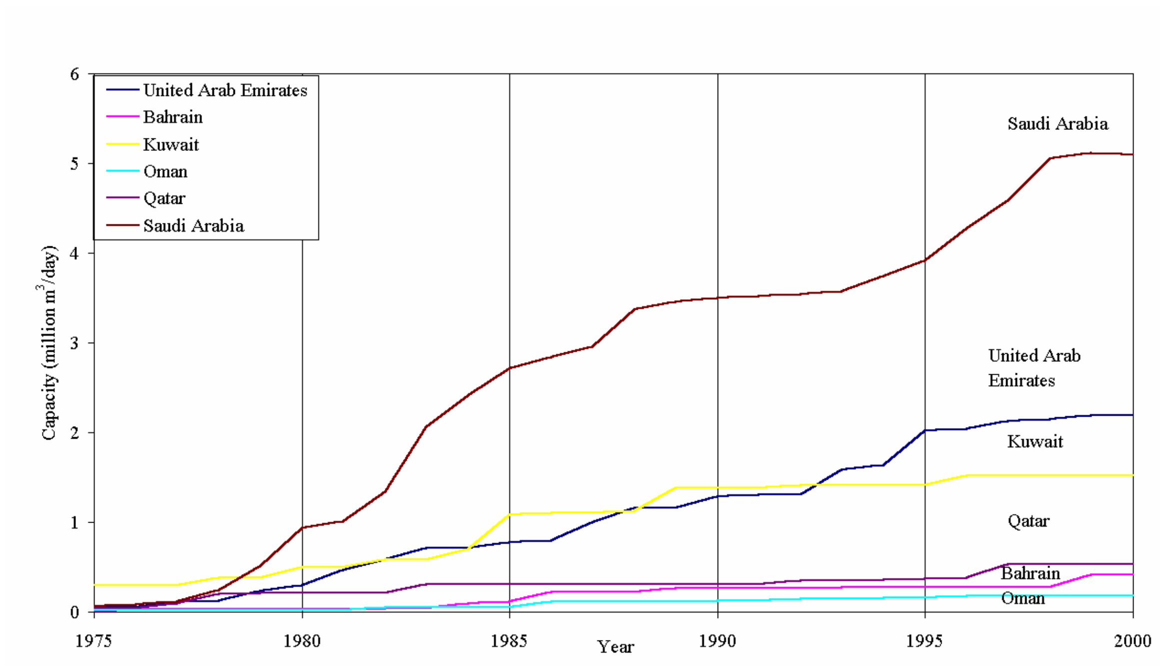
Source: M. Badawi, "Arab cooperation in the sphere of electricity", paper presented at the Sixth Arab Energy Conference, (Damascus, 10-13 May 1998) (in Arabic).

D. Development and distribution of the total installed desalination capacities

During the 1950s, the only countries to adopt seawater desalination were Kuwait and Qatar. They built total capacities of some 10,500 and 1,400 m^3 per day, respectively. Towards the end of the 1960s, Kuwait led all the GCC countries with a desalination capacity of some 116,400 m^3 per day. During the same period, desalination capacities for the United Arab Emirates, Qatar, and Saudi Arabia reached some 27,300, 15,000 and 3,200 m^3 per day, respectively. The 1970s was a dynamic time for the GCC countries. The region's oil boom paralleled momentous technological advances in the industrial world. This period was also characterised by the need for GCC countries to accelerate their infrastructure developments and, in particular, the economically crucial water and power sectors.

GCC countries witnessed unprecedented growth in their water infrastructures from 1975 to 2000. It was during this period that the largest water desalination installations in the world were constructed in the region. This phenomenon is reflected by the growth rate in installed desalination capacities (see figure III). This shows the combined growth rate in the total installed desalination capacities of each of the GCC countries during the 1975-2000 period.[12] It should be noted that although there are various estimates for the total installed capacities in 2000, these figures roughly correspond to some 10,000,000 m^3 per day with a plus/minus difference of some 10 to 15 per cent. Saudi Arabia, United Arab Emirates and Kuwait are the major consumers with approximately 5.11, 2.18 and 1.52 million m^3 per day, respectively. Qatar, Bahrain and Oman follow with 53,137; 416,861 and 186,121 m^3 per day respectively.

Figure III. Growth of overall installed desalination capacities in the GCC countries, 1975-2000



Source: Mahmoud Abdel-Jawad, "Energy sources for coupling with desalination plants in GCC countries", consultancy report prepared for ESCWA, (September 2001).

[12] Mahmoud Abdel-Jawad, "Energy sources for coupling with desalination plants in the GCC countries", consultancy report prepared for ESCWA, (September 2001).

TABLE 9. DESALINATION PRODUCTION TO DOMESTIC AND INDUSTRIAL FRESHWATER DEMAND RATIOS IN THE GCC COUNTRIES
(*Millions of cubic metres*)

Country	1990				2000			
	Installed desalination capacity	Actual desalination production	Domestic and industrial demands	Desalination to demand ratio (%)	Installed desalination capacity	Actual desalination production	Domestic and industrial demands	Desalination to demand ratio (%)
Bahrain	75	56	103	54	140	112	155	72
Kuwait	418	202	303	67	470	358	530	68
Oman	55	32	86	38	68	54	147	37
Qatar	112	83	85	98	216	172	140	100
Saudi Arabia	950	795	1 700	47	1 289	1 031	2 900	36
United Arab Emirates	502	342	540	63	772	617	832	74
Total	2 112	1 510	2 817	53.6	2 955	2 344	4 704	49.83

Source: Klaus Wangnick, *1998 IDA Worldwide Desalting Plants Inventory*, Report No. 15, Wangnick Consulting GMBH, (Germany 1998).

Table 9 shows the installed desalination capacities of the domestic and industrial sectors, in addition to actual fresh water production for 1990 and 2000. The table shows that the percentage contribution of desalination in satisfying the industrial and domestic demand in 2000 in the GCC countries was slightly less than in 1999. The situation varies greatly between countries.

However, most of the 6.5 bm^3 of freshwater projected for domestic and industrial use and a large portion of the present forecast of 30 bm^3 of freshwater for the agricultural sector for 2010 will have to be supplied by seawater in addition to groundwater desalination. When the abstraction of water from deep aquifers exceeds certain limits, water level and quality eventually declines. The water quality of some major aquifers in the Gulf region is not only inadequate, it is unsuitable for agricultural use without substantial treatment. The cost of such water treatments, combined with the increased cost of pumping groundwater from rapidly declining water supplies, could raise the total cost of groundwater to the cost of seawater desalination.

The major desalination plants in the Arabian Peninsula are shown in figure IV. More detailed information on plants installed since 1975 are reviewed in chapter IV.

Figure IV. Geographical distribution of desalination plants in the GCC countries

Source: Mahmoud Abdel-Jawad, "Energy sources for coupling with desalination plants in GCC countries", consultancy report prepared for ESCWA, (September 2001).

II. DESALINATION PROCESSES, CLASSIFICATION AND RELEVANT ENERGY ISSUES

Desalination is the process by which fresh water is extracted from saline water, for example, seawater, brackish water, or waste water. The evolution of the desalination industry over the past century has resulted in a variety of techniques for desalinating different categories of water for a number of uses. Commercially available desalination techniques are categorized either as distillation- or membrane-based technologies.

Preference of one desalination process over others is dependent on a number of factors. These include feed water characteristics, desired product water quality, energy availability, unit/plant capacity, brine disposal and economic factors. The most important factor is energy, since all water desalination processes are energy intensive and the energy costs represent some 20 to 30 per cent of the total production cost of desalinated water.

This chapter reviews the desalination processes, classification, energy requirements and the factors affecting the selection of desalination process for a specific application, with emphasis on energy issues. Furthermore, the chapter presents an analysis of energy consumption and performance of various processes.

A. CLASSIFICATION AND CHARACTERISTICS

Commercially available desalination processes are classified either as distillation- or membrane-based processes. Each of these processes utilizes a number of technologies for various application conditions. A common characteristic of all types of water desalination processes is that they are energy-intensive and involve complex systems. Furthermore, they differ in their capacities and performance rates. However, a complete water desalination plant based on any of these processes includes:

(a) Saline water intake and outlet systems;
(b) Saline water feed pre-treatment systems;
(c) Desalination units in which separation of pure water from saline water is processed;
(d) Energy supply systems;
(e) Auxiliary components required for proper operation and maintenance of the plant;
(f) Product water post-treatment storage and distribution systems.

This section examines the general classification, main characteristics and energy resource requirements of various desalination processes.

1. *Distillation-based processes*

The distillation process transforms water into vapour then condenses it back into a liquid state. This process separates water and salt and involves phase changes, namely, liquid into vapour into liquid. It requires a transfer of energy from an outside source or an internal exchange of thermal energy between process media. A distillation-based process, therefore, requires both thermal and electrical energy.

Three major distillation processes are in commercial use, namely, multistage flash evaporation (MSE), multi-effect distillation (MED) and vapour compression (VC).

Given that distillation-based processes have a relatively high energy consumption level that is largely unaffected by salt concentration, these methods are usually more economically viable for high salt-content waters, namely, seawater and concentrated brine, classified as above 35,000 parts per million (ppm) of total dissolved solids (TDS). Distillation-based processes produce the most pure water, ranging from some 5 to 50 ppm of TDS.

2. *Membrane-based processes*

There are no phase changes in the membrane-based process, which consumes only electric energy. This process can largely be, classified as reverse osmosis (RO) or electrodialysis (ED).

RO systems use semi-permeable membranes to rid water of dissolved salts by applying pressure to the feed water that is greater than its osmotic pressure. This produces fresh water through the membrane. In ED systems, a direct electric current is applied to the membrane stack in order to induce ions to migrate through the membranes from the main feed water stream. The product is fresh water and brine.

The energy consumption in membrane-based processes is proportional to the concentration of dissolved salts in the feed waters. This is particularly relevant to the ED process because, as the number of dissolved ions increase, electrical energy consumption increases, forcing the membrane area to increase proportionally. This renders the technology highly uneconomical. The ED process is, therefore, considered most suitable for lower salt-content brackish waters with saline levels less than 5,000 ppm.

RO is the most tolerant desalination process in terms of salt concentration in feed waters. It produces fresh water from feed waters with salt contents ranging from 100 to 10,000 ppm and above. This process copes with salt contents up to 10,000 ppm for brackish water and up to 50,000 ppm for seawater.

The product water from a single stage RO desalination system ranges between approximately 100 and 1000 ppm of TDS, depending on the feed water, type of RO membrane and its salt rejection characteristics. The product water from ED processes is generally within the range of 350 to 500 ppm of TDS.

Table 10 summarizes the main characteristics of these processes and compares the experiences of the GCC countries.

B. FACTORS AFFECTING THE SELECTION OF DESALINATION PROCESSES

Several factors determine the selection of a desalination process or processes. These include:

(a) Feed water characteristics in terms of salt concentration and composition, dependability related to quality and quantity and seasonal temperature distribution;

(b) Required product water quality and recovery ratio as a fraction of the feed;

(c) Availability of dependable energy supply, specific energy consumption rates and efficiency of energy utilization;

(d) Available unit/plant capacities;

(e) Brine disposal;

(f) Relative costs involved.

This section highlights energy-related factors. Annex I contains a more detailed discussion of the factors affecting the selection of desalination technology, with the exception of those related to energy consumption and processes performance. These are reviewed in section C of this chapter.

1. *Feed water characteristics*

Three types of saline water are suitable for desalination applications, namely, seawater, brackish water and waste water. These feed waters are very different, which is a significant factor when determining the suitability of various commercially available desalination processes.

The main characteristics that affect the suitability of a desalination system include: concentration of dissolved salts in feed water; feed water temperature; composition of dissolved salts in feed water and dependability of feed water sources.

TABLE 10. SUMMARY OF THE MAIN CHARACTERISTICS OF THE VARIOUS DESALINATION PROCESSES

Parameter \ Process	Distillation-based processes			Membrane-based processes	
	MSF	MED	VC	RO	ED
Operating temperature range (^oC)	90-120	<80	60-105 (MVC) < 80 (TVC)	15-40	15-40
Operating pressures range (Mpa)	Sub-atmospheric	Sub-atmospheric	Atmospheric and sub-atmospheric	2-8	Atmospheric
Sensitivity to feed water quality	Low	Low-medium	Low-medium	High	Medium-high
Pre-treatment requirements	Minimum	Minimum	Minimum	Extensive (Site dependent)	Minimum (Brackish water only)
Feed water salinity range	Seawater	Seawater	Seawater	Brackish and seawater	Brackish water only
Product water quality (ppm)	Very high	Very high	Very high	100-500	250-500
Product water recovery ratio (percentage)	10-15	10-25	40-55	25-50	-
Turnkey capital investment costs	Moderate	Low-moderate (lower than MSF)	Low-moderate (higher than MED)	Low-moderate	Low
Energy requirement: Heat (MJ/m^3) Electrical (kWh/m^3) Total electric equivalent (kWh/m^3)	 250-300 3.5-5 15-25	 150-220 1.5-2.5 8-20	 TVC 220-240 1.5-2 MVC 11-12	 None 5-9 –	 None –
Scaling/fouling and corrosion potential	Low-moderate	Moderate-high	Moderate-high	Low-moderate	Low
Spare parts replacement rate	Moderate (Large pumps)	Low (Small pumps)	Moderate (Vapour compressor)	High (high pressure pumps and membranes)	Low (Membranes)
High technology components	Large pumps, instruments and control	Instruments and control	Compressor, instruments and control	High pressure pumps, membrane, instruments and control	Membranes
Maintenance requirements	Low-medium	Low	Low-medium	High	Medium
Operators' skills requirements	Highest	High	High	Medium	Medium
Potential for further process developments	Low	Medium	High	Medium	Low
Market potential for the next 10-15 years	Moderate	High	High	High	Low-moderate

Source: Mahmoud Abdel-Jawad. "Energy sources for coupling with desalination plants in the GCC countries", consultancy report prepared for ESCWA, (September 2001).

(a) *Concentration of dissolved salts in feed water*

Various commercial desalination processes are capable of producing fresh water from feed waters with total dissolved salts ranging from hundreds of ppm, for example waste water at less than 1000 ppm, to tens of thousands of ppm, as is the case with seawater at more than 35,000 ppm. Distillation-based processes are mostly used for high salt-content waters. However, membrane-based technologies are salt tolerant and operate with different levels of salt concentration.

In summary, the most favourable salt-contents in feed waters for practical application of the various desalination processes are approximately as follows:

Distillation-based processes:	more than 35,000 ppm
Membrane-based processes:	
ED:	500 to 5,000 ppm
Brackish RO:	500 to 10,000 ppm
Seawater RO:	10,000 to 50,000 ppm

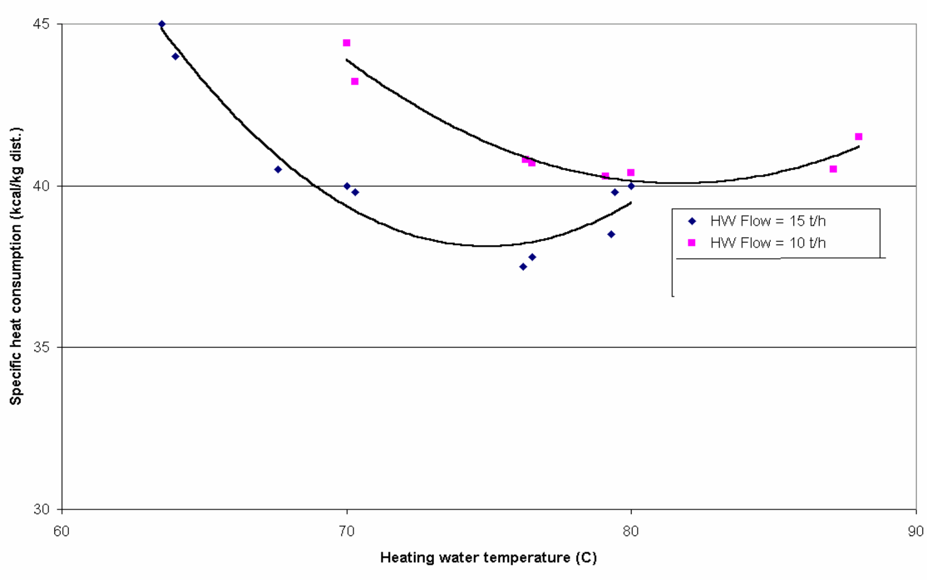
(b) *Feed water temperature*

Seawater temperatures in the GCC countries varies between 15°C in the winter and 35°C in the summer. Ground water is more stable, remaining at approximately 5°C throughout the year. The effects of feed water temperature on the different desalination process are as follows:

(i) *Distillation-based desalination processes*

Owing to its impact on the number of stages or effects, operating temperature and pressure ranges, brine concentration and mass flow to distillate ratios, performance factors and so on, the influence of feed water temperature on the optimisation of each specific process is quite complex. Generally, lower feed water temperatures are beneficial to MSF and MED desalination processes, while higher feed water temperatures are better for the VC process. The effect of heating water temperature on the energy consumption of a solar-operated MED desalination plant is illustrated in figure V.

Figure V. Effect of heating water temperature on the specific heat consumption



Source: Ali M. El-Nashar, "A Solar Assisted Sea Water Multiple Effect Distillation Plant – Ten Years of Operating Performance", paper presented at World Congress on Desalination and Water Sciences, International Desalination Association (IDA), Abu Dhabi Proceedings, 1995.

(ii) *Membrane-based processes*

Feed water of a higher temperature is usually required for this method. In the ED process, electrical conductivity and salt diffusion increase with temperature, resulting in a positive decrease in electric energy consumption. However, since ED technology is practically limited to brackish ground waters, it is more likely to be applied to feed waters with moderate temperatures.

In the RO process, membrane flux increases as feed water temperature rises. Recent RO industry improvements have increased the upper operating temperature limit to approximately 45°C leading to the possibility of hybridisation between seawater RO and MSF desalination. Integration of these processes will result in almost constant feed water temperatures for RO desalination systems throughout the year.

2. *Product water quality and recovery*

Product water quality and rate of recovery determine the selection of a desalination process for a given application. Product waters from various desalination processes range from a few to several hundred ppm of TDS. They also extend from 10 per cent to more than 50 per cent of the total feed water flow rate (see annex 1).

(a) *Product water quality*

Distillation-based processes produce the most pure product waters at approximately 5 to 50 ppm of TDS. It is possible, therefore, to blend these products with other types of water in order to adjust TDS to suitable levels. The product water from a single-stage RO desalination system ranges between approximately 100 and 1000 ppm of TDS, depending on the feed water, the type of RO membrane and its salt rejection characteristics. This varies according to the lifespan of the membrane. Brackish water feeds produce water with lower saline levels than seawater feeds. Product water from the ED processes is generally within the range of 350 to 500 ppm of TDS. The limits on product water with lower saline levels produced by ED are determined by economic constraints, which are dictated by the increase in electrical resistance as the concentration of ions decreases. Hence the increase in electrical energy consumption and the need for more stages for the additional removal of ions.

(b) *Product water recovery*

The amount of product water recovered from a certain feed water flow rate using a given desalination technology is known as product water recovery ratio. It is usually measured as a percentage ranging from about 10 per cent to more than 50 per cent depending on the type of desalination technology. This ratio is of some economic significance owing to the impact it has on the size of the feed water intake required for specific production capacity and the associated energy consumption. Generally, the MSF desalination process is found at the lower end of the above range, while brackish water RO, including waste water desalination applications, are at the high end of the range. Typical product water recovery ratios of the different processes are given in the relevant tables provided in the next section.

3. *Desalination unit capacity*

Selection of the correct unit capacity for the most suitable desalination process for a particular application is usually made according to the following criteria: maximum plant availability; minimum stand-by capacity; minimum per unit product water costs and maintaining reasonable operating and maintenance flexibility.

The scale of the capacities of a unit could significantly influence the cost of desalination and therefore the selection of certain processes. On the one hand, when the scale of the capacities of a MSF desalination unit reaches massive levels—approaching 60,000 m^3/d—it is possible to use this method extensively with used in seawater applications. On the other hand, when MED desalination unit capacities remain well below half of this capacity, implementation is limited.

4. *Relative costs of desalination processes*

Detailed economic assessment of the dominant desalination technologies in the GCC countries is reviewed in chapter IV. This subsection illustrates, in general terms, the relative importance of the major cost components of various desalination technologies, with particular reference to seawater desalination.

The selection of a suitable desalination process must include an appraisal of the potential capital investments in addition to the running costs associated with the continuous operation requirements in the forms of energy, chemicals, repairs and replacements and labour.

The cost components that affect the overall cost of water production in a certain process can be divided into groups that include: capital investment, energy related costs, membrane replacement costs and other remaining costs. Tables 11 and 12 review relative cost data based on averaged values. This information is a set of indicators, rather than finite and specific representations of actual cost data for the respective processes. Other studies have shown that an overall average cost breakdown of desalination plants in the GCC countries to be 38 per cent for capital investment 20.5 per cent for energy; 21.3 per cent for labour, 16.2 per cent for operations and maintenance and 4 per cent for chemicals.[13]

TABLE 11. RELATIVE CONTRIBUTION OF DIFFERENT COST COMPONENTS TOWARDS OVERALL PRODUCT COST FOR VARIOUS DESALINATION PROCESSES
(*Percentage*)

Cost component	MSF	MED	MVC	TVC	RO
Capital investment	44	47	49	46	41
Energy related costs	36	31	26	32	24
Membrane replacement	—	—	—	—	13
Other remaining costs	20	22	25	22	22
Overall product cost	100	100	100	100	100

Source: Mahmoud Abdel-Jawad. "Energy sources for coupling with desalination plants in the GCC countries", consultancy report prepared for ESCWA, (September 2001).

Note: All data are based on average cost data for large-scale seawater desalination applications.

TABLE. 12. RELATIVE VALUES OF DIFFERENT COST COMPONENTS AND OVERALL PRODUCT COST FOR VARIOUS DESALINATION PROCESSES WITH REFERENCE TO RO DESALINATION PROCESS
(*Percentage*)

Cost Component	MSF	MED	MVC	TVC	RO
Capital investment	120	114	118	115	100
Energy related costs	215	175	140	185	100
Membrane replacement	—	—	—	—	100
Other remaining costs	103	89	100	89	100
Overall product cost	114	109	107	111	100

Source: Mahmoud Abdel-Jawad. "Energy sources for coupling with desalination plants in the GCC countries", consultancy report prepared for ESCWA, 2001.

Note: All data are based on average cost data for large-scale seawater desalination applications.

C. ENERGY CONSUMPTION AND PROCESS PERFORMANCE

The minimum energy consumption required for separating a saline solution into pure water and concentrated brine under ideal conditions is dependent only on the salt content of the saline solution, regardless of the technology and configuration of the desalination system in question. In other words, all

[13] Ali M. El-Nashar, "The Role of Desalination in water management in the Gulf Region". Abu Dhabi Water and Electricity Authority, 2000 (Abu Dhabi 2000).

desalination systems, which may be based on different technologies and may have different configurations, share a common minimum energy requirement for driving the separation process, regardless of the system. In practice, however, the energy requirements in all desalination process are considerably higher than those computed for the reversible ideal separation. This is because a certain process irreversibility occurs due to friction losses, non-equilibrium and other thermal losses, including boiling point elevation, flow resistance through membranes and pump efficiencies. Hence, the deviation of the actual energy required in any given desalination system depends on the system's design and engineering characteristics and its principle of operation in the quantity and type of losses encountered during separation. The energy requirement and performance for each of the above desalination processes are reviewed separately below.

1. *Energy consumption and performance of the MSF process*

Two types of energy are required for the operation of a MSF desalination plant. The first is low-temperature heat, which represents the main portion of energy input to the MSF and is usually fed into the system through the heat input section. The second is electricity, which is used to drive the system's pumps. MSF desalination plants in the GCC countries are usually an integral part of dual-purpose power/water production systems. The technical reasons for this integration between power and MSF will be reviewed below. However, low-temperature heat is usually supplied to a MSF desalination system through imported steam from the power generation plant. This steam may be extracted from the steam turbine or from the boiler after entering a pressure-reducing station. Whether the steam is extracted from a turbine or from a boiler/pressure-reducing station, it usually goes through processes of expansion and desuperheating for conditioning prior to its entry to the MSF heat input section.

The efficiency of the utilization of low-temperature heat consumption in an MSF plant, which is an indicator of the process performance, depends on the following:

(a) The maximum temperature of the heat source. The threshold of sulphate-based scale formation in the brine solution and the performance characteristics of the soft scale inhibitor determine the upper limit on this temperature. The maximum temperature reached by the brine solution is usually known as top brine temperature (TBT);

(b) The temperature of the heat sink at which excess heat is rejected from the system. The limit on this temperature is determined by the year-round maximum seawater temperature;

(c) The number of stages of the system. In this case, the capital cost is the main limiting factor on the final number of stages;

(d) Salt concentration in the flashing brine solution;

(e) Geometrical configuration of the flashing stages, which have a direct influence on non-equilibrium losses, pressure drop losses and heat dissipation losses;

(f) Construction material and design configuration of the heat exchanger device inside the stages and the heat input section, which have direct influence on heat transfer losses and efficiency.

The efficiency of low-temperature heat is usually measured by:

(a) The ratio between the amounts of water produced per unit mass of dry saturated steam supplied to the system. This is known as the gain output ratio (GOR);

(b) The amount of product water in kilograms (kg) per one million Joules of low-temperature heat supplied to the system. This is known as the performance ratio (PR).

Typical GOR values for large-scale commercial MSF plants range between 8 and 10 kg/kg with PR between 3.5 and 4.5 kg/MJ. The GOR value of 8 is a very common figure for MSF plants in the GCC countries operating at TBT of approximately 91°C. As the TBT is increased to some 110°C for the same plant, GOR value reaches 8.6. Table 13 shows typical heat input values and their useful electrical equivalent, and performance indicators at two different operating temperatures for a typical MSF plant.

Table 13 indicates that whilst the heat input at GOR of 8.6 is less than that at GOR of 8 by some 9.2 per cent, the useful electrical equivalent is higher at the higher GOR by some 9.1 per cent compared to that at the lower GOR. This is because at the higher GOR, heat is supplied at higher temperature and thus has higher-grade energy. A direct comparison between thermally driven desalination systems on the basis of GOR or heat input values is often deceptive if the thermodynamic state of the heating steam is not taken into consideration.

In addition to the low-temperature heat, electricity is essential for the operation of MSF desalination plants. Pumps are the main consumers of electricity in typical MSF plants. These include the brine recycle, brine blow down, distillate and condensate pumps, in addition to feed water transfer pumps, main intake pumps and other auxiliary pumps for chemical dosing. Thus, specific electricity consumption is very much dependent on plant configuration and site characteristics, which are expected to vary from one plant to another. However, in the GCC region, values of specific electrical energy consumption range between 3.5 to 5.0 kWh/m^3 of product water (see table 10). As the plant/unit capacities increase, the specific electrical energy consumption is more likely to be at the lower end of the above range, and the reverse is also true.

TABLE 13. THERMAL ENERGY REQUIREMENTS AND GOR VALUES FOR A TYPICAL MSF DESALINATION PLANT OPERATING AT DIFFERENT TBT

TBT (°C) / Parameter/quantity	90.6[a/]	110[b/]
Number of stages	24	24
Cooling seawater temperature (°C)	32.3	32.3
Heating steam temperature (°C) and pressure at turbine extraction point	111 and 0.15	127°C and 0.25 Mpa
Heating steam temperature and pressure in the heat input section (Mpa)	100 and 0.1	120 and 0.2
Flashing temperature range (°C)	50.1	68.8
Average temperature difference between stages (°C)	2.1	2.9
GOR (kg/kg)	8	8.6
Product water recovery ratio (percentage)	10.51	13.44
Heat input/m^3 of distillate (MJ)	282	256
Useful electrical equivalent per m^3 of distillate (kWh)	16.72	15.32
Specific electrical energy input per m^3 of distillate	4.2	3.68

Source: Mahmoud Abdel-Jawad. "Energy sources for coupling with desalination plants in the GCC countries", consultancy report prepared for ESCWA, (September 2001).

a/ Based on a 27,300 m^3 per day plant capacity.
b/ Based on a 32,700 m^3 per day plant capacity.

2. *Energy consumption and performance of the MED process*

MED is similar to MSF in that it requires two types of energy, namely, low-temperature heat and electricity. The low-temperature heat is the main portion of the total energy input to the system regardless of whether it is supplied by the extracted steam from a power plant, waste heat recovery boiler, or fuel-fired boiler.

Ideally, the latent heat of a unit mass of the condensing saturated steam in the first stage, or the condensing vapour in the subsequent stages, is transferred to the seawater/brine solution generating an equivalent unit mass of vapour. In other words, 1 kg of product water may be generated in each stage for each 1 kg of heating steam supplied to the system. In practice, however, the situation is different. The temperature difference between the condensing vapour and the liquid solution subject to evaporation, in addition to the boiling point elevation, heat transfer losses and pressure drop losses, indicates that the fractional departure from the whole increases as the number of stages increases and as the temperature of the stage moves further from that of the first stage downward on the temperature scale.

Specific thermal energy consumption and, therefore, the process performance of the MED are measured by GOR as the amount of product distillate per unit mass of dry saturated heating steam. As for the MSF, the GOR value should equal the number of stages, which primarily depend on the available temperature difference between the heat source and the sink. However, in real practice, GOR is usually less than the number of stages, depending on the unavoidable losses described above being kept to a minimum in the practical design. The heat source temperature and therefore the maximum operating temperature in MED systems are usually less than their equivalent in the MSF systems. This is because thin film evaporation of the brine in the MED process occurs directly on the heating surface without any on-line cleaning mechanism, unlike the MSF process, in which flashing and evaporation occur in the brine pool at some distance from the heat transfer surface and on-line mechanical cleaning using sponge balls is used to maintain scale-free surfaces. There is a much greater chance of scale formations in the MED system than the MSF. It follows that top-operating MED temperatures are usually kept below the 80°C mark. This imposes severe limitations on the application of MED technology in seawater desalination, and is considered to be the main reason for its slow growth in the installed capacity compared to the growth rate in the MSF installed capacities. However, the latest advances in pre-treatment of seawater using nanofiltration (NF) membrane technology, where scale potential is significantly reduced by the removal of scale–forming ions from the feed water, could greatly influence the future application of the MED technology.

During the design of MED systems, reasonable balance between the performance and cost of the system must be maintained. For a given operating temperature range across the system, namely, the temperature difference between the heat source and the heat sink and maximum brine condensation limits, the designer manipulates the number of effects, temperature difference between effects, heat transfer area and flow rates, in order to maximize GOR and minimize the cost of the system cost. Maximizing GOR for a given heat source temperature means minimizing thermal energy consumption.

Table 14 shows typical heat input values and useful electrical equivalent at two GOR values for two MED systems.

As can be seen from tables 13 and 14, specific thermal energy consumption and the useful electrical equivalent of MED are less than those of MSF of similar GOR. However, as the number of stages in the MED is increased and hence in the GOR, the specific thermal energy consumption and the useful electrical equivalent are almost proportionally increased. A direct comparison between GOR of different systems without specific reference to the thermodynamic states of the heating steam could be seriously misleading.

TABLE 14. THERMAL ENERGY REQUIREMENTS AND GOR VALUES FOR A TYPICAL MED PLANT OPERATING AT DIFFERENT TBT

TBT (°C) / Parameter/quantity	66[a/]	72[b/]
Number of effects	12	16
Cooling Seawater temperature (°C)	32.3	32.3
Heating steam temperature (°C) and pressure at Turbine extraction point (Mpa)	106.5 and 0.127	110 and 0.14
Heating steam temperature (°C) and pressure in the heat input section (Mpa)	71 and 0.033	77 and 0.042
Operating temperature range across the system	27.6	33.6
Average temperature difference between effects (°C)	2.3	2.1
Product water recovery ratio (percentage)	14.4	12
Gain output ratio kg/kg	8.5	12.2
Heat input/m^3 of distillate (MJ)	263.5	189.9
Useful electrical equivalent per m^3 of distillate (kWh)	13.65	9.73
Specific electrical energy input per m^3 of distillate	1.8	2.3

Source: Mahmoud Abdel-Jawad, "Energy for coupling with desalination plants in the GCC countries", consultancy report prepared for ESCWA, (September 2001).

a/ Based on a 10,000 m^3/d plant capacity.

b/ Computed.

In addition to the low temperature heat input, an electric energy input is required to drive all the pumps in the system. The number and capacities of pumps in the MED systems may vary according to the system's configuration, as several configurations are used. These include forward, backward and parallel feed. It would be reasonable to expect electrical energy consumption to vary with the system's configuration. However, consumption of electricity in MED is in the range of 2 to 2.5 kWh/m^3 of distilled water, which is some 50 per cent less than that of MSF.

3. *Energy consumption and performance of the vapour compression process*

The VC desalination process is a modified form of the MED process where heat is internally supplied within the system using the principle of heat pumping. As saturated vapour is adiabatically compressed from a given thermodynamic state, using for example a mechanical compressor, its temperature rises as a result of the change in its pressure. Assuming that the compression process is reversible, the mechanical work exerted on the vapour during the compression should be equivalent to the rise in the vapour enthalpy. Therefore, this process of VC is equivalent to heat pumping. In practice, the losses involved during compression, other than heat dissipation to the surroundings, contribute to the enthalpy rise of the compressed vapour.

VC systems are either mechanically or thermally driven, namely MVC or TVC. MVC systems are directly driven by diesel engines or gas turbines, or indirectly by electricity. In the latter case, electricity alone is considered the prime source of energy, as it offers maximum flexibility owing to the independence of its power source. Electricity is used to drive the compressor in addition to the system's pumps. Generally—as a result of technical and economic considerations—older MVC systems operate at a relatively high temperature and at pressures near atmospheric conditions. This is to avoid an excessively large volume of vapour compressors and hence large-diameter rotors. However, high temperatures imply higher potential for scale formations. Therefore, the limits of the top operating temperature and of the lowest operating pressure indicate that MVC has an effectively narrow range of operation.

This situation has resulted in restricting the number of effects in MVC to three or less, therefore restricting the unit capacity to less than 6000 m^3 per day. However, advances in the design of mechanical vapour compressors have permitted and encouraged shifting the design and operation of the more modern MVC systems to incorporate lower temperatures and, hence, lower pressures. The advantages of the lower temperature systems, particularly with regard to lower sensitivity to scaling, fouling and corrosion and the improved heat transfer coefficients, has resulted in lower temperature differentials. This means that vapour compressors must pump against correspondingly lower heads, thus offsetting the effects of larger specific volumes at the lower vapour pressures. Efficiency of electricity utilization in MVC systems is measured directly by the electric consumption per unit mass of product distillate, namely, kWh/m^3.

However, TVC desalination technology utilizes the MED process with a steam-jet compressor as the heat pump. Steam-jet compressors use motive steam at pressures ranging between 0.3 to 1 Mpa. Steam at these pressures holds relatively high-grade energy, which implies high-cost energy. Such high-cost energy can only be justified by utilizing a relatively large number of stages and hence, relatively large unit capacities similar to those of the MED. Technically, performance evaluation, or efficiency of energy utilization in TVC systems can be expressed in a manner similar to that of the MED. Therefore, the concept of GOR can be used for TVC desalination systems while taking into consideration the thermodynamic state of the motive steam.

Tables 15a and 15b show specific energy consumption data for both MVC and TVC typical plants.

TABLE 15a. SPECIFIC ELECTRICAL ENERGY CONSUMPTION DATA FOR TYPICAL MVC PLANTS

Number of effects	1[a/]	2[b/]	3[c/]
Maximum TBT (° C)	74	74	74
Change of temperature per effect (° C)	2.5	2.3	2.1
Product water recovery ratio (percentage)	41.67	41.67	48.08
Total specific electrical energy consumption (kWh/m^3)	12.0	11.5	11.0

Source: Mahmoud Abdel-Jawad, "Energy sources for coupling with desalination plants in the GCC countries", consultancy report prepared for ESCWA, (September 2001).

a/ Based on a 700 m^3 per day unit capacity.
b/ Based on a 1,500 m^3 per day unit capacity.
c/ Based on a 3,000 m^3 per day unit capacity.

TABLE 15b. ENERGY REQUIREMENTS AND GOR VALUES FOR TYPICAL TVC PLANTS OPERATING AT DIFFERENT TBT

TBT (°C) / Parameter/quantity	63[a/]	70[b/]
Number of effects	16	16
Feed Seawater temperature (°C)	23.3	23.3
Motive steam temperature (°C) and pressure (Mpa)	135 and 0.313	135 and 0.313
Operating temperature range across the system (°C)	33.6	40.6
Average temperature difference between effects (°C)	2.1	2.5
Product water recovery ratio (percentage)	20.83	20.83
Gain Output Ratio kg/kg	12	12
Heat input/m^3 of distillate (MJ)	227.3	227.3
Useful electrical equivalent/m^3 of distillate (kWh)	14.56	14.56
Specific electrical energy input per m^3 of distillate	1.8	1.6

Source: Mahmoud Abdel-Jawad, "Energy sources for coupling with desalination plants in the GCC countries", consultancy report prepared for ESCWA, (September 2001).

a/ Based on a 6,000 m^3 per day plant capacity.
b/ Based on a 10,000 m^3 per day plant capacity.

4. *Energy consumption and performance of the RO process*

The RO desalination process allows saline solutions at above-atmospheric pressure to flow through a membrane of suitable porosity. This yields a permeated solution at atmospheric pressure that is enriched in pure water and leaves a concentrated solution on the high-pressure side of the membrane. According to basic thermodynamic principles, under isothermal conditions, RO requires that the preferential transport of water through the membrane always be proportional to the net applied pressure in excess of the differential osmotic pressure across the membrane. Pressurization of the saline solutions is usually accomplished using pumping devices, which are driven either directly by diesel engines, steam or gas turbines, or indirectly by electricity using electric motors. Only electrically driven pumping systems are considered in this study.

Energy consumption of RO pumping devices depends on the net pressure rise across the pump, flow rate of the saline solution and efficiency of the pumping device. The required pressure rise across the pump depends on the salt concentration and composition of the saline solution, quality of product water, product water recovery rate and membrane resistance, which is temperature-dependent. Owing to manufacturing and economic limitations, multiple RO membranes are usually packed in series inside the pressure vessels, which are stacked and connected in parallel configurations forming RO trains. This means that salt concentration and composition in the feed water in addition to the effective operating pressure experienced by each RO membrane element changes from one membrane to the next inside each pressure vessel. Hence, the product water recovery rate and salt rejection vary. Therefore, the final product water recovery rate, salt rejection and specific energy consumption are measured as average values specific to the plant configuration. In some cases where a substantial portion of the feed solution is rejected as concentrated brine at high pressures, it is possible to include an energy recovery device to convert the hydraulic energy in the rejected solution into useful energy. Inclusion of energy recovery systems helps to reduce the overall energy consumption of RO desalination systems.

It follows that specific energy consumption in RO desalination systems is highly dependent on feed water characteristics, plant design and operating conditions. Nevertheless, Table 16 lists some relevant data on typical RO desalination plants for brackish and Gulf seawater feeds, where energy utilization is measured directly by specific electricity consumption in kWh/m^3 of product water.

TABLE 16. MEMBRANE AREA REQUIREMENTS AND SPECIFIC ENERGY CONSUMPTION FOR TYPICAL RO DESALINATION PLANTS USING SPIRAL WOUND MEMBRANE TYPE AND DIFFERENT FEED WATER TYPES

Feed water type / Parameter/quantity	Brackish water[a/] (5,000 ppm)	Seawater (41,518 ppm)[b/] With ER	Without ER
Feed pressure (Mpa)	2.0	5.68	5.68
Feed temperature (^{o} C)	30	25.	25
Product water recovery ratio (percentage)	53	34.24	34.24
Salt Rejection (percentage)	99.6	98.7	98.7
Membrane area requirement m^2/(m^3 per day)	1.18	1.42	1.42
Specific electrical energy consumption of high pressure pump and other pumps (kWh/$m^{3)}$	2.1 + 0.0	5.1 + 1.05	6.4 + 1.05

Source: Mahmoud Abdel-Jawad, "Energy sources for coupling with desalination plants in the GCC countries", consultancy report prepared for ESCWA, (September 2001).

a/ Based on average values for different brackish waters.
b/ Based on long operation of 6,00 m^3/d plant capacity.

5. *Energy consumption in the electrodialysis process*

Similar to the RO process, desalination using the ED process is heavily dependent on the characteristics of feed water in terms of salt concentration, composition and temperature. However, the ED process operates at atmospheric pressures and the electrical energy supplied to the system is utilized mainly in the ions transported across the membranes. Table 17 lists relevant data on the ED process for three feed water salinities with calcium ions less than 100 ppm.

TABLE 17. MEMBRANE AREA REQUIREMENTS AND SPECIFIC ENERGY CONSUMPTION FOR THE ED DESALINATION PROCESS AT DIFFERENT FEED WATER CONCENTRATIONS

Feed water TDS (ppm)	2 500	3 500	5 000
Membrane area requirement m^2/(m^3 per day)	0.62	0.75	0.89
Total specific electrical energy consumption (kWh/m^3)	2.64	3.85	5.50

Source: Mahmoud Abdel-Jawad, "Energy sources for coupling with desalination plants in the GCC countries", consultancy report prepared for ESCWA, (September 2001).

This chapter provides a basic outline for the identification of appropriate desalination systems for a specific application, particularly regarding the types of energy resources required, the different desalination processes, the rate of energy consumption and the associated performance rating.

III. ENERGY SUPPLY OPTIONS FOR WATER DESALINATION IN THE GULF COOPERATION COUNCIL COUNTRIES

Although the GCC countries have extensive fossil and renewable energy resources, all desalination plants are dependent on fossil energy resources, except for the solar-assisted seawater MED demonstration plant that was established in Abu Dhabi in late 1984. The majority of water desalination plants in the GCC countries acquire their electric power requirements either directly from an electric grid or from an adjacent electric power plant in a power water cogeneration system. Thermal energy for distillation-based plants can additionally be obtained from waste heat from the power plants. A variety of power generation systems, all compatible with the desalination system, are available in the GCC countries. These include steam boiler-turbine-generator power cycle, gas turbine power cycle, combined power plants cycle and diesel engines. Annex II contains a brief description of the operating principle and conditions for each of these power generation systems.

However, renewable solar thermal, photovoltaic (PV) and wind energy, in addition to biomass technologies have reached such a level of maturity that within a short to medium time frame, renewable thermal and electric energy will become viable sources of energy for desalination processes.

In addition, desalination requires a large seawater inlet flow for processing and cooling. The rejected brine and cooling seawater with the chemicals or their by-products are in turn discharged into the sea at a higher temperature. This has an impact on the marine environment.

Therefore, this chapter reviews the existing energy supply systems for desalination processes in the GCC countries. It examines their operating principles and presents a comparative evaluation, focusing on the dual-purpose cogeneration systems. This chapter highlights potential renewable energy systems for desalination within the next five to 10 years. Furthermore, the environmental impact of power/water desalination systems on the marine environment of the Gulf, are discussed.

A. POWER-WATER COGENERATION OPTIONS

Chapter II, section C, demonstrated that one or two types of energy sources are required for the desalination process and that these are dependent on the type of desalination process itself. In the distillation-based MSF, MED and TVC desalination processes, the most important energy is heat. Electricity is required at much lower rates for driving the systems' pumps. In the distillation-based MVC and membrane-based RO and ED desalination processes, electricity is the only requirement. In the latter case, desalination plants obtain their electric power requirements either directly from an available electric grid or from an adjacent electric power generation plant in a power/water cogeneration system. The case of a direct connection with an available electric grid is considered to be more suitable for brackish water or wastewater applications. However, this will not be included in this study.

Owing to the variety of desalination processes and compatible electric power generation systems, there are a number of coupling schemes for power-water co-production. However, only the most promising coupling schemes are included in this study. This selection has been made on the basis of maturity and reliability of the relevant technologies and on their potential applicability to the GCC countries. Options for coupling schemes are classified according to the relevant desalination technologies.

1. *Coupling with MSF desalination systems*

Since the early years of the oil boom, the coupling of fuel-oil- and gas-based power generation and distillation-based water desalination by the MSF process has been the backbone of the power and water utilities infrastructure in GCC region.

The continued regional dependence on such dual-purpose power/water cogeneration schemes for nearly half a century is logically justified by the following:

(a) Availability of the most convenient and dependable energy resources, namely, fuel oil and gas, at very low costs compared to other energy resources;

(b) The high degree of compatibility between fuel-oil- and gas-based power generation and distillation-based MSF desalination technology and their particular suitability for the GCC region;

(c) The adaptability and relative flexibility of these technologies, particularly with regard to large production capacities. These are capable of satisfying regional demands for both power and water under extremely harsh operating conditions and where very difficult seawater conditions prevail.

The coupling schemes for this class of power-MSF comprises four alternatives, two of which have been the most dominant in the GCC countries and have reached the highest level of maturity and dependability. These are based on the steam boiler-turbine-generator power cycle where the turbines are either backpressure or extraction-condensing. The other two schemes are based on either a single gas turbine cycle, or a combined gas and steam turbine cycle, where both cycles include the heat recovery steam generators. A common feature is that both power and desalination plants must be adjacent to avoid heat transport over long distances. This minimizes costs and losses, maximizes availability and utilization of common feed water and outfall facilities in addition to other auxiliary systems. Figures VI.a through VI.d depict these power-MSF coupling schemes, each of which is reviewed separately below.

(a) *Steam boiler-extraction-condensing-turbine power cycle coupled with MSF*

This is the most common coupling scheme in the GCC countries. Coupling of the heat source to one or more MSF units is obtained by extracting a sizable portion of the expanding steam after completing its expansion in the medium pressure turbine and before entering the low-pressure turbine. The remaining steam continues its expansion through the low-pressure turbine stages followed by condensation in a vacuum condenser. In addition to the low-pressure heating steam, a very small portion of medium pressure steam, usually equivalent in mass to less than 3 per cent of the extracted steam for heating, is removed and then used as motive steam for the steam-jet air ejectors. This is necessary for maintaining the required vacuum in the MSF units. The relatively small amounts of electricity required for driving the MSF pumps are easily obtained through local electricity networks.

This scheme is usually more suitable for conditions where relatively low water to power production ratios are required and when marginal flexibility in meeting electric load variations is necessary. The power obtainable from the low-pressure turbine is further supplemented by introducing steam reheat process between high and medium pressure turbine stages to increase the overall turbine power output. Load variations within reasonable ranges are usually met by adjusting the amount of the low pressure extracted steam. Typical configurations are available in which one or two MSF units are usually coupled with each power unit at a range of water to power production ratio of about 150 tonnes per day (t/d) per MW. Furthermore, this coupling scheme has certain economic advantages. These include:

(i) Total elimination of a separate medium pressure steam boiler for stand alone MSF plants;

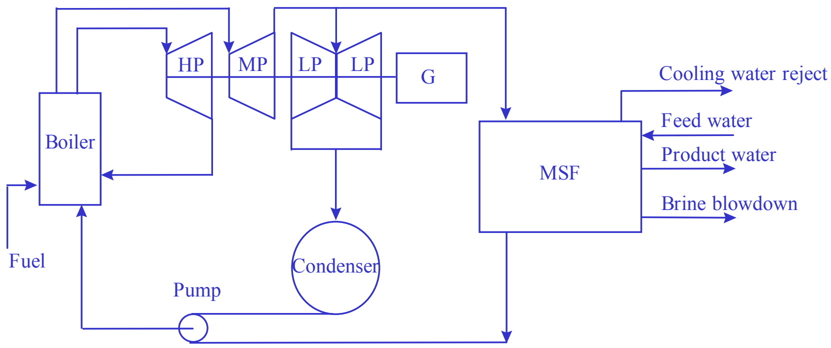
(ii) Utilization of relatively low grade heat at a lower cost, compared to stand-alone MSF systems, since this heat is a by-product of the power system;

(iii) Downsizing of the main vacuum condenser of the power system because of the reduced amount of exhaust steam from the low-pressure turbine;

(iv) An increased overall cycle efficiency. Therefore, this coupling offers better fuel utilization.

Owing to the high degree of interdependent operation of the two systems, the major drawback to this scheme is its rigidity. Independent operation is sometimes necessary because of the large seasonal climatic variations, especially in the Gulf region. The mismatch between demand patterns for power and water results in very significant departures from design conditions. Under such operating conditions, water to power production ratios greatly exceed the design values by three to four times and it is necessary to run the MSF plant independently from the steam turbine. In this type of situation, the steam, which is still generated in the steam boiler at high pressure, bypasses the turbine and is then drawn to a pressure reducing station for conditioning prior to its entry to the MSF unit or units. This practice resembles the operation of stand alone MSF systems using a cleverly designed boiler. As a result, MSF systems that operate under such conditions lose their economic edge.

Figure VI.a Simplified diagram for steam boiler extraction-condensing turbine with reheat power cycle coupled with MSF



Abbreviations:
HP: High pressure.
MP: Medium pressure.
LP: Low pressure.
G: Generator.

(b) *Steam boiler-back-pressure-turbine cycle coupled with MSF*

Figure VI.b illustrates this scheme. The backpressure turbines are the same as extraction-condensing turbines apart from the low-pressure turbine stages. For this reason, coupling of the heat source to the MSF units is obtained by utilizing 100 per cent of the exhaust steam, which has completed its expansion through the medium pressure turbine stages. Therefore, not only are the low-pressure turbine stages omitted, the main vacuum condenser of the power generation system is entirely eliminated as the MSF acts as the main condenser of the power cycle. The overall power output of the back pressure turbine is considerably less than that of the extraction-condensing turbine of the same mass flow rate and the same steam conditions at the inlet to the high pressure turbine stages. This is a result of the elimination of the low-pressure turbine stages in addition to the fact that this power cycle does not often include the steam reheat process between the high and medium pressure turbine stages.

Compared to the extraction-condensing turbine, this scheme is more suited to demand conditions where higher water to power production ratios prevail. The fact that the overall power output of the backpressure turbine is relatively lower, in comparison to the extraction-condensing turbines, makes it more suitable for such applications. Typical configurations of this scheme comprise four MSF units coupled with each power unit at a range of water to power ratios close to and above 1,000 (t/d)/MW. A typical example of this scheme is the dual-purpose power-MSF plants of Al-Jubail II complex in Saudi Arabia.

The specific consumption rates of the medium-pressure steam required for driving the steam-jet air ejectors and the electricity required to drive the MSF pumps are similar to those of the above coupling scheme of the extraction-condensing turbine. Additional economic advantages of this scheme are:

(i) Much lower costs associated with the turbine due to the elimination of the more costly and cumbersome low-pressure turbine stages;

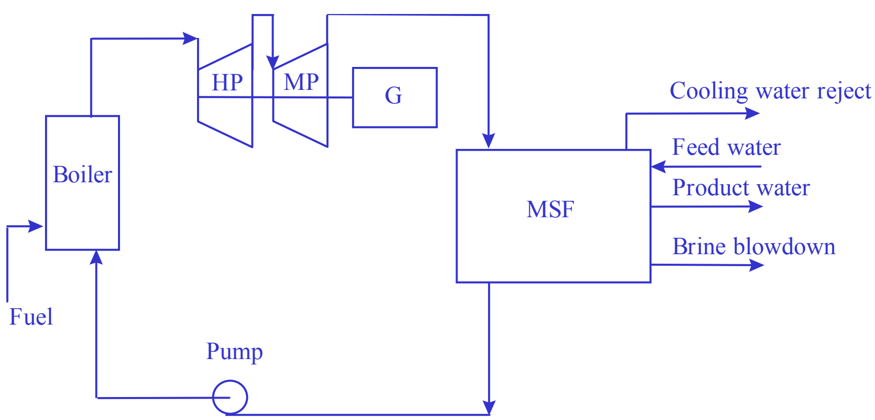
(ii) Total elimination of the main vacuum condenser of the power generation system;

(iii) Higher increase in the overall cycle efficiency and hence even better fuel utilization;

(iv) Downsizing of the feed water intake and the associated energy consumption.

A combination of these factors could result in significant savings both in terms of capital investment and operating costs, which in turn will reflect on the overall specific product costs. The disadvantage of this coupling scheme is that it is considered to be less flexible in matching power load variations since the only way to adjust the power output of the back pressure turbine is by adjusting the exit pressure of the exhaust steam. This can be varied only within a very narrow range to avoid excessive load variation on the turbine blades and performance deterioration. In addition, load variations in the MSF system are difficult to match since there is no low-pressure turbine stage or any other device capable of absorbing the changes in the mass flow rate or the thermal conditions of the exhaust steam, except the MSF itself.

Figure VI.b. Simplified diagram for steam boiler-back-pressure – turbine power cycle coupled with MSF



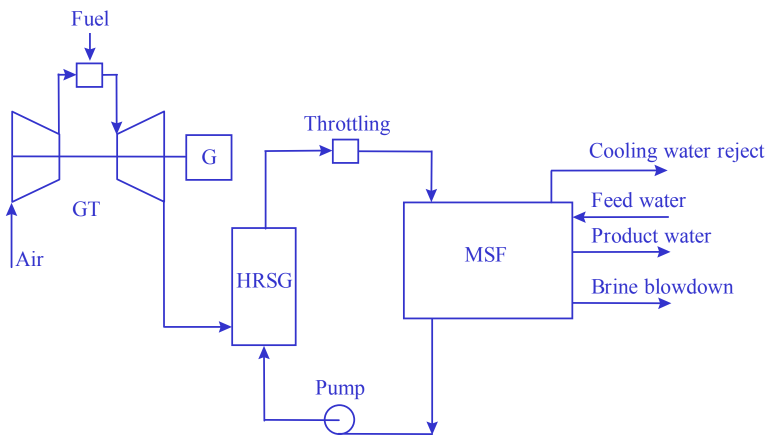
(c) *Gas turbine cycle with heat recovery steam generator coupled with MSF*

This scheme is depicted in Figure VI.c. The exhaust gases from the gas turbine are the source of heat that drives the heat recovery steam generator. Coupling of the heat source to the MSF units is provided directly from the heat recovery steam generator. Exhaust gas temperatures, which range between 400^{o} to 500^{o}C depending on design and on whether regeneration has been included, are passed on to the heat recovery steam generator. The steam in this type of coupling scheme is generated at some 230^{o}C and 1.7 Mpa. The steam in this thermodynamic state must go through a throttling and conditioning process prior to its entry to the MSF at the required state, namely at approximately 105^{o}C and 0.12 metric barometer pressure (Mpa). The medium pressure steam required to drive the steam-jet air ejectors is supplied directly before throttling. The overall power output of the gas turbine cycle is of the same range as that of the back-pressure turbine in the coupling option described above. However, the water to power production ratios are some 50 per cent less or even lower.

From the power generation viewpoint, this scheme may have some certain advantages over the back-pressure turbine scheme especially with regard to its rapid response to electric load variations. However, from a cogeneration viewpoint, this scheme does not offer any advantage over the previously described option. On the contrary, the overall cycle efficiency is less and hence fuel utilization is lower. Therefore, associated energy costs are much higher.

To maintain high operational flexibility, the heat recovery steam generator must be designed for possible independent operation from the gas turbine at times when the gas turbine is shutdown, because of low electric demands, for example. For this reason, the steam generator must have fuel-oil- or gas firing capabilities that will allow it to act as an ordinary stand alone steam boiler. In such cases, the complete system becomes a single-purpose water producer. Compared to the optional steam turbine cycle-based schemes reviewed in this study, forced operation in single-purpose water production mode is easier and more acceptable from an engineering point of view and also far more economically viable. This is because the heat recovery steam generator is already designed for operation at moderate pressures and temperatures, unlike the steam boilers of previously mentioned schemes, which are designed for far greater pressures and temperatures.

Figure VI.c Simplified diagram for combined gas turbine cycle with heat recovery steam generator coupled with MSF



Abbreviation: HRSG: Heat recovery system generator.

(d) *Combined gas turbine and back-pressure steam turbine cycle coupled with MSF*

The combined gas turbine heat recovery steam generator back-pressure turbine cycle is depicted in figure VI.d. The steam generated in the heat recovery steam generator is used to drive a backpressure steam turbine, which produces an additional 15 to 20 per cent of the power produced by the gas turbine. Often, supplementary firing may be introduced into the heat recovery steam generators to increase the thermal capacity of the generated steam, and therefore increase the power output of the back-pressure turbines installed in the system to some 40 to 50 per cent of those produced by the gas turbine. Coupling of the heat source to the MSF units is obtained from the exhaust steam of the back-pressure turbine. Whether supplementary firing is included or not, the full expansion of the steam in the back-pressure turbine to a condition suitable for the MSF brine heater reduces the specific available heat by as much useful work as is obtained from the turbine. Compared to the single gas turbine cycle, lower water to power production ratios can be expected.

A typical example of this scheme is Taweelah A2, a combined gas turbine, heat recovery steam generator with supplementary firing back-pressure steam turbine cycle coupled with MSF desalination system, in the United Arab Emirates. Three gas turbine-heat recovery steam generators are integrated with two back-pressure steam turbines forming the combined power cycle, which is coupled with four MSF units. The design water to power ratio in this scheme is approximately 300 (t/d)/MW.

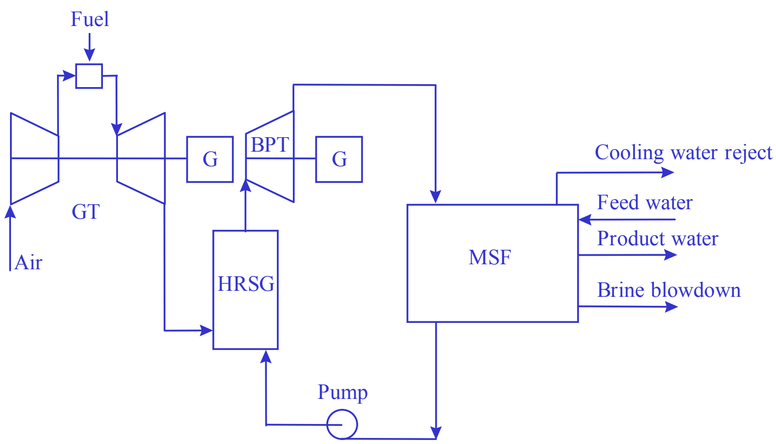
The medium pressure steam for driving the steam-jet air ejectors of the MSF is provided by bypassing or extraction from the back-pressure steam turbine depending on the system's design. Electricity is provided directly from the local electric power network. The economic advantages of this scheme include:

(i) High power cycle efficiency, which is further enhanced by the coupling with the MSF desalination system, resulting in significantly improved fuel utilization;

(ii) Improved flexibility in matching variable load demands as a result of the rapid response of the gas turbines and the possible independent operation of the two types of turbines;

(iii) Improved economics of operation at off-design conditions, especially as the system shifts towards higher water to power ratios or even towards single-purpose water only production, as compared to alternative schemes.

Figure VI.d Simplified diagram for combined gas turbine and back-pressure steam turbine power cycle coupled with MSF



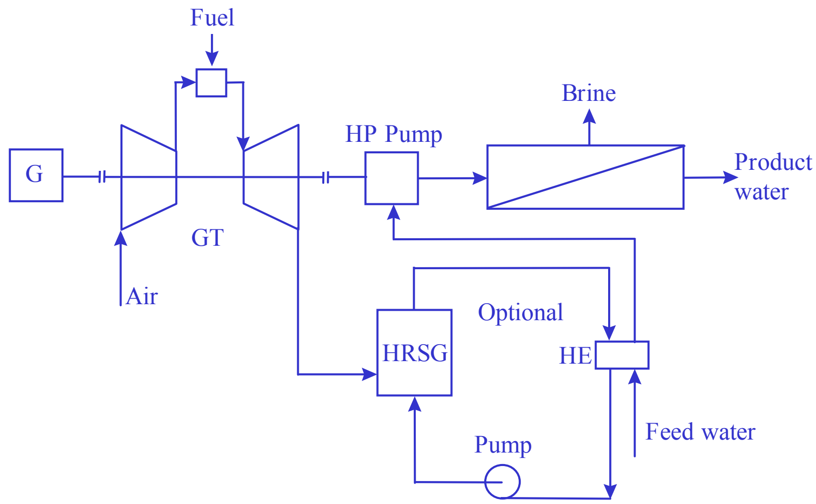
2. *Coupling with RO desalination systems*

Coupling of power systems and MSF have always dominated the desalination process in the region. Therefore, this type of power-RO coupling has not been widely available, particularly in the GCC countries. Although several coupling schemes between power cycles and RO are possible, only the two most feasible schemes are considered here for large seawater desalination applications. The first scheme is based on a single gas turbine power cycle. The second is based on a combined gas turbine, heat recovery steam generator, condensing turbine power cycle.

(a) *Gas turbine with optional heat recovery steam generator coupled with RO*

Figure VII.a illustrates this scheme, which is based on direct coupling of the gas turbine and the high-pressure pump of the RO system with the inclusion of small capacity electric generator to provide electricity to auxiliaries including transfer pumps, chemical dosing pumps and control devices. An optional configuration is possible where a full-scale electric generator with a capacity matching the gas turbine is included. In this configuration, mechanical couplings on one single shaft permit disengagement of the RO system and full utilization of the gas turbine-generator system as a single-purpose power-only producing system. If a heat recovery steam generator is included, the recovered waste heat may then be used to preheat the seawater feed to the RO system, especially during the winter season to improve the RO performance in terms of its product water recovery and electric energy consumption.

Figure VII.a Simplified diagram of the power-RO coupling schemes gas turbine cycle with optional heat recovery steam generator



Abbreviation: GT: Gas turbine.

This scheme is suitable for systems that are very much on either end of the single-purpose water or power-only production scales. In other words, the water to power production ratio is either infinite or zero. Although this scheme is unavailable in the GCC region, it has some potential advantages. These include:

(i) Very low capital investment costs, as a result of lower initial cost gas turbines and elimination of the full-scale electric motor that drives the high pressure pump and possible elimination of the heat recovery steam generator, in addition to the relatively lower capital investment cost of the RO itself;

(ii) Very high flexibility under variable power and water demands. The system may be used to produce only power at times of peak electric loads, and may be utilized to produce water, which can be stored, during off-peak electric loads;

(iii) Rapid response to any of the two modes of operation.

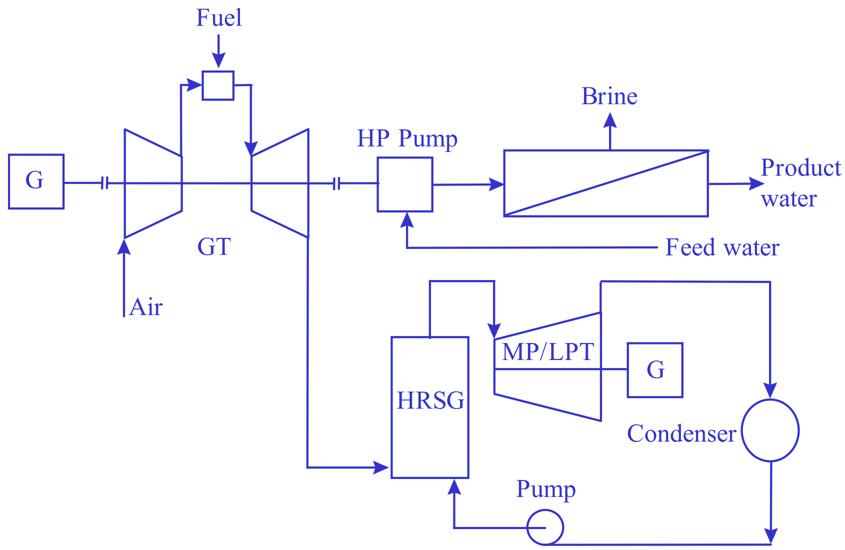
The main drawback to this scheme is its lower overall fuel utilization efficiency especially during the hot season that lasts from six to eight months. Performance of gas turbines deteriorates under these conditions, and the benefit of using a heat recovery steam generator to preheat the seawater feed to the RO diminishes.

(b) *Combined gas turbine and condensing steam turbine power cycle coupled with RO*

This is another optional scheme that is highly flexible and has certain merits. However, it is not commercially available (see figure VII.b). It comprises a typical combined gas turbine-heat recovery steam generator with or without supplementary firing condensing steam turbine power cycle coupled with an RO desalination system. It is similar to the scheme reviewed above in that the coupling between the power and RO systems is provided by direct coupling of the gas turbine to the high-pressure pump of the RO. The electricity required for driving the auxiliary pumps is provided either from the electric generator coupled with the condensing steam turbine or from an optional auxiliary generator coupled coaxially with the gas turbine and the high-pressure pump. Furthermore, similarities to the scheme described above include an alternative configuration that may be used where a full-scale electric generator is coupled with the gas turbine with a matching full capacity, while mechanical couplings allow alternate engagement-disengagement of the RO high pressure pump. In such a configuration, the complete system could be alternately operated as a dual-purpose power-water cogeneration system or as a single-purpose power-only producing system. Including supplementary firing in the heat recovery steam generator can increase the power production capacity. This would increase the power output of the condensing steam turbine.

This coupling scheme is suitable for situations that require rapid response to demand variations, especially electricity. The flexibility of switching from gas turbine-RO mode to gas turbine-generator mode in addition to the power generated by the condensing steam turbine should provide maximum power output when the demand for electricity is a priority. However, full utilization of the system is achieved in the dual-purpose production mode. Unlike the above scheme, the inclusion of a condensing steam turbine improves the overall fuel utilization and the cycle efficiency varies significantly. However, the fact that the gas turbine performance is low during hot weather conditions must be carefully weighed against the advantages of the combined power cycle.

Figure VII.b Simplified diagram of the power-RO coupling schemes, combined gas turbine and condensing steam turbine power cycle



3. *Coupling with MSF-RO hybrid desalination systems*

MSF desalination technology has been the backbone of seawater desalination in the GCC countries for the last four decades. However, RO desalination has been steadily gaining ground as a viable technology with certain advantages and technical merits. MSF and RO are both suitable for side-by side coexistence and for full integration in what is known as MSF-RO hybrid desalination systems. Integration between MSF and RO in certain hybrid desalination process configurations can be greatly beneficial both technically and economically.[14] Some of these benefits include greater flexibility in dual-purpose power-water cogeneration, increased product water recovery, lower specific energy consumption for water production, utilization of common seawater intake systems with lesser capacities, lower chemical consumption and RO membrane replacement rates and prolonged life cycle of these RO membranes. The reductions in the product water costs under hybrid MSF-RO desalination systems are guaranteed and significant.[15]

There have been studies of several MSF-RO hybridisation schemes and design configurations.[16] However, this study reviews only the most feasible hybrid configuration. The MSF-RO hybrid configuration (see figure VIII) is the simplest of its kind. It can be easily implemented in existing MSF plants. It utilizes the cooling seawater reject from the MSF heat rejection section to feed the RO desalination system. The

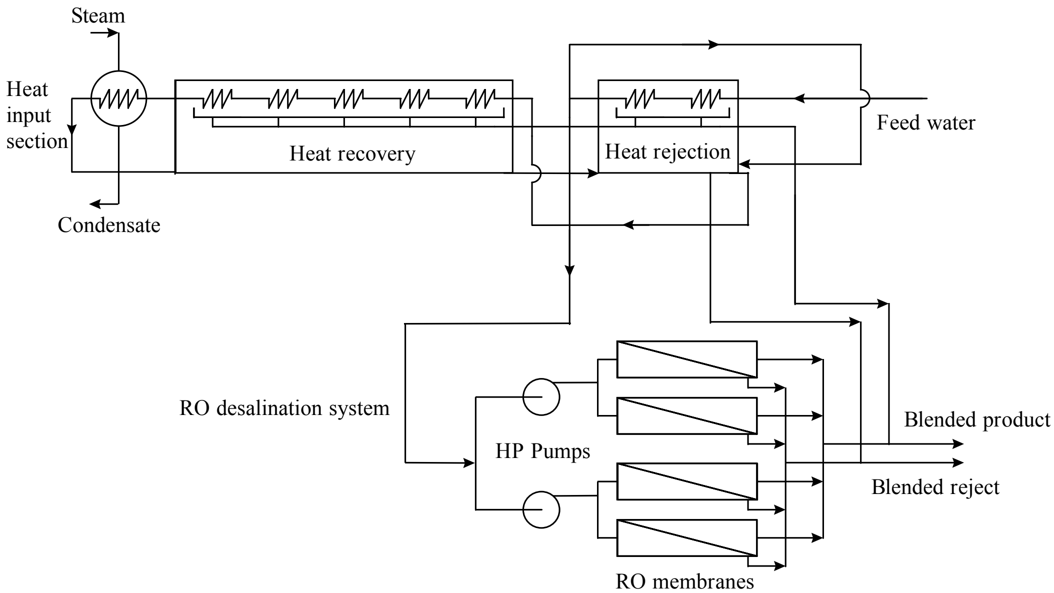
[14] Mohammed A.K. Al Sofi, Ala M. Hassan and Essam E.F. El Sayed, "Integrated and non-integrated powers MSF/SNRO plants", part I, *The International Desalination and Water Reuse Quarterly*, vol. 2/3, pp. 10-16 and vol. 2/4, pp. 42-46.

[15] Mahmoud Abdel-Jawad and others, "Sea water desalination by reverse osmosis-phase III WD-005", *KISR Report*, No. 5350, vol. 4, Kuwait Institute for Scientific Research, (July 1998).

[16] E. El-Sayed and others, "Research and development on desalination by reverse osmosis, system configuration WD-002", *KISR Report*, No. 4884, vol. 4, Kuwait Institute for Scientific Research, (June 1996).

product distillate from the MSF is then blended with permeate from the RO process to yield the final product water.

Figure VIII. Simplified diagram of basic MSF-RO hybrid configuration



There are also a number of options for coupling schemes between MSF-RO hybrid configurations and relevant power generation options. This study examines three of these optional schemes in relation to the MSF-RO hybrid configuration (see figure VIII). Since it requires no alteration of existing MSF plants, this configuration could be immediately implemented in GCC countries. The coupling schemes are identified on the basis of the following power cycles:

(a) The steam boiler extraction-condensing turbine;
(b) The steam boiler back pressure turbine;
(c) The combined gas turbine heat recovery steam generator backpressure turbine cycle.

The main reason for selecting the first two power cycles for coupling with the MSF-RO hybrid system is that they are the most commonly used in the GCC countries. The third power cycle is the most feasible improvement, for example, it was used at the Taweelah A2 plant in the United Arab Emirates.

The main characteristics of these coupling schemes are similar to those discussed in section A.1 of this chapter and represented graphically in Figures. VI. a, b and c. Coupling of the heat source to the MSF desalination system is obtained from the extracted or exhaust steam of the extraction-condensing or backpressure turbines, respectively. Coupling of the electrical source to the RO desalination system is obtained from the generated electricity of the local electric network. Technical and economic advantages of the corresponding schemes mentioned above, remain in force. However, owing to MSF-RO hybridisation, other advantages are possible. These include:

(a) Increased water productivity from RO because of preheated feed water;

(b) Increased overall product water recovery ratio since no additional feed water is required for RO except for MSF requirements;

(c) Maximum operational flexibility and maximum rapid response to load variations and alternation between different modes of operation, particularly in the combined power cycle coupling scheme. This is a result of the possible rapid start-up and shutdown of both the gas turbine and RO systems;

(d) Significant savings in both capital investment and operating costs owing to the elimination of redundant auxiliary systems and the utilization of common facilities for power, MSF and RO systems.

These systems have many advantages, particularly the steam boiler back pressure turbine cycle and the combined gas turbine heat recovery steam generator back pressure turbine cycle coupled with the MSF-RO hybrid desalination system. Desalination experts and decision-makers in the GCC countries must therefore seriously consider these options for future studies, research and implementation plans.

4. *Coupling with MED or TVC desalination systems*

From a technical viewpoint, the factors that contribute to higher thermal performances in the MED and TVC desalination processes as compared to the MSF system, are the same factors that limit their operating temperature and pressure ranges and that limit growth in the per unit capacity. These limitations have contributed to slowing down the growth in utilization of MED and TVC technologies in seawater desalination applications in general and their coupling with power in cogeneration systems, in particular. However, irrespective of the technical limitations of the MED or TVC processes, the potential of power-MED and power-TVC coupling is feasible and has valid technical and scientific merits similar to those of the power-MSF coupling. Recent advances in NF membrane technology for softening seawater feed to the RO and MSF desalination plants and for reducing scale formation potential in these plants indicate that similar MED and TVC advances are possible. Reducing scale formation potential will significantly encourage the future utilization of these two technologies and will substantially ease the associated technical limitations. Under such circumstances, the future of power-MED and power-TVC coupling may become even more attainable.

Nevertheless, since both the MED and TVC processes are thermally driven, they can be coupled with different power generation systems using schemes that are similar to those of the MSF desalination. However, there are some basic differences between power-MED, power-TVC and power-MSF couplings under the four schemes presented in section A, subheading 1 of this chapter. These differences include the following:

(a) The MED desalination process runs at lower TBT values compared to the MSF. For this reason, coupling of the heat source to the MED, under any of the relevant coupling schemes reviewed for the MSF system, requires steam at lower thermal levels. In other words, the expansion range of the extracted or exhaust steam from the extraction-condensing turbine or from the backpressure turbine, respectively, can be further extended on the lower end. This in turn means that the specific power output of these turbines with respect to the heat input to the process, is higher compared to coupling with the MSF. The case is quite different for the TVC desalination process in that the TVC runs at TBT comparable with that of the MED, coupling of the heat source to the TVC requires steam at a state suitable for operating the steam-jet thermo-compressor, namely, saturated steam at about 0.3-0.5 Mpa. Therefore, the expansion range of the extracted or exhaust steam in the power cycle is effectively less than that in the MSF coupling. This in turn implies less specific power output from the power cycle with respect to the heat input to the process for the case of TVC coupling when compared with the MSF coupling;

(b) Both MED and TVC desalination unit capacities available are still very much smaller than those of the MSF. Increasing the number of MED or TVC units in a given system to satisfy large capacity requirements could adversely affect the cost of the coupling. Hence, coupling schemes based on MED or TVC desalination are expected to be more appropriate for the following:

(i) Smaller power and water production capacities than those required by enormous plants, namely, MSF;

(ii) Lower water to power production ratios, namely below 150 (t/d)/MW.

(c) Under the single-purpose water only mode of operation, possible during periods of low power demand, supply of the lower-pressure steam to the MED process directly from the high pressure steam boilers of the extraction-condensing or back pressure turbine cycles has worse economic implications than for the TVC and MSF, since the supplied steam must be further throttled to lower pressures and must be conditioned to lower temperatures.

B. Potential renewable energy options

The ESCWA region in general, and the GCC countries in particular, have three main renewable energy resources. These are the abundant solar radiation throughout the year at utilizable levels, wind resources and biomass resources. In fact, during the past two decades, several renewable energy technologies have approached maturity for both large-scale and small-scale applications.

Given that conventional desalination processes are energy intensive and that energy represents one of the major cost elements of produced water, available and affordable energy resources are essential for the development of desalination systems, particularly in remote areas.

In view of this situation, this section reviews possible renewable energy options for powering water desalination. ESCWA's Energy Issues Section (EIS) recently completed a study entitled "Potential and prospects for renewable energy electricity generation".[17] The study revealed that solar and biomass resources are available in the region and that their current technological status makes them suitable for desalination plants with both small and large capacity systems. Furthermore, the study showed that wind technology for electricity generation has developed considerably with competitive costs in quality wind areas. However, available wind resource data in the GCC countries are not sufficient and more resource assessment is required.

Solar technologies are developed enough for direct conversion to electricity using PV cells, low and medium temperature thermal application, in addition to high temperature steam and electricity generation, using solar concentrators. In other words, solar technologies could power water desalination systems of different types and capacities. The suitability of the technology, system configuration, performance rating and costs depends on the specific site, application characteristics and requirements of the desalination plant. Meanwhile, biomass technologies for producing electricity have been tested and can be used with steam and gas turbines for electricity generation.

1. *Low and medium temperature solar option*[18]

Low and medium temperature solar collectors can be used for small-scale solar stills and medium scale MED desalination processes, since MED exhibits high thermal performance in a low operating temperature range. However, these systems do not compete favourably with fossil-based energy desalination. Nevertheless, they remain a valid option for remote areas.

Desalination using the MED process is probably the most suitable for solar desalination applications. The reasons for such a preference are as follows:

(i) MED exhibits higher thermal performance, compared to MSF, especially in the lower temperature range;

(ii) MED units are more compact and require relatively less capital investment costs;

(iii) MED requires least specific electrical power compared to MSF and VC.

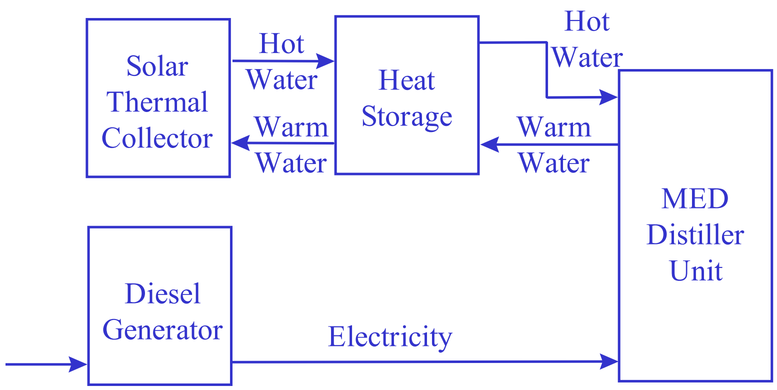
[17] Published in three volumes covering the three solar, wind and biomass technologies for electricity generation, namely, ESCWA, "Overview of wind and biomass systems", *Potential and Prospects for Renewable Electricity Generation*, vol. 1, (E/ESCWA/ENR/2001/4); vol. 2, "Solar thermoelectric systems" "النظم الشمسية الحرارية للكهربـاء", (E/ESCWA/ENR/2001/4/Add.1) (in Arabic); and vol. 3, "Solar photoelectric systems" "النظم الشمسية الكهروضوئية", (E/ESCWA/ENR/2001/4/Add.2) (in Arabic).

[18] Mahmoud Abdel-Jawad, "Energy sources for coupling with desalination plants in the GCC countries", consultancy report prepared for ESCWA, (September 2001) and Ali M. El-Nashar, "The role of desalination in water management in the Gulf region", Abu Dhabi Water and Electricity Authority, (Abu Dhabi, 2000).

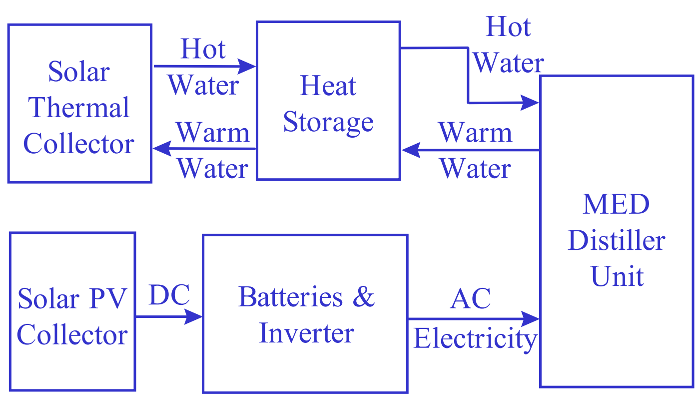
The two alternative configurations based on the utilization of MED are illustrated in Figure IX.a and b. The first configuration comprises solar thermal collectors, which feed heated water to a heat accumulator. This supplies heat to the MED system. An auxiliary diesel generator generates the electricity needed to drive all pumps including vacuum pumps, in addition to other electrically powered devices. The second configuration is similar to the first in all aspects except that solar powered PV collectors integrated with direct current battery cells and electric current inverters are used instead of the diesel generator to supply the necessary electricity.

Figure IX. Simplified diagram of two different solar desalination options

(a) *Solar-assisted MED desalination system*



(b) *Solar stand-alone MED desalination system*



Source: Ali M. El-Nashar. "The role of desalination in water management in the Gulf region", Abu Dhabi Water and Electricity Authority, (Abu Dhabi, 2000).

2. *PV solar electricity*

PV solar electricity is technically valid and a reliable solar option for powering RO and ED desalination processes in remote areas. Despite the fact that its costs are still high at $4 to 6 per kWp, it has a better economic and environmental impact than fossil fuel transport for these areas. Additionally, water can be stored rather than using electric batteries.[19]

3. *Solar thermal concentrating technology options*

Concentrating solar power (CSP) technologies are well established. Commercial applications from a few kilowatts (kW) to hundreds of MW are now feasible, and plants totalling 354 MW have been in operation in California since the 1980s. Plants can function in dispatchable, grid-connected markets or in distributed, stand alone applications. They are suitable for fossil-hybrid operation or can include cost-effective storage to meet dispatchability requirements. They are able to operate in regions that have high direct-normal insolation of 1800 kWh/m^2 per year. This includes the ESCWA region in general and the GCC countries in particular where direct solar insolation varies between 2000 to 2700 kWh/m^2 per year. Commercial solar plants have achieved costs of some 10 cents per kilowatt hour (kWh), the lowest cost of any solar technology) and the potential for cost reduction will ultimately lead to costs as low as 5 cents per kWh. The following is a brief on the available technologies and the possible system configurations for electricity generation that can be coupled with desalination plants.

(a) *Status of the technologies*

According to SolarPACES, *Concentrating Solar Power in 2001*, there are three main types of CSP systems (see figure X.a). These include:

(i) *Trough systems.* These use linear parabolic concentrators to focus sunlight onto a receiver running along the focal line of the collector. The solar energy is absorbed in a working fluid, typically a heat-transfer oil, or in advanced systems, steam. This is then piped to a central location to power a conventional steam turbine;

(ii) *Power tower system*. This is a field of large two-axis tracking mirrors that reflect the solar energy onto a receiver that is mounted on top of a centrally located tower. The solar energy is absorbed by a working fluid, typically molten salt or air, and then used to generate steam to power a conventional turbine. The thermal energy can be effectively stored for hours, if desired, to allow electricity production during periods of peak need, even when there is an absence of sun;

(iii) *Dish/engine system*. This uses a parabolic dish concentrator to focus sunlight onto a thermal receiver and a heat engine/generator, located at the focus of the dish to generate power. More detailed descriptions of these technologies are widely available.

Because of their thermal nature, each of these technologies can by hybridised, or operated with fossil fuel as well as solar energy. Hybridization has the potential to dramatically increase the value of CSP technology by increasing its availability and dispatchability, decreasing its cost—by making more effective use of power generation equipment—and reducing technological risk by allowing conventional fuel use when needed. Figures X.a, X.b and X.c illustrate the solar thermal concentring technologies, the integrated solar/Rankine cycle system and the integrated solar/combined cycle system, respectively.

(b) *System characteristics*

According to SolarPACES, *Concentrating Solar Power in 2001*, typical solar-to-electric conversion efficiencies and annual capacity factors for the three technologies are listed in table 18. The values for parabolic troughs, by far the most mature technology, have been demonstrated commercially. Those for dish and tower systems are, in general, projections based on component and large-scale pilot plant test data and

[19] ESCWA, "Solar photoelectric systems", "الـنظم الشمسـية الكهروضـوئية" Potential and Prospects for Renewable Electricity Generation, vol. 2, (E/ESCWA/ENR/2001/4/Add.2) (in Arabic).

the assumption of mature development of current technology. While system efficiencies are important, they are, only one factor in the final measure of competitiveness-cost and value.

TABLE 18. CHARACTERISTICS OF CONCENTRATING SOLAR POWER SYSTEMS
(*Percentage*)

System	Peak efficiency	Annual efficiency	Annual capacity factor[c/]
Trough	21	10 to 12 (d)[a/] 14 to 18 (p)[b/]	24 (d)
Power tower	23	14 to 19 (p)	25 to 70 (p)
Dish/engine	29	18 to 23 (p)	25 (p)

Source: SolarPACES, *Concentrating solar power in 2001. An IEA/SolarPACES summary of present status and future prospects*, SolarPACES Task l: Electric Power Systems, (2001).

a/ Demonstrated.
b/ Projected, based on pilot-scale testing.
c/ Annual capacity factor refers to the fraction of the year that technology can deliver solar energy at rated power.

Several ongoing research activities in the United States and Europe aim to reach a 20 to 25 per cent energy cost reduction versus conventional oil trough systems. The main improvement targets include:

(i) Improvements in the collector field as a result of lower-cost designs and more durable receivers and collector structures;

(ii) Development of thermal energy storage systems suitable for solar-only deployment of the technology;

(iii) Continued improvements in the overall operation and management of the systems;

(iv) System cost reductions and efficiency improvements by substituting water for synthetic oil as the heat-transfer fluid;

(v) Development of advanced solar/fossil hybrid designs, especially coupling with combined-cycle power plants. In a dispatchable system, central-station power plants are able to meet the peak-load to near-base-load needs of a utility, while a distributed modular plant can serve for both remote and grid-connected application.

(c) *The system costs*

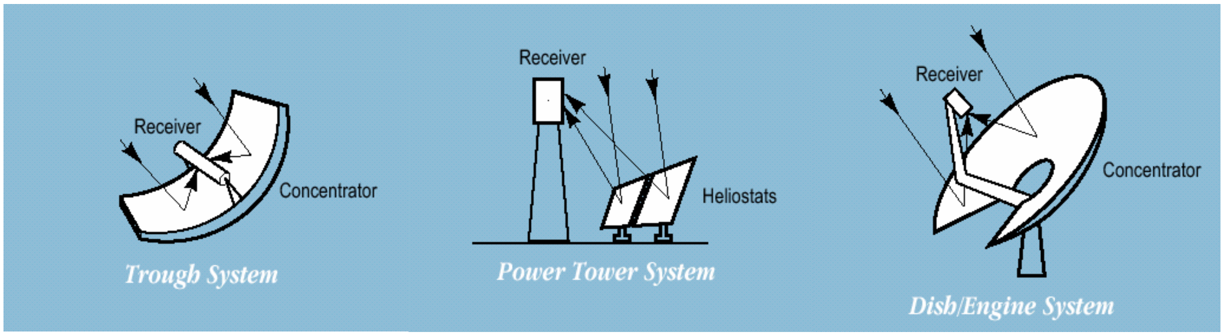
The continued technological improvements in CSP systems, along with the cost reductions achieved by system scale-up to larger mass-production rates, have made CSP systems the lowest cost renewable energy in the world. These systems predict cost competitiveness with fossil-fuel plants in the near future, particularly for integrated solar combined cycle systems (ISCCS) that use a mix of solar and fossil fuel resources. Whilst solar power generation costs using CSP systems – solar only – are in the range of 12 to 20 cents per kWh, SolarPACES expects that with continued development and early implementation opportunities, dispatchable system costs could drop to 8 to 10 cents per kWh within five years and 4 to 6 cents per kWh by 2010-2015. Meanwhile, distributed system costs are expected to drop to 12 to 15 cents per kWh within approximately five years and to 5 to 7 cents per kWh by 2010, in the event that reliability problems are solved.[20]

[20] Winifred Grasse, "Concentrating solar (thermal) power—the IEA-SolarPACES vision, strategy and activities towards its large scale commercial application", paper presented at the Expert Group Meeting on Disseminating Renewable Energy Technologies in ESCWA Member States, held in Beirut from 2-5 October 2000 (E/ESCWA/ENR/2000/WG.2/4).

(d) *Expected potential applications*

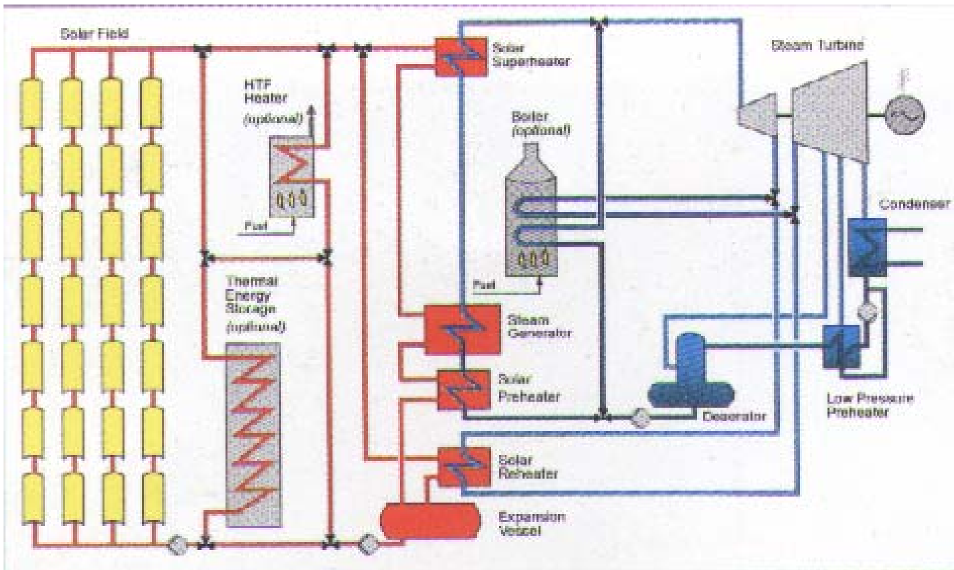
By 2010, concentrating solar thermal power (CSTP) plants are expected to make a significant contribution to the delivery of clean, sustainable energy services in the world's sun belt. A detailed assessment of electricity generation in the Mediterranean region showed a realistic potential by 2020 to 2025 of 23 GW, as compared to an estimated worldwide market of 120 to 140 GW. Furthermore, the assessment indicated a need for activities that would support project development to tackle non-technical barriers and to build awareness of the importance of CSP applications in resolving energy and the environmental problems.[21]

Figure X.a Solar thermal concentrating technologies



Source: SolarPACES, *Concentrating solar power in 2001. An IEA/SolarPACES summary of present status and future prospects*, SolarPACES Task I: Electric Power Systems, (2001).

Figure X.b Integrated solar/Rankine cycle system



Source: Pilkington Solar International, *Solar thermal power – now. A proposal for the rapid market introduction of solar thermal technology*, (Cologne, 1996).

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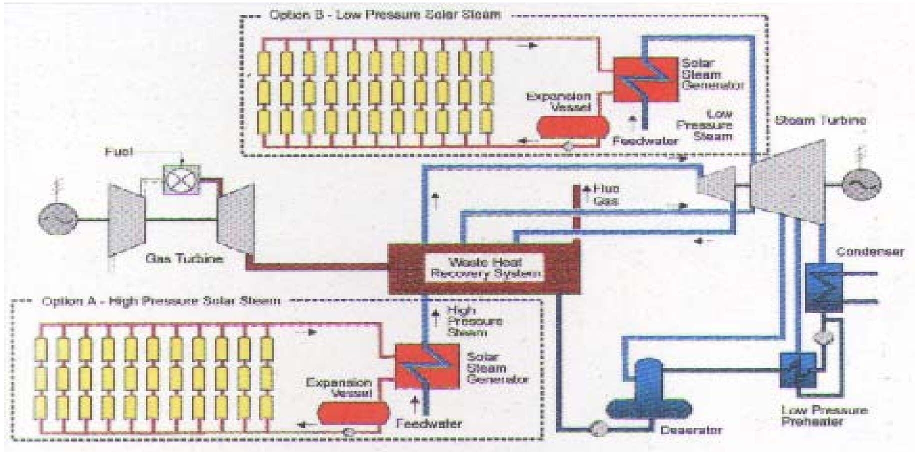
[21] Ibid.

Figure X.c Integrated solar/combined cycle system



Source: Pilkington Solar International, *Solar thermal power – now. A proposal for the rapid market introduction of solar thermal technology*, (Cologne, 1996).

4. *Biomass technologies for electricity generation*

A variety of technologies are able to convert solid biomass efficiently and cost-competitively into clean and more convenient forms, namely, gases, liquids, or electricity. Most of these are commercially available today. Since desalination plants can be coupled with electricity generation plants in different modes, four categories of biomass technologies for producing electricity must be considered:

The first technology burns the biomass from various resources using different combustion systems – conventional or improved fluidized bed. It uses heat to generate steam that drives a conventional steam turbine to produce electricity. This is the most widely used method.

The second approach is to gasify the biomass – gasification – generating a combustible gas that can then be burned, either in a boiler to generate steam or in a gas turbine or piston engine. The capital cost of the gasification route appears to be lower than the cost for a conventional steam generating plant.

Another approach is to ferment the biomass – anaerobic digestion – to generate gases or liquid fuel. This can then be burnt in a boiler, engine or gas turbine to generate power. However, the primary attraction of fermentation is that it produces a fuel, which can be used to power cars and trucks. Power generation is not necessarily the best option.

The most modern technology for producing electricity uses fuel cells. However, this requires further investigation before it can be considered to be field applicable and competitive, particularly for power generation.

The first two categories are excellent candidates for producing electricity and potential coupling with desalination plants of all types particularly large-scale MSF with cogeneration systems. Detailed technical, cost data and environmental impacts of these two technologies can be found in Volume I of the EIS study mentioned above (E/ESCWA/ENR/2001/4). However, a summary of that information is reviewed below.

(a) *Direct combustion, combined heat and power*

Biomass can be directly burnt in a boiler to generate steam, which is then used to drive a steam turbine. This turns a generator and produces electricity. In the United States, installed biomass-electric generating capacity exceeds 8000 MW.[22]

[22] ESCWA, "Overview of wind and biomass systems" *Potential and Prospects for Renewable Energy Electricity Generation*, vol. 1,. (E/ESCWA/ENR/2001/4) and S. Kirvan and E. Larson, *Bio-energy Primer: modernized biomass energy for sustainable development*, United Nations Development Programme.

(i) *The technology*

The predominant commercial technology for generating MW levels of electricity from biomass is the steam-Rankine cycle ranging between 5 to 100 MW. Most steam cycle plants are located at industrial sites, where the waste heat from the steam turbine is recovered and used for meeting industrial-process heat needs. Such combined heat and power (CHP), or co-generation systems provide greater levels of energy services per unit of biomass consumed than systems that generate power only. Figures XI and XII show schematic diagrams for two biomass fired CHP systems using a back-pressure steam turbine and a condensing-extraction steam turbine. This is used when industrial processes need heat or desalination. A purely condensing steam turbine is generally employed where there is no demand for process heat to maximize electricity production. Therefore it can be used with membrane desalination systems. The boilers used with biomass systems burn different fuels or mixtures of fuels. The best biomass plants today have total efficiencies of 20 to 25 per cent. Low efficiencies, together with relatively high capital costs, explain the reliance of existing biomass power plants on low-, zero-, or negative-cost biomass. Table 19 summarizes the characteristics of a biomass steam-Rankine cycle combined heat and power system.

TABLE 19. TECHNOLOGY SUMMARY: STEAM TURBINE COMBINED HEAT AND POWER

Typical electrical capacity (MWe)[a/]	1 to 50
Typical heat to power ratio[b/]	5
Technical parameters	
Typical steam conditions[c/]	20 to 80 bar; 400-500°C
Biomass fuels	Any/all (boiler design varies with fuel)
Typical biomass rate[d/]	1 to 2 dry kg/kWh; 6575 to 13150 dry tonnes/year per installed MWe
Technology availability	Boilers and turbines manufactured in most large developing countries
Key cost factors	Capital investment (especially at smaller scales), fuel cost
Technical concerns	Deposition on boiler tubes with high-ash biomass with low ash softening temperature; Boiler feed water purity (at minimum, demineralization and dearation are required)
Environmental and socio-economic parameters	
Environmental strengths	Efficient use of biomass with CHP; multi-fuel capability
Environmental issues	Particulate emissions, thermal pollution; as disposal
Total direct jobs	Two per MWe at 10 MWe; One per MWe at 30 MWe (California experience)

Source: E. El-Sayed and others, "Research and development on desalination by reverse osmosis, WD-002, phase IV, system configuration", *KISR Report*, No. 4884, vol. 4, Kuwait Institute for Scientific Research, (June, 1996).

a/ Megawatt electric.

b/ This varies significantly with the amount of process steam produced. The number shown is typical for a back pressure steam turbine. No process heat is produced in a fully condensing steam turbine.

c/ Steam pressures can be as low as 20 bar, for example in sugar factories in developing countries, or as high as 100 or 120 bar, as is the case with large coal-fired thermal power plants.

d/ These figures assume an input biomass with a moisture content of 50 per cent and energy content of 18 GJ per dry tonne. Furthermore, assumed overall conversion efficiencies to electricity are 10 per cent, representative of a system using 20-bar steam in a back-pressure turbine, to 20 per cent - which might be representative of a system using a fully-condensing turbine with a steam pressure of 60 bar. For the biomass rate per MWe, a 75 per cent capacity factor is assumed, namely, the annual electricity production per installed kWe is 6575 kWh.

(ii) *The cost*

Biomass steam-Rankine systems are constrained to relatively small scales because long-distance transport of biomass fuels is costly. As a result, they are generally designed to reduce capital costs at the expense of efficiency. The capital costs per kWe is some \$2000 and the generating cost is in the range of \$0.104 per kWh, including some \$0.012 for biomass collection and transport.

(iii) *The environmental impact*

Biomass steam-Rankine systems pose a number of environmental threats, including the potential for particle emissions to the air. Flue-gas-filtration systems are required to minimize these. Ambient-temperature air or water is used to cool the condenser in biomass steam cycles. If the reservoir of water or air available for cooling is not sufficiently large, thermal pollution is possible. Ash generated during combustion contains much of the inorganic minerals found in the original biomass. Ideally, the ash is returned to the oil. In many cases, it is sent to a landfill.

(b) *Biomass gasification systems*

(i) *The technology*

The term gasification commonly refers to high temperature conversion of biomass, where it is burned without sufficient air for full combustion, but with enough air to convert the solid biomass into gaseous fuel. The produced gas, generally known as producer gas, has a calorific value of some 14 to 15 per cent of NG. It can then be used for electricity generation using steam or gas turbines and, can be coupled to water desalination systems using steam and electricity. Furthermore, it can be used for producing shaft power, which can activate MVC desalination systems.

In approximate terms, the biomass-gasifier gas turbine (BIG/GT) technology shown in Figure XIII, will increase the efficiency of electricity generation by two or more times as the steam cycle and the capital cost per installed kW for commercially mature BIG/GT units is expected to be lower than for comparably-sized steam cycles. The overall economics of biomass-based power generation are expected to be considerably better with a BIG/GT system than with a steam-Rankine system, especially in situations where biomass fuel is relatively expensive. BIG/GT technology is expected to be commercially available within a few years.

Table 20 summarizes the main characteristics of the biomass gasification technology for electricity generation and shaft power.

(ii) *The environmental impact*

At a biomass gasification facility, environmental emissions of potential concerns are primarily liquid effluents from the gas cleanup system. Tar-contaminated liquid effluent contains carcinogenic compounds, namely, phenols and thus requires appropriate treatment before discharge to the environment. The solid residue from gasification of most biomass types is an inert inorganic material that has some by-product value, for example, as a mineral fertilizer or as a construction material, as in the case with rice husk ash.

TABLE 20. TECHNOLOGY SUMMARY: BIOMASS GASIFICATION

Energy services	Electricity (diesel)	Shaft power	Gas turbine/combined cycle
Range of output	5 to 500 kWe	5 to 500 kW	5 to 100 MWe
Range of biomass input	5 to 500 kg/hour		
Technical parameters			
Basic equipment	Gasifier, gas cleanup, diesel engine or		Gas turbine, heat recovery boiler, steam boiler
Fuel inputs	Per kWh: 1-1.4 kg biomass + 0.1 liter diesel (gives 60-70 per cent diesel replacement)		0.5 to 0.67 dry kg per kWhe generated
Energy outputs	1 kWh per (kg biomass + 0.1 liter diesel)		3288 to 4405 dry tonnes per year per MWe installed
Acceptable biomass	Wood chips, corn cobs, rice hulls, cotton stalks		
Biomass requirements	Sized (10-150 mm, depending on gasifier design)		
Useful byproducts	Waste heat, mineral ash		
Key to good performance	Good gas cleanup (especially tars), high capacity utilization		
Special safety concerns	Leakage of (poisonous) carbon monoxide, exposure to tar		
Technology availability	Available from several multinationals		
Difficulty of maintenance	Diesel engine maintenance		Only Demonstrated
Key cost factors	Capital, diesel fuel, operating labour		Capital, fuel cost

Source: S. Kirvan and E. Larson, *Bio-energy Primer: modernized biomass energy for sustainable development*, United Nations Development Programme (2001).

Figure XI. Schematic diagram of a biomass-fired steam-Rankine cycle for combined heat and power production using a back-pressure steam turbine

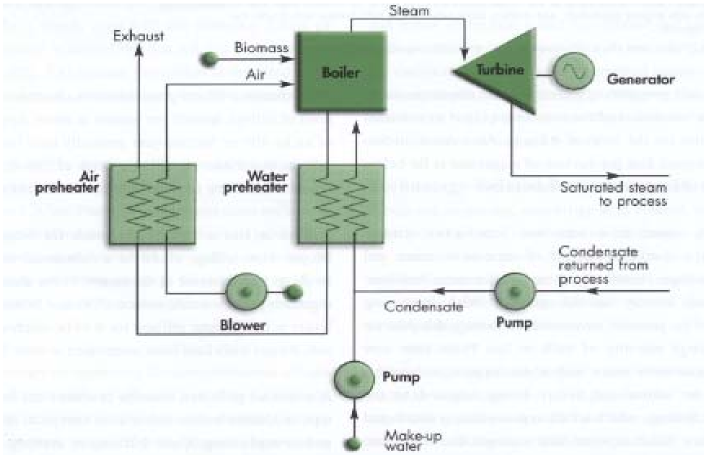


Figure XII. Schematic diagram of a biomass-fired steam-Rankine cycle for combined heat and power production using a condensing-extraction steam turbine

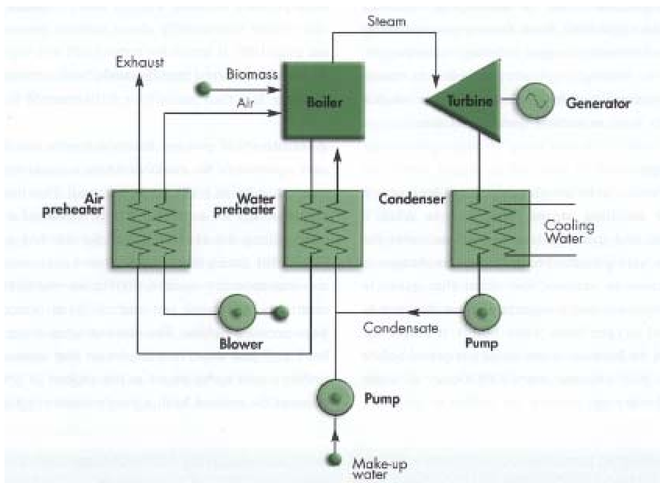
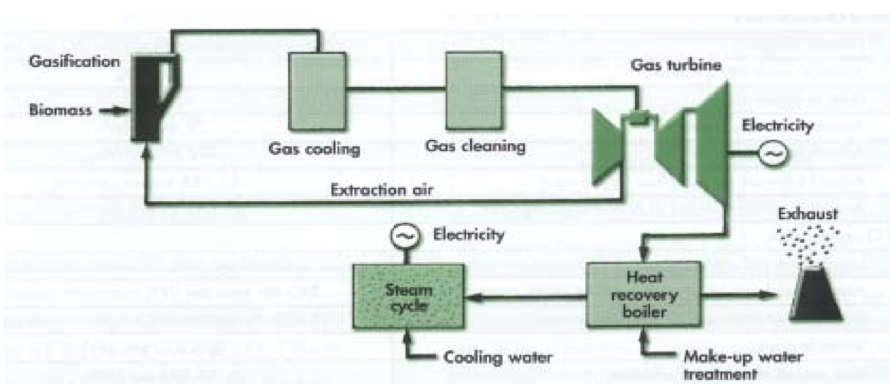


Figure XIII. Schematic diagram of one possible configuration of a biomass-gasifier/ gas turbine combined cycle



Source: S. Kirvan and E. Larson, *Bioenergy Primer: Modernized Biomass Energy for Sustainable Development*, United Nations Development Programme (2001).

C. Impact of power/water cogeneration on the marine environment

This section briefly reviews the impact of both water and power systems on the marine environment of the GCC countries. Annex III examines this subject in more detail.

Natural circulation and flow of seawater through the Strait of Hormuz results in a full exchange of Gulf water over two to five years. Natural evaporation rate from the Gulf water surface is very high, and is estimated at 140 to 500 cm annually. By comparison to other seas, Gulf seawater has one of the highest average salinity rates, 36.3 to 43.6 grams per litre (g/l). Power generation and water desalination activities require large seawater inlet flow for processing and cooling. Chemicals are added to the feed water for different technical reasons, some of which are related to biological control, corrosion and scale prevention and the measure of acidity (pH) adjustment. The rejected brine and cooling seawater combined with the added chemicals or their by-products are in turn discharged into the sea at a higher temperature than feed water by 5^{o} to $6^{o}C$.

Chemical and thermal pollution can affect the environment and modify the marine biota. The concentrated brine discharged from MSF plants is usually mixed with the cooling seawater reject from both the MSF and the power generation plants at a ratio that is less than 10 per cent. The final salinity of this mixture in the outfall culvert is only very slightly higher than the normal seawater salinity. Hence, the increase in density of the brine-seawater reject is very small and is usually offset by a reduction due to the temperature rise. Hence, there is no significant effect on the buoyancy of the brine-seawater mixture discharged.

Chlorine is injected into the seawater feed in the range of 2.5 mg/l and its discharged concentration is always below 0.5 mg/l. Between 85 to 95 per cent of the chlorine active concentration is lost within 30 minutes after injection and approximately 90 per cent is lost at a distance of about 1 km from the discharge location. For this reason, minor potential impacts, restricted to the brine and seawater discharge location, are expected.

Antiscalant and antifoam agents are biologically degradable and are certified by the United States Food and Drug Administration (FDA) as non-toxic. Therefore, their impact on the marine environment is insignificant. In addition, anticorrosion agents that are sometimes added to the seawater feed and metal leaching, namely, copper, nickel, chromium and iron are released with the brine reject and cooling seawater to the sea. Their concentrations are very low, approximately 50 times less than current drinking water standards. An increase of 5^{o} to $6^{o}C$ in the outfall water temperature has the two following effects:

(a) Increase biological activity from April to June and during October and November;

(b) Temporary lethal to sub-lethal impacts during August and September, in the vicinity of the discharge outlet of power/water cogeneration plants only. However, since the second undesirable effect is very limited in time and place, it is possible to conclude that the advantages of temperature increase outweigh the disadvantages.

IV. THE DOMINANT DESALINATION PROCESSES: IMPLEMENTATION STATUS AND COST EVALUATION IN THE GULF COOPERATION COUNCIL COUNTRIES

The GCC countries have been using desalination systems since the 1950s. This trend was accelerated during the 1970s, with the focus on large-scale systems linked to power generation plants as described in chapter III. The total installed capacities in all GCC countries in 2000 was some 10 million m^3 per day.

This chapter reviews the implementation status of water desalination systems in GCC countries as of 2000. It presents a comparative cost evaluation methodology, indicates results and identifies means for cost reduction of desalinated water.

A. 2000: IMPLEMENTATION STATUS AND DISTRIBUTION

This section identifies the appropriate energy options for water desalination based on the diversity of prevailing conditions, technological advances and the available resources including rural and remote sites. A survey of the desalination capacities for each GCC country will initially help to identify, map and evaluate alternative systems for various locations and needs in the region. This type of survey was conducted within the scope of this study for plants that are 25 years old and under, on the basis that older plants are no longer in operation. An inventory including the survey results was developed on a plant-by-plant basis.

Based on the results of the inventory, this section reviews the implementation status of water desalination systems in the GCC countries as of 2000. Table 21 includes a summary with process type, total capacity in m^3 per day and feed water sources.

1. *Distribution by country*

Table 21 reveals that the total installed capacity of desalination plants in the GCC countries reached close to 9.951 million m^3 per day by 2000. This accounted for 45 per cent of the total installed desalination capacities worldwide distributed among GCC countries as illustrated by figure XIV.a. The largest capacities are in Saudi Arabia, United Arab Emirates and Kuwait which reached 5.111, 2.184 and 1.52 millions m^3 per day respectively. These capacities amounted to 532,370 in Qatar, 416,861 in Bahrain and 186,121 in Oman.

2. *Distribution by saline water resource*

Since, the main water resource for all GCC countries is seawater with much less brackish water resources, most of the desalination plants in the region use seawater resources. As shown by figure XIV.b, in 2000 seawater totalled about 87 per cent of the desalination plant capacity and accounted for a capacity of 8.634 million m^3 per day. Meanwhile brackish water totalled 1.242 million m^3 per day, a capacity of 12.48 per cent, while waste water and other types of water reached only 74,733 m^3 per day representing 0.74 per cent.

3. *Distribution by desalination technology*

MSF desalination plants and RO systems are the most predominant installed desalination plants in the GCC countries. These systems reach 7.859 and 1.811 million m^3 per day respectively. VC systems reach 194,69 m^3 per day, ED 64,424 m^3 per day. The minimum installed capacity for ME is only 21,204 m^3 per day (see figure XIV.c).

If these capacities are compared to the total installed capacity of each technology in the world, (see figure XIV.d) it can be shown that:

(a) GCC countries have the largest installed MSF desalination capacities in the world, accounting for 80 per cent of the world total of 9.8 million m^3 per day;

(b) However, GCC countries have 9.35 million m^3 per day or some 19.4 per cent of the total RO world capacity;

(c) The world total of ED, ME and VC technologies in 2000, was 2.95 million m^3 per day. This figure amounted to 280,319 m^3 per day for GCC countries, representing only 9.5 per cent only of the world total.

B. COST EVALUATION OF DOMINANT DESALINATION TECHNOLOGIES

The cost of product water from various water desalination processes depends on the energy supply option that is in place and on the required unit/plant capacity. Furthermore, these costs vary for different site locations, infrastructure requirements, availability of local construction material and other necessary technical resources. These site variations and cost factors are very similar within the GCC countries. For this reason, the comparative cost evaluation presented in this section can be viewed as a general representation for the GCC region, focusing on the two dominant desalination technologies, namely, MSF and RO.

TABLE 21. AVAILABLE DESALINATION CAPACITY IN THE GCC COUNTRIES, 2000 BY TYPE OF TECHNOLOGY AND SALINE WATER RESOURCES
(*Cubic metres per day*)

Desalination type	Feed water	GCC countries						Total by technology
		Bahrain	Kuwait	Oman	Qatar	Saudi Arabia	United Arab Emirates	
RO	Brackish	65 504	44 103	5 151	4 154	974 201	73 969	1 167 082
	Sea	48 217	3 000	13 840	5 000	444 363	58 344	572 764
	Waste and others	-	-	-	1 130	70 133	-	71 263
	Total	113 721	47 103	18 991	10 284	1 488 697	132 313	1 811 109
MSF	Brackish	-	-	-	-	1 300	-	1 300
	Sea	297 020	1 468 036	161 015	499 954	3 491 385	1 940 596	7 858 006
	Total	297 020	1 468 036	161 015	499 954	3 492 685	1 940 596	7 859 306
VC	Brackish	-	-	1 515	-	6 362	-	7 877
	Sea	1 635	-	1 600	19 590	59 012	103 735	185 572
	Waste	-	-	-	-	1 242		1 242
	Total	1 635	-	3 115	19 590	66 616	103 735	194 691
MED	Brackish	1 135	-	-	-	-	500	1 635
	Brine	-	1 272	-	-		-	1 272
	Sea	-	1 200	3 000	2 542	6 900	4 655	18 297
	Total	1 135	2 472	3 000	2 542	6 900	5 155	21 204
ED	Brackish	3 350	2 418	-	-	56 156	2 500	64 424
	Total	3 350	2 418	-	-	56 156	2 500	64 424
Total		416 861	1 520 029	186 121	532 370	5 111 054	2 184 299	

Source: Calculated and classified based on survey data from Mahmoud Abdel-Jawad, “Energy sources for coupling with desalination plants in GCC countries”, consultancy report prepared for ESCWA, (September 2001).

Figure XIV-a. Total desalination capacity in GCC countries (m3/day)

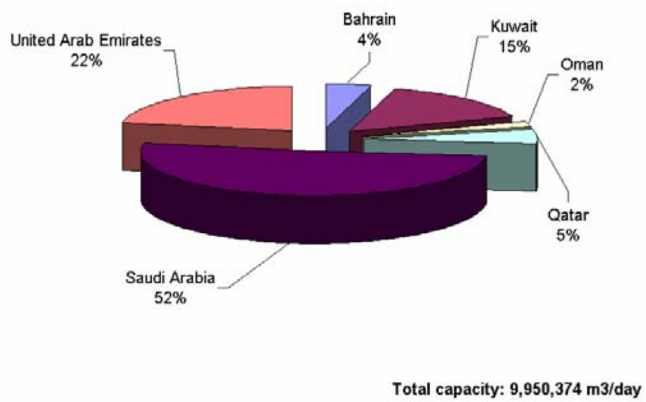


Figure XIV-c. Technology share of desalination capacity

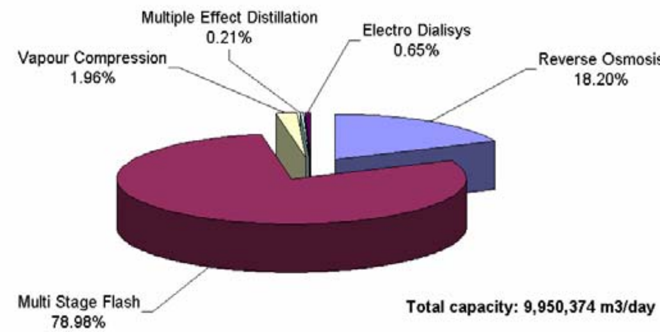


Figure XIV-b. Desalination capacity by saline water resources

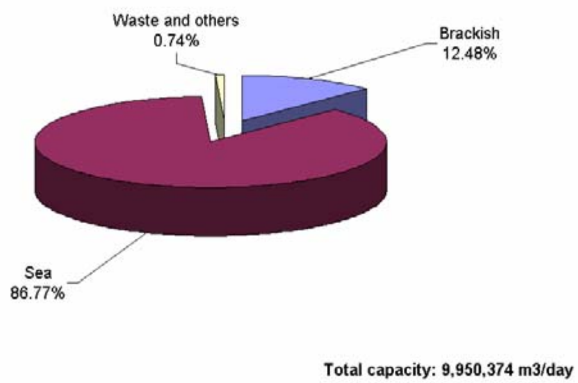
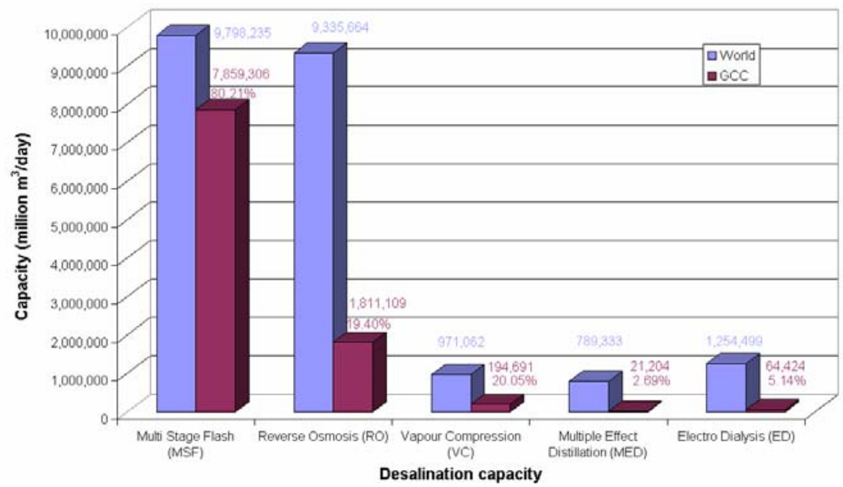


Figure XIV-d. Desalination capacity by technology - world vs. GCC countries



Source: Based on table 21.

1. *Cost evaluation methodology*

The procedure for evaluating the normalized costs for any of the two desalination technologies under consideration is straightforward and is based on the present value concept that takes into account the time value of money. However, in line with the scope of this report, all the expenditures associated with any cost element will be considered only up to the plant outlet and will exclude any costs associated with storage, transportation and distribution of the final product water to the consumers. The main cost components of any of the specific water production systems under consideration are:

(a) *Capital investment costs*

The elements that make up capital investment costs of any given desalination plant are divided into either direct or indirect costs. Direct costs include site acquisition, preparation and development, equipment and structural facilities associated with seawater intake and brine disposal, construction of the power source and its transmission to the desalination site, and the installed desalination equipment complete with piping, electrical, instrumentation and control auxiliaries. Indirect costs are those that do not involve the purchase of equipment or construction services, but include interest on costs incurred prior to operation, in addition to expenditures associated with contingencies, design and engineering and management fees.

In the case of MSF as a component in dual-purpose cogeneration systems, allocation of capital costs between the two production components must be estimated as fairly as possible. This can be done by selecting an applicable unit capital cost of a reference single-purpose power generation system and establishing a value for the electricity. Using that value to compute the capital cost of electricity in the dual-purpose cogeneration system can yield the capital costs associated with the water production. In this case, however, water production appears to be unduly credited with the economic advantages associated with the dual-purpose cogeneration. However, this is somewhat balanced by the fact that the net electrical output from the reference single-purpose power generation system is greater than that of the dual-purpose, and hence the reference unit capital cost for electricity is proportionally reduced.

(b) *Operating costs*

Costs are incurred steadily throughout the operation of a desalination plant. Energy is the most expensive cost. In the MSF system, this includes thermal and electrical energies, whilst the RO process comprises electrical energy alone. Other operating costs include chemical supplies, maintenance materials and spare parts for regular and special repairs, in addition to labour costs, which include salaries, benefits and administrative expenditures.

The sum of these cost components can be translated into a unit production cost using a universal currency such as the United States dollar per m^3. The term unit production cost is useful in the comparison between different desalination systems and in determining the economic merit of a particular desalination system. However, in addition to the unit production cost and in fact, to determine this term, one must consider another key factor known as the plant load factor. Plant load factor is defined as the ratio of actual production over the design production. For the purpose of the present evaluation, a lifetime average value of the load factor is used.

2. *Reference parameters and assumptions for cost evaluation*

Economic evaluation of various desalination processes requires that computations of normalized cost of the product water must be based upon consistent sets of financial and performance parameters. Such parameters include interest or discount rates, amortization period or economic life, average unit investment costs, lifetime average load factor, average unit energy costs, seawater feed characteristics, plant performance and product water recovery ratios. The main reference parameters for the present economic assessment are summarized in table 22.

TABLE 22. MAIN REFERENCE PARAMETERS

Parameter	Desalination technology	
	MSF	RO
Interest rate (percentage)	8	8
Plant economic life in years	25	25
Plant lifetime average load factor (percentage)	90	90
Unit/line capacity (m^3/d)	31 800	10 600
Number of units/line	2	6
Total plant capacity (m^3/d)	63 600	63 600
Number of stages	22	1
Feed water source	Surface	Surface
Feed water TDS (ppm)	43 800	43 800
Feed water temperature (^{o} C)	32	32
Maximum operating temperature (^{o} C)	90.6	35-40
Product water TDS	<25	<500
Pre-treatment	Chlorination Chemical dosing Dearation	Chlorination In-line coagulation Filtration Chemical dosing De-chlorination
Membrane type	-	Spiral-wound
Membrane life in years	-	5

Source: Mahmoud Abdel-Jawad, "Energy sources for coupling with desalination plants in GCC countries", consultancy report prepared for ESCWA, (September 2001).

Annual interest rates vary between 5 and 10 per cent, depending on the country and other economic factors. However, for the purposes of this study, 8 per cent will be taken as the moderate value between these upper and lower limits. In the present evaluation, the amortization period is taken as the economic life of the plant, which is the period ended by shutdown of the plant due to obsolescence. The economic life of 25 years is considered a representation of typical MSF plants in the GCC countries and appears to be reasonable for RO plants especially with regard to the latest technological advances. The availability of high-grade materials of construction that exhibit high degree of corrosion resistance and high levels of durability has contributed significantly to the latest improvements in the availability and reliability of desalination plants. Therefore, based on historic operating data in the GCC countries, the average lifetime availability of 90 per cent seems to be a reasonable value.

The unit/line capacities considered here, are of typical values commonly used in the GCC countries. The number of units or lines was selected to reflect real medium-sized government-owned plants of similar capacities for both MSF and RO. The MSF plant comprises two units each of 31, 800 m^3 per day, while the RO comprises six lines each of 10,600 m^3 per day. Feed water is surface seawater with typical characteristics based on design values of actual plants in the Gulf.

For the RO system, only one type of membrane element is considered in this evaluation: the spiral-wound membrane. The reason for this preference is because spiral-wound membranes perform better than the hollow-fibre membranes, which are becoming commercially limited.[23]

Assumptions for energy consumption levels, which are based on typical MSF and RO plants, are listed in table 23. Values are given in relation to an imagined power plant. Performance parameters for both MSF and RO are of typical design specifications. Only operation at the standard low temperature of 90.6 ^oC is considered for the MSF in the present evaluation. An additional 5 per cent of the low-pressure steam thermal energy is considered as a substitute for the medium pressure steam required for the steam-jet air ejector of

[23] M. Abdel-Jawad and others, "Seawater desalination by reverse osmosis, phase III, WD-005, *KISR Report*, No. 5350, Kuwait Institute for Scientific Research, (July 1998).

the MSF. The total electrical energy requirements for driving brine recycling feed water, make-up, condensate, blow down and distillate pumps, in addition to chemical dosing and other auxiliary operations, is taken at the rate of 3.7 kWh/m^3 of product water for the MSF. The energy required by the RO is the electrical power supply necessary to drive the high-pressure pumps for one RO stage only, in addition to the feed pumps and other chemical dosing and auxiliary systems. The electrical energy consumption of the high-pressure pump has been reduced by 30 per cent to account for the utilization of energy recovery systems. Hence, the final total specific, electrical energy consumption for the RO is estimated at 5.5 kWh/m^3 of product water.

3. *Cost data and results*

(a) *Cost data*

For the present cost evaluation, the unit price of the fuel cost is calculated at $0.0015 per MJ of thermal energy. At this rate, the unit cost of electrical energy generated under the previously described reference plant is estimated at $0.04 per kWh. This value may vary with the capacity of the power plant and with the power to water production ratio under the dual-purpose cogeneration systems. However, this value is considered a reasonable representation in the GCC countries. Results of the estimated costs for the different cost elements in the above MSF and RO reference plants are shown in table 24.

Direct capital investment costs, which include desalination equipment, seawater intake and brine disposal facilities and site developments and buildings, are given in millions of dollars for the installed capacities of both MSF and RO. In addition, indirect capital investment costs are also given using one figure for each of the two desalination plants. The sums of the capital investment costs are used to compute the unit capital charges in dollars per cubic metre of product water for each plant. Other unit costs for energy, labour, spare parts, chemicals and membrane replacement are also given in dollar per cubic metre of product water for both plants.

TABLE 23. ENERGY CONSUMPTION FOR MSF AND RO PLANTS WITH A TOTAL CAPACITY OF 63,600 M^3 PER DAY

	Desalination	Technology
Parameter	MSF	RO
Desalination plant data		
Unit/line capacity (m^3/d)	31 800	10 600
Number of units/line	2	6
Gain output ratio	8.0	–
Product water recovery (%)	11	35
Heat consumption (MJ/m^3)	290	–
Low pressure steam temperature (^{o}C)	100	–
Low pressure steam flow (t/h)	331.3	–
Electric energy consumption (kWh/m^3)	3.7	5.5
Power plant data		
Plant rated output (MW)	210	210
Plant economic life (years)	30	30
Plant lifetime average load factor (%)	80	80
Actual cycle efficiency (%)	38	51
Heat input for actual cycle in (MJ/s)	442	323
Reference cycle efficiency (%)	51	51
Heat input for reference cycle in (MJ/s)	323	323
Energy allocated to water		
Heat consumption in (MJ/m^3)	161.5	0.0
Electrical power in (kWh/m^3)	3.7	5.5

Source: Mahmoud Abdel-Jawad, "Energy sources for coupling with desalination plants in GCC countries", consultancy report prepared for ESCWA, (September 2001).

TABLE 24. COST RESULTS FOR MSF AND RO PLANTS WITH A TOTAL CAPACITY OF 63,600 M^3 PER DAY

	Process	Costs
Cost element	MSF	RO
Capital investment costs (millions of dollars)		
Desalination equipment installed	66.9	57.4
Site developments and buildings	11.2	9.2
Seawater intake and brine disposal	5.6	4.0
Other indirect costs	17.2	14.0
Total	100.9	84.6
Unit costs (dollars per m^3)		
Capital charges	0.452	0.380
Energy:		
Heat	0.242	0.0
Electricity	0.148	0.220
Labour	0.126	0.126
Spare parts	0.068	0.057
Chemicals	0.024	0.048
Membrane replacement	0.0	0.098
Total	1.06	0.929

Source: Mahmoud Abdel-Jawad, “Energy sources for coupling with desalination plants in GCC countries”, consultancy report prepared for ESCWA, (September 2001).

(b) *Cost results*

The sum of all unit costs yields the overall unit cost for each of the two desalination plants, namely, \$1.06 per m^3 for MSF and \$0.929 per m^3 for RO. These results indicate that the overall unit cost of the MSF system is higher than that of the RO by some 15 per cent. Although the unit capital and energy costs of the MSF are significantly higher than those of the RO by 20 and 77 per cent, respectively, these costs were offset by the membrane replacement unit cost, which is applicable only in the case of the RO.

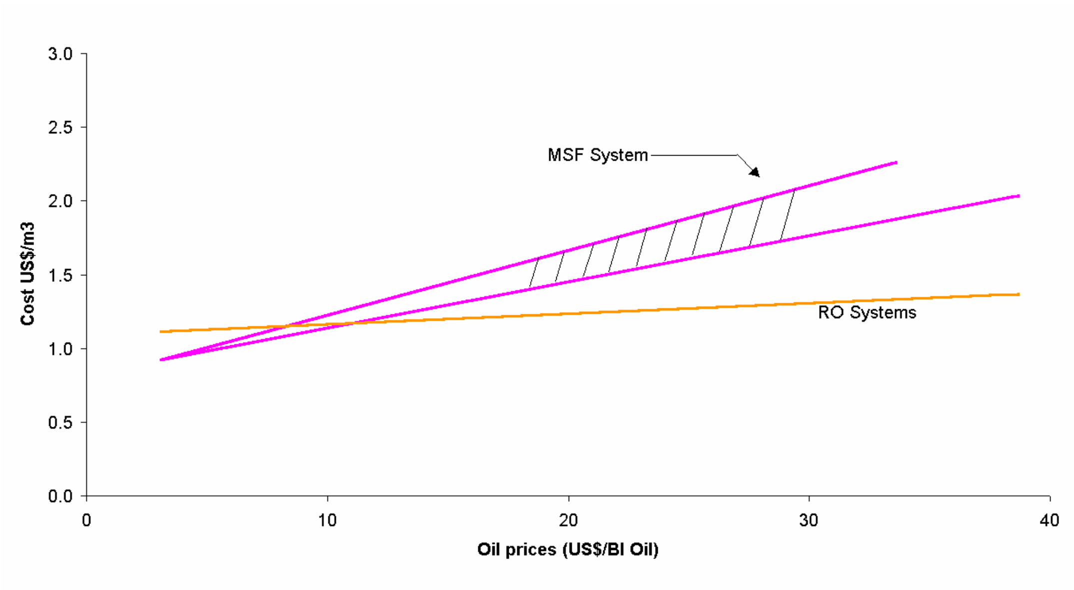
(c) *Effect of fuel prices*

Energy costs represent a remarkable contribution to the cost of produced water from the different desalination systems, with an average that varies between 20 and 30 per cent up to 50 per cent for MSF.[24] As a result, energy costs could become prohibitive for the MSF and it would far exceed the membrane replacement unit cost. In this case, the economic advantages of the RO system would be very significant. Figure XV illustrates the effect of fuel prices on the cost of desalinated water using MSF and RO systems. It shows the slight impact of energy prices on RO systems and the remarkable impact on MSF systems and that this would also vary with the capacity of these systems as shown by the range of prices.[25]

[24] ESCWA, “Development of freshwater resources in the rural areas of the ESCWA region, using non-conventional techniques”, (E/ESCWA/ENR/1999 (16), p. 13.

[25] Ahmad Belhaj Faraj, “Desalination and energy for potable water supply in Arab countries”, “التحلية والطاقة وإمدادات مياه الشرب في الـوطن العربـي”, paper presented at seminar on Development of Energy Policies and their Relation to the Water Sector in the Arab World, (Amman, October 2000) (in Arabic).

Figure XV. Effect of fuel prices on the cost of desalinated water using MSF and RO systems



Source: Ahmad Bel Hag, Faraj "Desalination and energy for potable water supply in Arab countries", Seminar on Development of Energy Policies and their Relation to the Water Sector in the Arab world (Amman, October 2000) (in Arabic).

C. APPROACHES FOR COST REDUCTION

There are a wide variety of water production costs, depending on plant size and energy prices. Usually, costs decrease with increased plant capacity. Costs reported by the GCC countries are usually less than for countries in the rest of the world because of minimal energy charges. For example, the cost of producing 1 m^3 of water in Saudi Arabia ranges from $0.48 to $2.20; from $1 to $1.45 in the United Arab Emirates; $1.14 to $1.64 in Qatar and $0.56 in Bahrain. In other parts of the world, where energy costs are not subsidized, production costs are somewhat higher; for example, in Florida and the United States Virgin Islands, costs range from $2.06 to $2.60; in Malta the cost is $1.18, and in the Canary Islands it is $1.62.[26]

Over the past 15 years, major advances have been made in certain desalination technologies, which have resulted in notable cost reduction. Several approaches were proposed by different experts in the field for reducing the cost of desalinated water from conventional desalination plants. The following sections summarize the most important ones.

1. *The trends for large capacity MSF plants*

It is expected that the capacity of future MSF plants will increase steadily. Currently, the maximum unit capacity is that of the Taweelah B desalination plant, which comprises six units, each with a capacity of 57,000 m^3 per day. This capacity is expected to increase steadily to 100,000 m^3 per day ensuring a 20 per cent drop in investment cost and a 24 per cent savings in water cost.[27]

[26] Ali M. El-Nashar, "The role of desalination in water management in the Gulf region", Abu Dhabi Water and Electricity Authority, (Abu Dhabi, 2000).

[27] Ibid.

2. *Returning to the once-through evaporator design*

The MSF process is either a once-through or a brine recirculation system. Comparison of the two design arrangements clearly indicates that, whilst the brine recirculation system helps to minimize the corrosion problems in the evaporator, the once-through option is more economical, particularly for MSF units of large capacities because of its simplicity of construction and lower pumping power requirements. With the trend towards larger unit capacities, it is therefore expected that large once-through units will be designed to produce water at a reduced cost compared with the conventional recirculation system.

3. *Controllers for optimum operation of MSF units*

The use of process computer systems (PCS) in MSF plants has led to the following: improvement in plant efficiency due to optimisation of control parameters; better operational cost due to minimisation of operation and site supervision staff; enhanced safety of personnel and equipment.

The use of PCS in process automatic control contributes to optimizing the operation by obtaining all necessary field data to achieve the set point adjustment on the computed optimal set point for closed loop controls. With the development of the new generation of composite RO membranes, based on aromatic polyamide, performance has improved dramatically. A lower salt passage results in lower permeate salinity, enabling the RO system to operate at a higher recovery rate. The recovery rate has a major impact on the economics of the seawater RO process.

4. *Seawater RO plants with high recovery rate*

RO for seawater desalination is gaining popularity in many parts of the Gulf over the predominant MSF system. The obvious reason for this is the low specific energy consumption of the RO process in comparison with the MSF system. The additional advantage is the lower capital cost of the RO system compared with the MSF

5. *Hybrid RO/MSF seawater desalination to compromise quality cost constraints*

In the hybrid MSF/RO desalination-power process, seawater RO plant is combined with either a new or existing dual purpose MSF plant with the following advantages:

(a) The capital cost of the combined RO/MSF plant can be reduced;

(b) Common seawater intake is used;

(c) Product waters form RO and MSF plants are blended to obtain suitable product-water quality;

(d) A single-stage RO process can be used and the RO membrane life can be extended, thus the annual membrane replacement cost can be reduced by nearly 40 per cent;

(e) Electric power production from the MSF plant can be efficiently utilized in the RO plant, thereby reducing net export power production. In addition, the electric power requirement to drive the high-pressure pumps of the RO system, which is a major factor of energy consumption, can be reduced by 30 per cent by adding an energy recovery unit to the brine discharge of the RO;

(f) Blending with RO product water reduces the temperature of the MSF product water. A common problem in the Middle East is the high temperature of product water.

The first large-scale MSF/RO hybrid project,[28] the Jeddah I rehabilitation project in Saudi Arabia, is run by the Saline Water Conversion Corporation (SWCC). This 56,800 m^3 per day RO plant, the world's largest facility for seawater conversion, has demonstrated the attractiveness of the hybrid concept.

6. *Other approaches*

Other useful approaches to reduce the cost of desalinated water include: optimising the selection of cogeneration plants for power and desalination; use of off-peak electrical energy in seawater RO desalination systems; the highly effective MED plants, and integrating solar energy with desalination systems in order to reduce water cost.

The status of wide implementation of water desalination systems in the GCC countries, in addition to the increased demand of those countries for more installed capacities, indicates the need for further development of desalination systems with appropriate energy supply options. Desalination is stable, predictable and reliable and increasingly affordable over time, especially as oil is readily available as the primary source of energy. It is reasonable to conclude that desalination will continue to be a component of freshwater supply infrastructure in the GCC countries.

[28] More information on this project can be accessed at http://www.swcc.gov.sa.

V. SUMMARY, MAIN CONCLUSIONS AND RECOMMENDATIONS

There is a lack of freshwater supplies in the GCC countries, despite the fact that they have abundant energy resources and excellent access to seawater. As a result desalination has become a basic necessity to sustain national plans for social, economic, industrial and agricultural urban development. As energy is a basic ingredient in all desalination processes, and as it is a major cost component for freshwater production the choice of energy source is key and deserves special attention when freshwater production by desalination is under consideration.

The core objective of this study is to identify and evaluate appropriate energy supply options in the GCC member countries that could meet the acute need for water desalination. It does this by surveying the available and future possible options, their implementation status and cost evaluation. This chapter summarizes the main conclusions of the study and offers relevant recommendation for further actions in the field.

A. SUMMARY AND MAIN CONCLUSIONS

1. *The integration of water and energy resources in the GCC countries*

The study has reviewed the available water and energy resources in the GCC countries, the need for water desalination and the possible integration of water and energy resources for satisfying these needs. The main conclusions include the following:

(a) *The challenge*

The water scarcity problem in the GCC countries is critical. GCC countries are under the poverty level of renewable water resources of 500 m^3 per year per capita. In fact, five of them are 40 to 50 per cent below this level.[29] GCC countries have tremendous fossil and renewable energy resources but 16.7 per cent of the region's population is concentrated in rural and remote areas with almost no water or energy resources. The available energy resources have been effectively employed to power large desalination plants in urban areas. Two challenges have to be faced. These include the rapidly growing demand for fresh water in general, and the problem of water scarcity in rural and remote areas in particular. These can be tackled by integrated planning based on both available water and energy resources.

(b) *Freshwater demand versus supply*

The 1950s saw the beginning of GCC reliance on desalination as a major freshwater resource. Desalination developed during the last quarter of the twentieth century and was able to meet the staggering increase in demand by constructing the largest water desalination installations in the world. The total freshwater demand for all the GCC countries combined, increased from 4.25 billion m^3 in 1980 to 29.22 billion m^3 in 2000, namely, nearly sevenfold from 1980 to 2000. This figure is expected to increase to 49.38 billion m^3 over the first quarter of the twenty-first century, or 170 per cent of the current value.

The agricultural sector has been, and continues to be, the main consumer of freshwater in the GCC countries. For example in 1980, the agricultural sector represented some 76.7 per cent of total freshwater demand, whilst the domestic and industrial sectors represented 21.4 per cent and 1.9 per cent, respectively. In 2000, these figures were 84 per cent, 14.5 per cent, and 1.5 per cent, respectively. Both the United Arab Emirates and Saudi Arabia exhibit the highest per capita consumption of water, amounting to some 900 to 1,100 m^3 annually, with the agricultural sector as the major consumer. Kuwait has the lowest per capita consumption of water, at some 370 m^3 annually, with the domestic sector consuming the most water. From 1990 to 2000, GCC countries have been able to meet a large percentage of their freshwater demands for

[29] Taysir Ali Dabbagh, "The role of desalination and water management in obtaining economic growth in the Gulf", IDA, (Abu Dhabi, 18-24 November 1995).

domestic and industrial purposes using water desalination. However, these percentages vary widely from one country to another, for example from 100 per cent for Qatar, approximately 70 per cent for Bahrain, Kuwait and United Arab Emirates and some 36 per cent for Saudi Arabia and Oman.

The agricultural sector is the main consumer of water in the GCC countries by approximately 85 per cent. The majority of this water is supplied from ground waters through over-exploitation of deep aquifers. However, more than 80 per cent of water demand for the domestic and industrial sectors in Kuwait, Bahrain, Qatar and United Arab Emirates in 2000 was supplied by water production using desalination. In Saudi Arabia and Oman, water production using desalination supplied some 45 per cent of the water demands for these sectors in 2000, with the remaining 55 per cent being supplied from ground waters.

(c) *Energy resources and consumption*

Energy is an essential ingredient for developing water desalination. Therefore, the availability of appropriate energy resources at reasonable prices would facilitate the planning and implementation of water desalination projects.

(i) *Energy resources*

The GCC member countries are in an ideal situation regarding the energy resources issue since they have excellent fossil energy resources including oil, gas and highly available renewable energy resources, namely, solar, wind and biomass energy resources. In 1999, proven oil reserves in the GCC member countries were estimated at 468.2 billion barrels. This accounted for 45 per cent of the world's total proven reserves. The NG reserves totalled 22,675 bm^3 in 1999. The main gas reserves are in Qatar, Saudi Arabia and the United Arab Emirates.

(ii) *Electric power sector*

The electric power sector in the GCC countries has developed considerably during the past two decades. The total installed capacity of the electric power plants in the six countries reached 44,645 MW of thermal general in 1999. The electric energy generated in the GCC countries in the same year reached 189,261 GW. The growth rate of power demand in GCC countries during the last decade averaged 5 per cent.[30] The development of electric installed capacities in the GCC countries is expected to reach 103.654, 127.272 and 148.053 GW for 2005, 2010, and 2015, respectively. This would cover both needs for electric energy and desalinated water. The installed capacity is expected to reach 103.645 GW by 2005.

(iii) *Energy consumption trend*

In 1999, the primary energy consumption in the GCC countries reached 149.56 mtoe of which 73,963 mtoe is crude oil and 75.6 mtoe natural gas, with a tendency to move towards more natural gas consumption at 50.6 per cent according to OAPEC, *Annual Statistic Report, 2000*. Compared to primary energy consumption in the ESCWA region, GCC consumption is 60.4 per cent of the total region's consumption, while the population is only 17.6 per cent of the region's population. This is emphasized by the average per capita consumption, which reached 5023 kgoe per year and accounted for almost 3.4 times the average in the region.

(d) *Installed desalination capacity*

There were various estimates for the total installed desalination plants capacities in the GCC countries in 2000. However, they all reached approximately 10 million m^3 per day with a plus/minus 10 to 15 per cent variability. Saudi Arabia, United Arab Emirates and Kuwait are the major consumers with about 5.11, 2.18

[30] Ali M. El-Nashar, "The role of desalination in water management in the Gulf region", Abu Dhabi Water and Electricity Authority, (Abu Dhabi, 2001).

and 1.52 million m^3 per day, respectively, while Qatar, Bahrain and Oman follow with 53,137; 416,861 and 186,121 m^3 per day respectively.

2. *Desalination processes, characteristics and relevant energy issues*

(a) *Classification*

Water desalination processes are classified into two groups: distillation-based processes, which include MSF, MED, and VC, and membrane-based processes, which include RO and ED. For characteristics of each category with specific emphasis on its energy needs see chapter II, section A.

Energy consumption in desalination processes, particularly membrane based ones, is dependent on the feed water salinity. The most favourable salt-contents in feed waters for practical application of the various desalination processes are approximately as follows:

Distillation-based processes:	greater than 35,000 ppm
Membrane-based processes:	
ED:	500 to 5,000 ppm
Brackish RO:	500 to 10,000 ppm
Seawater RO:	10,000 to 50,000 ppm

However, it must be emphasized that, occasionally, applications outside these ranges might be considered.

(b) *Factors affecting the selection of a desalination process*

Preference of one desalination process is dependent on a number of factors, such as feed water characteristics, desired product water quality, available energy resources, unit/plant capacity, brine disposal, and economic factors. The most important of these is energy, since all desalination processes are energy-intensive. The energy cost represents 24 to 36 per cent of the total production of desalinated water. Distillation-based processes, namely, MSF, MED and VC, involve phase changes and require thermal and electrical energies. However, membrane-based processes do not involve any phase changes and consume only electrical energy, for example, alternating current for RO to drive electrically driven pumps and direct current for ED. Furthermore, the RO process uses a mechanical mover such as a gas turbine to directly drive its high-pressure pump to generate the required hydraulic pressure.

(c) *Energy consumption and process performance*

All desalination processes, regardless of their technology or configuration, share a common theoretical minimum energy requirement for driving the separation process. Deviation from theoretical energy requirements depends on the process design, principle of operation, and losses of energy encountered in the actual separation process. With regard to energy consumption for seawater desalination of specific feed water and specific production capacity, MSF is the most intensive among applicable processes, where energy cost exceeds one third of the overall cost of product water. RO is the least intensive as energy costs are less than a fifth of the overall cost of product water.

Table 25 summarizes the results of the study based on the performance of several plants using various technologies under different operating conditions. Typical GOR values for large-scale commercial MSF plants range between 8 and 10 kg/kg (PR between 3.5 and 4.5 kg/MJ). The GOR value of 8 is a very common figure for MSF plants in the GCC countries operating at TBT of approximately 91°C. As the TBT is increased to some 110°C for the same plant, GOR value reaches 8.6.

TABLE 25. SUMMARY OF ENERGY CONSUMPTION AND PERFORMANCE PARAMETERS FOR VARIOUS WATER DESALINATION TECHNOLOGIES

Desalination technologies	TBT (^{o}C)	Energy consumption			Product water recovery ratio
		Thermal energy			
		HI/m^{3} [a] (MJ)	Equipment electricity (kWh/m^3)	Electric energy (kWh/m^3)	
A. Distillation-based processes					
1. MSF	90.6	282	167	4.2	10.5
	110.0	256	15.3	3.6	13.4
	Average	250-300	12-20	3.5-5.0	-
2. MED	66	263.5	13.65	1.8	14.4
	72	189.9	9.73	2.3	12
	Average	150-220	8-20	1.5-2.5	-
3. TVC	63	227.3	14.56	1.8	20.83
	70	227.3	14.56	1.6	20.83
	Average			1.5-2	
4. MVC	Based on number of effects	-	-	11-12	40-50
B. Membrane-based processes					
1. RO	Brackish				
	5000 ppm	-	-	2.1	53
	Average	-	-		
	Seawater			1-2.5	
	With ER	-	-	6.15	34.24
	Without ER		-	7.45	34.24
2. ED	Based on salinity				
	2500-5000 ppm	-	-		-
				2.6-5.5	

Source: Compiled from chapter II, tables 13 to 17.

a/ Heat input per cubic metre.

3. *Energy supply options for water desalination in the GCC countries*

Fossil and renewable energy sources have been reviewed in this study, on the basis that they are most suitable for direct or indirect coupling with desalination plants, and are abundantly available in the GCC countries. The most common system in the GCC countries is the dual-purpose power and water cogeneration plants.

(a) *Power water cogeneration option*

Regarding power generation coupling with water desalination under cogeneration options in the GCC countries, consideration is given to four types of couplings:

(i) Power with MSF only;
(ii) Power with RO only;
(iii) Power with MSF-RO hybrid systems;
(iv) Power with MED or TVC.

Regarding the first type, four coupling schemes are possible, namely:

(i) Steam boiler-extraction-condensing-turbine power cycle coupled with MSF. This is the most common coupling scheme in the GCC countries;

(ii) Steam boiler-back-pressure-turbine cycle coupled with MSF. This scheme operates in some power/water cogeneration plants in the GCC countries;

(iii) Gas turbine cycle with heat recovery steam generator coupled with MSF;

(iv) Combined gas turbine and back-pressure steam turbine cycle coupled with MSF.

Regarding the second type, the two most applicable coupling schemes are:

(i) Gas turbine with optional heat recovery steam generator coupled with RO;
(ii) Combined gas turbine and condensing steam turbine power cycle coupled with RO.

It has been established that integration between MSF and RO desalination processes in what is known as hybrid desalination, is highly beneficial. This hybrid configuration offers greater flexibility in dual-purpose power/water cogeneration, increases product water recovery, reduces overall energy consumption per unit product water, utilizes common infrastructure facilities, lowers chemical consumption and prolongs lifetime of the RO membranes. Therefore, coupling of such hybrid systems with any of the steam-boiler-turbine based power cycles or with the combined power cycles is of great interest. Product water savings are guaranteed and significant. However, although several MSF-RO hybrid configurations are possible, only the simplest has been considered in this study. Further attention must be focused on this particular type of coupling because of its relevant and highly significant, advantages.

Coupling of both MED and TVC with power generation is similar to the MSF coupling, since these processes are driven by extracted steam from the power generation system. However, the thermodynamic states of the extracted steam for any of these two processes are quite different from the MSF. This in turn reflects on the specific power outputs from the power cycle with respect to the heat input to any of these desalination processes.

(b) *Renewable energy options*

This study reviewed the current status of a number of solar thermal, solar PV and biomass technologies that can be coupled with water desalination systems for the GCC countries. Wind technologies, although under development, were not taken into consideration as improved resource assessment is needed. In conclusion, solar and biomass systems have the potential to power desalination plants, both large-scale coupled with electricity generation and small-scale in remote areas.

The MED desalination process is the most suitable for coupling with low temperature solar energy collectors, since it exhibits high thermal performance in the low operating temperature range. These systems still cannot compete favourably with fossil fuel based energy desalination. Nevertheless, these systems remain a valid option for remote areas in the GCC countries. However, large-scale namely, tens to hundreds of MW, solar thermal concentrating technologies and biomass technologies for steam and electricity generation are well-developed and will be soon be competitive in terms of generation costs. They are expected to be commercially available no later than 2005 to 2010, when coupling with desalination plants using both Rankine and combined cycle systems will be a viable option.

(c) *Impact on marine environment*

The impact of seawater distillation and power generation on ecosystem components is not as serious as might have been expected. Indeed, it has been shown that the high temperatures related to thermal pollution have certain benefits for the marine environment. It has also been demonstrated that concentrated brine is diluted to a level very close to the quality of the receptor water body. The variation in salinity is less than the annual variation of Gulf seawater. There is no doubt that the aforementioned activities have some adverse impacts on the marine ecosystem in the short term and on localized and limited areas surrounding the outfall of the brine and cooling water of these stations. In this case, the affected areas are in the inter-tidal level that is considered ecologically sensitive. However, the areas that would be affected are judged to be minor. For this reason, complaints regarding migration of fish and shrimp larvae are insignificant, since migration might only be up to a few kilometres.

Natural evaporation from the Gulf waters exceeds the total river runoff by 10 times and is between 125 to 415 times the total desalinated water produced by all the Gulf countries, at any time. However, the environmental impacts of water production and energy generation in the Gulf region should be seriously considered by long-term studies. Properly designed and operated plants are capable of producing enough vital commodities, namely, water and electricity, to outweigh minor environmental risks associated with these operational activities.

4. *Water desalination: implementation status, cost evaluation and cost reduction approaches in the GCC countries*

This study reviews the implementation status of water desalination systems in GCC countries as of 2000. It also presents a comparative cost evaluation methodology, indicates results and identifies means for the cost reduction of desalinated water.

(a) *2000: implementation status*

The preceding analysis has shown that:

(i) The total installed capacity of desalination plants in the GCC countries reached almost 9.951 million m^3 per day. This accounted for 45 per cent of the total installed desalination capacities worldwide in 2000;

(ii) Installed capacity is distributed between Saudi Arabia, UAE and Kuwait at 5.111, 2.184 and 1.52 millions m^3 per day respectively followed by 532,370 in Qatar and 416,861 and 186,121 in Bahrain and Oman respectively;

(iii) Seawater totalled some 87 per cent of the desalination plant capacity and counted for 8.634 million m^3 per day capacity. Brackish water totalled 1.242 million m^3 per day, accounting for 12.48 per cent, while waste water and other types of water were valued at 74,733 m^3 per day, representing 0.74 per cent;

(iv) The MSF desalination plants and RO systems dominate the installed desalination plants in the GCC countries. The two systems reach 7.859 and 1.811 million m^2 per day respectively;

(v) GCC countries have the largest installed MSF desalination capacities in the world. They account for 80 per cent of the world's total of 9.8 million m^3 per day. They also have some 19.4 per cent of the total RO world capacity of 9.35 million m^3 per day; and only 9.5 per cent of the world total of MED and VC systems.

(b) *Cost Evaluation*

(i) *Comparative cost evaluation*

Chapter IV, focuses in section B on the two dominant desalination technologies in the GCC countries, namely, MSF and RO. The evaluation procedure is based on the present value concept. Costs associated with product water storage, transportation and distribution are excluded from the current evaluation. The sum of all cost components are then converted into unit production cost in dollars per m^3. Reference parameters and required assumptions for the cost evaluation include capital investment, interest rate, amortization period, plant lifetime average load factor, average unit energy cost, seawater feed characteristics, unit/plant capacity, operating parameters and costs. For the purpose of this study, values assigned to each of these parameters are usually based on typical MSF and RO plants. With regard to energy costs and energy consumption levels, values are assigned on the basis of an assumed power plant that is coupled with the desalination plant in a dual-purpose cogeneration system.

(ii) *Cost evaluation*

Cost evaluation results show that the product water unit cost is within 10 per cent above or below the \$1 per m^3 mark for both MSF and RO, respectively. Capital charges, energy, labour, spare parts, and chemicals contributions to the total unit cost are estimated at about 43, 37, 12, 6, and 2 per cent, respectively, for the MSF; and at 41, 23, 14, 6, and 5 per cent respectively, in addition to 11 per cent for membrane replacement for the RO. Both capital and energy charges for the MSF are significantly higher than those for the RO by about 20 and 77 per cent, respectively. However, the final effect of these on the total unit cost is offset by the membrane replacement cost. If fuel oil prices double, energy contributions to the total unit cost could exceed the contribution from the capital investment, especially for the MSF. In this instance, energy costs would become prohibitive for the MSF and the economic advantage of the RO would become significant.

(c) *Approaches for cost reduction*

The study investigated a set of concepts and methods for cost reduction and their probable impact on the cost of produced water. These included:

(i) Trends for large capacity MSF plants;
(ii) Returning to the once-through evaporator design;
(iii) Controllers for optimum operation of MSF units;
(iv) Seawater RO plants with high recovery rate;
(v) Hybrid RO/MSF seawater desalination to compromise quality cost constraints;
(vi) Optimising the selection of cogeneration plants for power and desalination;
(vii) Use of off-peak electrical energy in seawater RO desalination systems;
(viii) Highly effective MED plants;
(ix) Integrating solar energy with desalination systems to reduce water cost.

B. RECOMMENDATIONS

If water demand for social and economic development is to be satisfied, desalination will continue to be a vital requirement for GCC countries. Future developments must take the following factors into consideration:

(a) Energy is important and one of the most costly ingredients of water desalination;

(b) The GCC countries are the major consumers of desalination technologies worldwide;

(c) Water is desperately needed for rural populations in areas where desalination would often be more economical than water transport from central plants;

(d) Renewable energy technologies are currently mature or maturing for large-scale thermal and electric energy generation plants of different types.

With this in mind, the following recommendations are made:

1. *National and regional capacity-building*

Since the GCC countries in particular and the ESCWA region in general, use desalination systems more than any other region in the world, it follows that Governments, Arab funds, regional organizations and the private sector must direct concerted efforts towards enhancing the region’s capacity for developing, manufacturing, installing, operating and maintaining desalination systems. This would include the following:

(a) *Performing field case studies*

Different factors affect the performance and costs of desalination processes. In this case, where several of those factors are site-specific, it is recommended that a set of detailed site-specific case studies be performed on existing plants, with in depth techno-economic analysis of the plant with particular regard to the performance ratings, difficulties faced, energy consumption and cost as well as operation and maintenance history and cost. The results of those field studies would form an effective database for future decision-making and selection of desalination systems for a specific application.

(b) *Research and development*

Supporting and enhancing research and development on desalination systems, with the objective of adapting the technologies to local/regional conditions and capabilities in addition to optimising systems to respond to increased market needs for desalination systems. It is estimated that an appropriate research and development programme that addresses the needs of the region would cost some $650 million over five years.

(c) *Technical and operational expertise*

Technical and operational field expertise in addition to local and regional capabilities and expertise must accommodate the requirements of the installation and operation and management of new systems. Moreover, advanced technical expertise is essential for the selection of appropriate technology and energy systems. Therefore governments and concerned regional organizations should arrange workshops, training and field missions for chemists, engineers and technicians both on national and regional levels to enhance their expertise in the field.

2. *Development of appropriate energy supply options*

(a) *Upgrading energy efficiency for existing systems*

The relevant power and water authorities must direct efforts towards more accurate evaluation of the possible cost reductions of energy consumed for existing desalination processes by upgrading system efficiency and adopting the off peak desalination concept described in this study.

(b) *Promoting renewable energy options*

For the 2005 to 2015 period, renewable energy options for powering desalination plants, particularly solar thermal and biomass for large-scale and PV for small scale plants, must be evaluated as potential options. It is expected that frame solar and biomass systems will reach maturity and cost competitiveness by this stage.

(c) *Research and development: energy issues*

Research and development must examine energy issues for desalination that can reduce cost, improve energy utilization, efficiency and develop new technologies. The following must be considered:

(i) Hybrid solar and solar/conventional fuel desalination plants;

(ii) Development of energy efficient small desalination systems;

(iii) Assessment of the impact of fuel cell integrated recovery systems and technology on desalination;

(iv) Innovative alternate energy desalination plants.

Annex I

THE FACTORS AFFECTING THE SELECTION OF DESALINATION TECHNOLOGY

Preference of one desalination process or processes is usually attributed to a number of factors. These are summarized as follows:

(a) Feed water characteristics in terms of salt concentration and composition, dependability related to quality and quantity and the seasonal temperature distribution;

(b) Desired product water quality and recovery ratio as a fraction of the feed;

(c) Availability of dependable energy supply, specific energy consumption rates and efficiency of energy utilization;

(d) Available unit/plant capacities;

(e) Brine disposal;

(f) Relative costs involved.

Each of these factors will be reviewed in some detail in this annex, focusing on desalination in the GCC countries.

A. FEED WATER CHARACTERISTICS

Three groups of very different saline waters are suitable for desalination applications: seawater, brackish water and wastewater. The differences in saline waters are very significant in determining the fitness and suitability of the various commercially available desalination processes for each of these groups. The feed water characteristics under consideration in this study include the following:

1. *Concentration of dissolved salts in feed water*

Various commercially available desalination processes are capable of producing fresh water from feed waters with total dissolved salts ranging from a few hundred parts ppm, namely wastewater at less than 1000 ppm, to tens of thousands ppm, as is the case of seawater at more than 35,000 ppm. Distillation-based processes are mostly used for high salt-content waters, namely, seawater and concentrated brine. In practice, there are no technical difficulties with the distillation of feed waters of lower salt-concentrations. However, distillation involves a phase change, operating on the principle of converting large amounts of liquid water into vapour and back into liquid water. This involves relatively high-energy consumption that is barely affected by the salt concentration. Therefore, it is more economically sound to restrict distillation-based technologies to high salt-content feed waters, namely, those above 35,000 ppm.

In contrast, energy consumption in membrane-based processes is proportional to the concentration of the dissolved salts in the feed waters. For example, ED operates on the principle of separating a small number of ions dissolved in large quantities of water. As the number of dissolved ions increases, electrical energy consumption increases and the membrane area increases proportionally. This renders the technology highly uneconomical. The ED process is considered to be more suitable for lower salt-content brackish waters with salinity less than 5,000 ppm.

RO, however, is the most tolerant membrane-based desalination process with respect to salt concentration in the feed waters. RO membranes are capable of producing fresh water from feed waters with salt contents ranging from few hundreds to tens of thousands ppm. RO membranes designed for brackish waters are used for feed waters with salt-contents reaching to approximately 10,000 ppm. RO membranes with sufficiently high salt rejection and acceptable flux characteristics for feed waters with salinity above 10,000 to approximately 50,000 ppm are used in the GCC countries and elsewhere in the world.

Therefore, the most favourable salt-contents in feed waters for practical application of the various desalination processes are approximately as follows:

Distillation based processes:	greater than 35,000 ppm
Membrane-based processes:	
ED:	500 to 5,000 ppm
Brackish RO:	500 to 10,000 ppm
Seawater RO:	10,000 to 50,000 ppm

However, it should be emphasized that applications outside these ranges can be justified.

Table 1 lists the distribution of different feed water sources against the various desalination processes in the GCC region. According to statistics, above salinity ranges for various desalination applications are maintained within the region.

2. *Composition of dissolved salts in feed water*

Various dissolved substances in the feed water have certain deleterious effects on different desalination processes. The most important of those substances are the hardness components in feed waters, particularly calcium, magnesium and sulphate. The extent of pre-treatment of feed water depends on the concentration of the hardness components in addition to the desalination process itself. Normal pre-treatment of feed water prevents the detrimental effect of magnesium. Furthermore it retards and prevents precipitation of calcium carbonate scales. However, the limited solubility of calcium sulphate remains the most restrictive parameter on the maximum allowable brine concentration ratio and hence on the maximum allowable product water recovery ratio for all desalination processes. In addition, it is the major restrictive parameter on the maximum allowable operating temperature in the distillation-based processes.

Softer feed waters, namely, feed waters with low concentrations of hardness ions, permit higher brine concentration and higher product water recovery ratios and also extend the upper limit on the operating temperature range in distillation-based desalination processes. Recent advances in pre-treatment techniques have identified the possibility of using NF for softening feed waters to seawater RO and distillation-based technologies. Table 2 lists and compares typical compositions of brackish and seawater feeds prevalent within the GCC countries.

3. *Dependability of feed water sources*

Dependability of the feed water sources relates to both quality and quantity of the feed water to the desalination system. Ground waters and seawater from beach wells are sources for naturally filtered feed waters that have very low densities of suspended solids and pose an insignificant biological threat. Thus, feed water from these sources requires no further pre-treatment, beyond fine filtration and chemical treatment, when used to feed membrane-based desalination processes. However, there are certain limitations on the quantities of these types of feed water sources. Feed waters from non-renewable ground water aquifers are limited in quantity, since both water level and salinity are liable to change drastically with high pumping rates. Limitations on feed water quantities from renewable sub-surface brackish water and beach well seawater are determined by the hydrological characteristics of these water sources. Thus, although application of membrane-based desalination process using these high quality feed water resources is highly desirable, it is limited by quantity restrictions.

TABLE 1. GROWTH DISTRIBUTION OF THE VARIOUS DESALINATION PROCESSES AGAINST THE DIFFERENT FEED WATER SOURCES IN THE GCC COUNTRIES, 1975-2000
(*Cubic metres per day*)

	Seawater				Brackish water				Wastewater & other waters			Total
Year	MSF	RO	VC	MED	RO	ED	VC	MED	RO	MED	VC	capacity
1975	68 680	0	0	0	5 112	946	0	0	0	0	0	74 738
1980	1258 539	18 605	4 924	2 771	296 059	28 730	1 664	0	17 030	0	0	1 628 322
1985	4 026 743	58 820	21 474	6 271	502 532	49 605	1 664	500	17 530	0	0	4 685 139
1990	5 276 133	247 307	33 737	10 771	788 706	54 075	5 120	500	54 038	1 272	0	6 471 659
1991	5 276 133	247 307	54 197	10 771	796 335	57 307	5 120	500	54 038	1 272	0	6 502 980
1992	5 348 913	249 632	57 347	10 771	847 110	57 307	5 120	500	54 038	1 272	0	6 632 010
1993	5 626 023	253 742	69 707	10 771	860 790	58 747	5 120	500	56 588	1 272	0	6 943 260
1994	5 657 823	323 425	80 502	10 771	992 892	58 747	6 635	500	57 688	1 272	0	7 190 255
1995	6 017 923	464 110	90 002	10 771	1 019 652	59 747	6 635	500	66 848	1 272	0	7 737 460
1996	6 328 307	565 614	105 612	11 971	1 128 692	59 747	6 635	500	70 763	1 272	0	8 279 113
1997	6 832 107	569 214	119 252	11 971	1 149 092	59 747	7 877	500	71 263	1 272	1242	8 823 537
1998	7 308 807	571 864	124 272	13 371	1 166 128	59 747	7 877	500	71 263	1 272	1242	9 326 343
1999	7 477 167	571 864	164 067	13 371	1 166 128	59 747	7 877	500	71 263	1 272	1242	9 534 498
2000	7 481 967	571 864	164 067	13 371	1 166 128	59 747	7 877	500	71 263	1 272	1242	9 539 298

Source: Mahmoud Abdel-Jawad, "Energy sources for coupling with desalination plants in GCC countries", consultancy report prepared for ESCWA, (September 2001).

TABLE 2. TYPICAL FEED WATER COMPOSITION FROM DIFFERENT SOURCES IN THE GCC COUNTRIES

Feed water / Parameter	Brackish water (ppm)	Seawater (ppm)	
		Surface	Beach-well
Na^+	904	13 170	13 981
K^+	6	474	386
Ca^{++}	282	550	614
Mg^{++}	88	1 578	1 467
Sr^{++}	<0.1	1	11
Ba^{++}	<0.01	<0.5	<0.5
Cu^{++}	<0.01	<0.05	<0.05
Zn^{++}	<0.01	<0.05	<0.05
Mn^{++}	<0.01	<0.05	<0.05
Al^{+++}	<0.01	<0.05	<0.05
Fe_{total}	<0.01	<0.05	<0.05
Cl^-	1 460	22 277	22 354
Br^-	<0.01	80	<0.05
HCO_3^-	76	128	144
NO_3^-	<0.01	<0.05	<0.05
SO_4^{--}	771	3 841	3 109
CO_2	2	8	9
TDS	3 587	46 110	41 518

Source: Mahmoud Abdel-Jawad, "Energy sources for coupling with desalination plants in GCC countries", consultancy report prepared for ESCWA, (September 2001).

Surface seawater, however, is the ultimate unlimited water resource. All GCC countries have unlimited access to the sea. Seawater feed quality is very much dependent on the intake site location and is subject to seasonal variations and to sudden changes, particularly in turbidity. For distillation-based processes, two to three stages of screening are usually sufficient to remove coarse suspended particles that could damage mechanical components, namely, pumps, valves, instruments and tubes. Very small and fine suspended solids in the feed water usually cause no concern in the operation of distillation-based desalination systems. In addition, normal treatment by chlorination prevents undesirable biological activities in distillation-based desalination systems.

In contrast, surface seawater feed to RO requires extensive pre-treatment. Few techniques are available. These include conventional pre-treatment using sedimentation, coagulation and filtration through media filters and advanced filtration, namely, micro-filtration. The density of the suspended solids in RO feed waters must meet certain minimum levels before entering the membrane vessel. In addition to turbidity, an index known as silt density index (SDI) is commonly used as a measure of the feed water quality of RO systems. RO membrane manufacturers usually specify values between three and four for feed water SDI values. The SDI, however, does not include the effects of biological activities in the feed water, which is usually another major concern in the RO applications. In conclusion, the extent of the required pre-treatment for seawater RO systems is very much site-dependent. Thus, it is recommended that a pilot study of the relevant feed water characteristics and the extent of pre-treatment and its design requirements should precede the actual implementation of RO projects using surface seawater.

Brackish RO membranes are used to produce water of potable quality from wastewater for non-drinking and non-personal uses. Wastewater feed for such RO systems must undergo proper pre-treatment to control feed water quality.

4. *Feed water temperature*

Seawater temperatures vary between 15°C in the winter and 35°C in the summer in the GCC countries. Ground water temperatures remain more constant, at approximately 5°C throughout the year. Generally, higher temperature feed water is desirable for the membrane-based process. In the ED process, for example, electrical conductivity and salt diffusion increase with temperature resulting in favourably decreased electrical energy consumption. However, since ED technology is practically limited to ground brackish waters, it is more suitable for feed waters with moderate temperatures.

RO membrane flux increases with the increase in feed water temperature. It has been shown that an approximate 2 per cent increase in the seawater RO flux is associated with a unit temperature rise in the feed water on the Celsius scale.[1] The latest improvements in the RO membrane industry have increased the upper allowable operating temperature limit to some 45°C. The improved RO membrane performance using warmer feed water has led to the possibility of hybridisation between seawater RO and MSF desalination. Integration between these two processes results in a nearly fixed feed water temperature for the RO desalination system throughout the year. In the case of ground water and beach well water for brackish and seawater RO applications, respectively, the operating temperature is in the middle range and is nearly fixed all year round.

In the distillation-based desalination process, the influence of the feed water temperature on the optimisation of each specific process is quite complex as a result of its impact on the number of stages/effects, operating temperature and pressure ranges, brine concentration and mass flow to distillate ratios, performance factors and so on. Generally, lower feed water temperatures have a beneficial effect on MSF and MED desalination processes, whilst a higher feed water temperature benefits the VC process.

B. PRODUCT WATER QUALITY AND RECOVERY

Whilst feed water characteristics influence the preference of desalination processes for technical and economic reasons, desired product water quality and rate of recovery influence the selection of a desalination process for a given application. Product waters from various desalination processes, range between a few to several hundreds ppm of TDS, and range from 10 per cent to more than 50 per cent of the total feed water flow rate. This section examines the following aspects of product water: product concentration, product composition and product recovery ratio with respect to feed water.

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[1] Essam El-Sayed and others, “Performance evaluation of two reverse osmosis membrane configurations in a MSF/RO hybrid system”, *DESALINATION*, No. 128, (December 1999), pp. 231-245.

1. *Product water concentration*

Distillation-based processes produce the purest product water ranging from about 5 to 50 ppm of TDS. Hence, product water produced by distillation can be blended with other waters, namely, ground water, brackish water or water produced from other membrane-based processes, to adjust its TDS to the required levels.

The case is quite different in the membrane-based desalination processes. The product water from a single stage RO desalination system ranges approximately between 100 and 1000 ppm of TDS, depending on the feed water itself, the type of RO membrane and its salt rejection characteristics. These vary over the lifetime of the membrane. Lower salinity product water from brackish water feed and higher salinity product water from seawater feed is a possible outcome. The product water from the ED processes is generally within the range of 350 to 500 ppm of TDS. The limits on lower salinity product water from the ED processes are set by economic constraints dictated by the increase in the electrical resistance with the decrease in the ions concentration and hence the increase in the electrical energy consumption, in addition to the necessity for more stages for the additional removal of ions.

2. *Product water composition*

Product water compositions from various desalination processes in the GCC countries have been the subject of many publications. Detailed discussion of this subject is beyond the scope of this report. However, some basic remarks are made here.

Some of the undesirable materials or compounds found in the feed water can be removed during pre-treatment processes, while others are removed in the desalination process itself. Product waters from various desalination processes often contain some of these materials or compounds and this will require further treatment in order to reach the required quality of the product water.

Distillation-based processes essentially remove all suspended and dissolved substances in the feed water. Only dissolved gases, which were already present in the feed water or formed during the desalination process itself, can be found in the product water, namely carbon dioxide and ammonia.

Membrane-based processes operate on the principle of ion rejection. The ability of any given membrane to reject ions is not uniform. Therefore, rejections of the various ions, when calculated as percentages between product water and feed water, are usually different. In the ED desalination process, for example, monovalent ions are usually rejected more efficiently than multivalent ions. Therefore, the ratio of concentration of multivalent ions in the product water with respect to the TDS is usually higher than that in the feed water. In addition, in the ED desalination process, non-electrolyte impurities, which might be present in the feed water, usually remain in the product water.

Contrary to the ED process, passage allowance of monovalent ions with pure water through RO membranes is usually higher than that of multivalent ions. Therefore, the ratio of concentration of monovalent ions in the RO product water with respect to the TDS is higher than that in the feed water. Furthermore, the RO process is capable of removing most impurities and any undesirable contamination present in feed waters, namely, toxic compounds, organic compounds and even bacteria and viruses in the case of wastewater desalination.

3. *Product water recovery*

The amount of product water recovered from a certain feed water flow rate using a given desalination technology is known as product water recovery ratio. It is usually measured as a percentage ranging from some 10 to more than 50 per cent for the various desalination technologies. This ratio is of economic significance owing to its impact on the size of the feed water intake required for specific production capacity and the associated energy consumption. Generally, the MSF desalination process is found on the lower end of the above range, while brackish water RO, including wastewater desalination applications, are at the high end of the range.

C. DESALINATION UNIT CAPACITY

Selecting the most suitable unit capacity for the most suitable desalination process for a particular application is usually made according to the following criteria:

(a) Maximum plant availability;
(b) Minimum stand-by capacity;
(c) Minimum per unit product water costs;
(d) Ability to support reasonable operating and maintenance flexibility.

Accordingly, there are always upper and lower limits on the desalination unit capacity and hence on the number of units in any given desalination plant of a specific capacity. Meeting a minimum capacity for fairly large capacity desalination plants, for example, seawater desalination complexes in the GCC countries, depends on the availability of large unit capacities. Therefore, the availability of large unit capacities for certain desalination applications is of a particular technical importance. In addition, the scale-up of a desalination unit's capacities can significantly influence the costs of desalination and therefore influence the preference of some processes over others.

To describe the scale-up of a desalination unit capacity of a certain desalination process and how it influences the preference of such a process, it is necessary to determine which effects and physical quantities are of importance. These must be classified and related to the quantity that represents the physical unit capacity, based on observations and mathematical reasoning in terms of what can be identified as controlling variables in the process. This is not always a straightforward task, particularly in the distillation-based processes, namely, the MSF, MED and VC processes. This is because of the complexity and multiplicity of the controlling variables involved in scaling-up and associated with the change of phases, transfer of energy from an outside source and/or exchange of energy between phases and the multiple dynamic conditioning, namely, staging where proper temperature, pressure, flow rate and salinity gradients in addition to thermodynamic equilibria must be established. This may explain the relatively slow progress in the scale-up of desalination unit capacities for MED and VC technologies. In contrast, the RO desalination process is a very much simpler. In this case, the feed pressure and membrane characteristics, in terms of permeability and salt-rejection, are the only controlling parameters. Consequently, a simpler modular approach can be taken since these parameters are pre-set for standard RO membrane modules, which are manufactured to yield certain nominal product flow rates and salt rejection at specific operating temperature and pressure ranges. The number of membrane modules is determined directly by the desired overall plant capacity and method of connecting and arranging these modules together in trains, which parallel the units in MSF desalination.

D. WASTE BRINE DISPOSAL

Desalination processes have fewer problems with process effluents compared to most other individual processes, since they discharge less harmful waste to the environment. Nevertheless, desalination plant waste must be properly disposed of to prevent environmental pollution and damage to natural resources. Depending on the type of the desalination technology, waste includes brine concentrate, cooling water, particulate matter commissions and heat. These are all usually referred to as waste brine. The physical application, capacity limitations and compatibly of available brine disposal systems with respect to a particular desalination plant, are of great importance because of the significant engineering and economic aspects involved.

Waste brine from seawater desalination plants in the GCC region is usually in the range of 60,000 to 80,000 ppm as TDS. As for brackish water applications, the waste brine TDS is in the range of 5,000 to 20,000 ppm. Furthermore, depending on the process type, waste brine might be at elevated temperatures, within single digit degrees on the Celsius scale above feed water temperature. It may have a pH ranging from 4 to 9 and very low levels of dissolved oxygen. It can contain corrosion-erosion products from various components of the plant and traces of residual chemical additives.

Disposal of waste brine from desalination plants is possible through one of the three methods reviewed below.

1. *Waste brine disposal to surface waters*

This is the most common method in all seawater desalination plants where waste effluents are discharged directly to the sea at a safe distance downstream of the feed water intake. There is however, some concern about the harmful effects that some of the corrosion-erosion products, namely copper, which might be present at higher concentrations and above the lower levels of dissolved oxygen in the disposed waste brine. Such harmful effects can be reduced or even totally eliminated by the dilution effect of the cooling water that is usually required in thermally driven distillation plants. In such cases thermal pollution is probably the primary concern, nevertheless, even this can be avoided by proper selection of the outfall location to ensure unrestricted discharge to the open sea and effective, quick dilution by the natural seawater currents.

2. *Waste brine disposal using evaporation ponds*

Waste brine is disposed of into manmade ponds in which the brine is subject to natural evaporation. This method is therefore, only suitable for application in warm, dry climates where low land costs prevail. It is possible to use this method of waste brine disposal for desalination plants in inland locations where access to surface water disposal systems is not available. There are, however, certain restrictions that must be met to prevent possible pollution of both above and underground environments, and to prevent any other adverse effects. The necessary lining of fairly large surface areas, required in most inland locations for protection against seepage, means that this method may be costly.

3. *Waste brine disposal using deep-well injection*

This is another method of waste brine disposal for inland locations where suitable underground formations for receiving waste brine exist. This method is promising for relatively smaller flow rates of waste brine, since the cost of injection into the deep wells is primarily dependent upon the volume of the disposed effluents. To ensure full protection of natural ground waters from contamination by disposed waste brine, sound engineering and geological principles must be properly observed when designing deep wells.

Annex II

FUEL OIL AND GAS-BASED POWER GENERATION OPTIONS IN THE POWER SECTOR OF THE GCC COUNTRIES

This annex reviews available options for coupling electric power generation systems with water desalination plants. It examines the operating principles and main characteristics of these systems.

Figure I illustrates the basic components of an electricity generation system. Figure II details three typical systems for large-scale electricity generation.

A. STEAM BOILER TURBINE-GENERATOR POWER CYCLE

Fuel oil and gas fired steam boiler-turbine-generator power plants are among the most dominant power generation systems in the world, particularly in the Middle East and in the GCC countries. These systems are considered to comprise well-established technology that is based on the simple Rankine cycle or the Rankine cycle with reheat.[2] In these systems, fuel oil or gas are burned at some 1000°C and generate steam in the boiler at approximately 550°C and 15 Mpa. The generated steam then expands adiabatically through a turbine, which comprises a series of rotor blades separated by sets of stationary blades. These rotating and stationary blades, each is a pair, are considered as one stage. They act in tandem, to allow the steam flow to exert work on the rotor blades, which is then transmitted to the turbine shaft that is coupled with an electric generator. As the steam works on each stage, it loses pressure and heat and cools down. It is known as expanded steam. Steam turbine stages are usually divided into three groups: high, medium and low-pressure stages. Between the high and medium pressure stages, it is possible to reheat steam to a temperature corresponding to its original temperature at the inlet of the high pressure stages, thus the cycle includes reheat. As the steam exits the low-pressure turbine stages fully expanded, it enters a condenser as exhaust steam under vacuum and at some 40° to 50°C. It is possible to return the condensed steam to the boiler as feed water for regeneration.

These systems are available in a wide range of unit capacities between approximately 50 to 800 MW, with thermal efficiencies exceeding 42 per cent. Generally, these power generation systems are characterized by high specific power outputs that are never matched by any other types of energy. Furthermore, they have very high load factors, low maintenance requirements, excellent regulation and they offer very high levels of reliability under harsh operating conditions.

B. GAS TURBINE POWER CYCLE

Gas turbine power plants are flexible energy sources of electric power supply, based on the Brayton Cycle. They were developed as a result of advancements in metallurgy and computational fluid dynamics of compressors and turbines. Simple gas turbine cycles are comprised of three basic processes: adiabatic compression, constant-pressure heating and adiabatic expansion. During the first process, namely, adiabatic compression, air is withdrawn at approximately atmospheric conditions and is compressed to a certain pressure that is several times higher than the inlet air pressure. Latest designs allow compression ratios up to 30, for example, the ABB GT24. In the constant-pressure heating process, which occurs in a combustion chamber, fuel is introduced and mixed with the compressed air allowing combustion to produce high temperature gases, which then expand through the turbine while exerting work on its rotor blades. Turbines are usually of multiple stages allowing the gas flow to expand in such a manner that minimizes losses. Since the work exerted by the hot expanding gases is much greater than the work exerted during the air compression, the difference between these two works is the net useful work that is transmitted to the electric generator. In some cases, where exhaust gases are discharged at temperatures considerably higher than the compressed air temperature at the inlet to the combustion chamber, it is possible to incorporate a regenerator

[2] Bernard D. Wood. *Applications of Thermodynamics*, second edition, Howard W. Emmons, consulting ed. (Massachusetts, Addison-Wesley, 1982).

to recover the excess heat of the exhaust gases by heating the compressed air, hence it is called gas turbine cycle with regeneration.

Simple gas turbine cycles, or gas turbine cycles with regeneration are available in unit capacities exceeding 200 MW and with thermal efficiencies approaching 40 per cent. Gas turbine power plants are simple, compact and light. It is possible to build them faster and at much lower specific capital costs than steam boiler-turbine plants, especially since they do not require cumbersome cooling water feed and condenser components. Furthermore, they have the capability of rapid start-up and loading and therefore exhibit greater flexibility for peak or standard load modes, with low standby losses. However, gas turbines remain extremely sensitive to air quality in terms of temperature, humidity, and suspended impurities. The extremely harsh weather conditions in most of the GCC countries negatively influence the performance, operational stability and maintenance requirements of these systems.

C. COMBINED CYCLE POWER PLANTS

Up-to-date energy systems are composed of a combination of gas and steam turbine power plants with power generation capacities exceeding the 600 MW mark. In these systems, heat recovery steam generators recover heat from the gas turbine exhaust gases and generate steam for the steam turbines. In some cases, particularly in large capacity power plants, it is possible to supplement heat recovery steam generators with extra firing to increase the steam turbine cycle power output. Combined gas and steam turbine cycles offer higher levels of thermal efficiencies of approximately 60 per cent when fuelled with NG. Nevertheless, they have higher technology levels, which might be lacking in the GCC countries.[3] The excellent performance of this type of energy systems is of particular interest and deserves careful consideration especially under the extreme variable load conditions in the GCC countries.

D. DIESEL ENGINES

Diesel engines have made significant gains in thermal efficiency as a result of recent technological advancements in design, manufacturing and materials. Low-speed diesel engines have thermal efficiencies approaching 50 per cent and capacities up to 50 MW. High-speed diesel engines, however, have efficiencies of more than 30 per cent and are built for the lower power output capacities. Lower speed diesel engines are more tolerant with regard to fuel type and maintenance requirements, when compared to the high-speed diesel engines, which only run on good quality diesel oil. Low speed diesel engines operate on fuels ranging from NG to crude oil. Moreover, they require lower levels of maintenance, which in turn reflects on the availability of these systems. The main drawback of low-speed diesel engine systems are the difficulties associated with compliance with air pollution standards, which requires additional cost.

[3] Bruno Facchini, D. Fiaschi and G. Manfrida, "Exergy analysis of combined cycles using latest generation gas turbines", *Journal of Engineering for Gas Turbines and Power,* No. 122, pp. 233-238.

Figure I. Basic electricity generation system

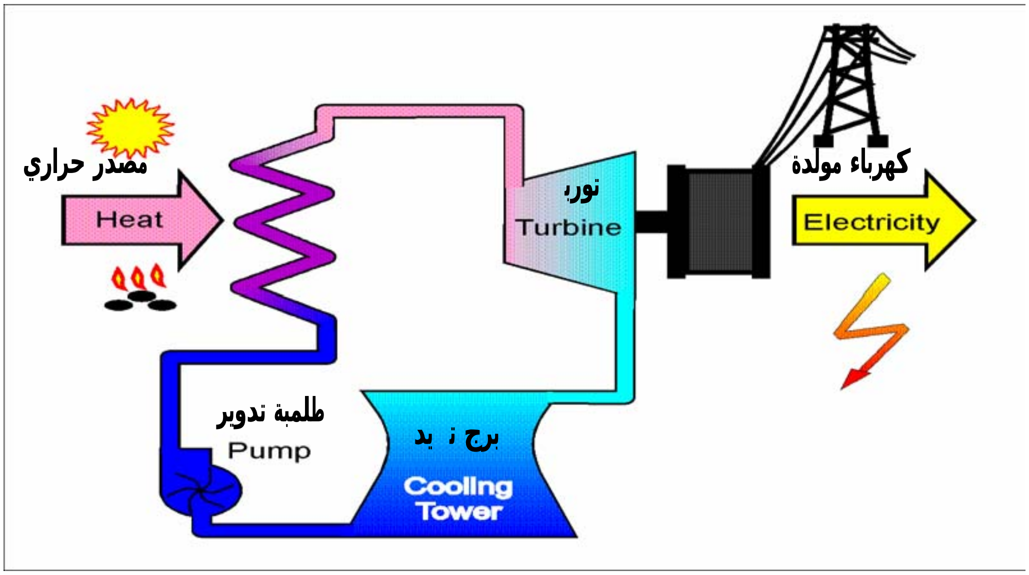
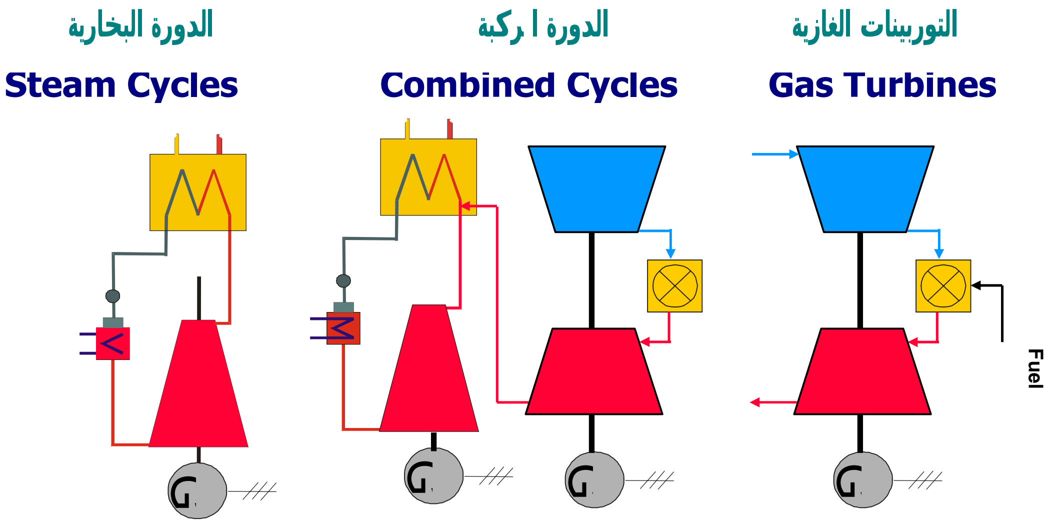


Figure II. Different thermal electricity generation systems



Source: "Electricity generation with fossil thermal power plants", A Technical Report, DLR Germany.

Annex III

IMPACT OF POWER/WATER COGENERATION ON THE MARINE ENVIRONMENT OF THE GCC COUNTRIES

The GCC countries have always relied on the marine environment for commerce and food. Recently, extensive development and continuing demand for further access to marine resources have resulted in certain conflicts of interest. Power and water cogeneration tops the list of flourishing activities in the Gulf, which also include oil production and processing, fishing and marine recreational activities, coastal and industrial developments. How these activities affect marine resources is of great concern. Although information on this subject is limited, it is a fact that the petroleum industry is a major source of marine pollution in the Gulf. Other sources include wastewater effluent, industrial wastewater discharges in general and seawater desalination and electrical power generation discharges, in particular.

The high rate of population growth in the GCC countries and the associated urban development has generated intense pressure to continue expanding construction of desalination and power production facilities. This section will review the impacts of current power and water cogeneration activities on the marine environment.

A. CHARACTERISTICS OF THE GULF

The surface area of the Gulf is some 2.39 by 10^5 km^2 and its average volume is 8.63 by 10^3 km^3. The circulation exchanges water between the Arabian Gulf and the Gulf of Oman via the Strait of Hormuz.[4] The circulation in and out of the Strait of Hormuz is very limited. It is estimated to be in the range of two to five years.[5] Total river runoff into the Gulf is estimated to be in the range of 110 km^3 per year, equivalent to 46 cm per year of depth according to the *Mt Mitchell Leg Reports*, National Oceanic and Atmospheric Administration, (February-June 1992). The evaporation is very high for most of the year, estimated at a rate between 140 to 500 cm annually.[6] Based on this information, the evaporation from the surface of the Gulf Seawater exceeds the total river runoff by an approximate factor of 10.

The temperature of the seawater is in the range of 12° to 35 °C in the winter and summer, respectively, with an average of 23.1°C.[7] The salinity of Gulf seawater varies seasonally, on average, from 36.3 to 43.61 g/l. It is lowest during May and highest during October. Salinity gradually decreases northward mainly due to the diluting influence of the river's runoff in the northern waters of the Gulf. In general, the salinity is higher during summer and autumn compared to winter and spring.

B. POWER/WATER COGENERATION

GCC countries have adapted to the extremely arid environment by installing appropriate technologies to desalinate seawater and to generate electrical power supply. Without Gulf seawater, these activities are not possible. These activities use large volumes of seawater and hence, profound changes in the marine and coastal environment are the likely outcome. Moreover, the availability of fresh water and electrical power has resulted in dramatic changes in the demography and development of infrastructure, which now supports previously unfeasible industries.

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[4] R. Michael Reynolds, "Physical oceanography of the Gulf, Strait of Hormuz, and the Gulf of Oman – Results from the Mt. Micthell Expedition", *Marine Pollution Bulletin*, vol. 27, (1993), pp. 35-59.

[5] J.R. Hunter, "A review of the residual circulation and mixing processes in the Kuwait Action Plan (KAP) region, with reference to applicable modeling techniques", *Oceanography Modeling of the KAP region*, M.I. El-Sabh, ed. (1983), pp. 37-45 and UNESCO reports in *Marine Science*, No. 28, (Paris).

[6] R. Michael Reynolds, "Physical oceanography of the Gulf, Strait of Hormuz, and the Gulf of Oman – Results from the Mt. Micthell Expedition", *Marine Pollution Bulletin*, vol. 27, (1993), pp. 35-59.

[7] Faiza Al Yamani, J.M. Bishop and G.R. Morgan, "Assessment of the effects of the Shatt El-Arab's altered discharge regimes on the ecology of the Northern Arabian Gulf", final report, *KISR Project FM006K*, Kuwait Institute for Scientific Research, (July 1995).

Seawater desalination generally requires a large seawater inlet flow resulting in an increase in salinity of the discharge flow known as brine. Various chemicals are added to the feed water to control formation of mineral scale and biological growth that would otherwise interfere with the processes. These chemicals or their reaction products are in turn discharged with the reject brine to the sea. Cooling water used in the power generation processes is discharged to the sea at a higher temperature than the ambient temperature of the surface seawater, normally by 5° to 6°C.

1. *Desalination activities*

Seawater is the main ingredient for the production of distillate from MSF and for the cooling purposes inside the desalination plants. Most of these plants operate normally at temperatures of some 90°C. During summer some MSF plants operate at an elevated temperature of 110°C to produce about 1.2 times the quantity normally produced at the lower temperature. The amount of seawater utilized for MSF process varies between 11,000 to 8,000 m^3 per hour for every unit of a distillate capacity of 1,000 m^3 per hour, summer and winter, respectively. Two mg/l of chlorine is injected into this quantity, in addition to 4 mg/l of chlorine for 20 minutes every 8 hours. Therefore, total injected chlorine amounts to 2.5 mg/l on a continuous basis. To produce more than 2,500 million tonnes of distillate per year for the GCC countries, seawater feed is injected with between 140 to 200 tonnes of chlorine daily. Approximately a third of this quantity is fed to the distillation plants as make-up ingredient for the distillation process, whereas, the rest is discharged with the blowdown brine from the distillation plants into the sea with an increase in temperature of some 5° to 6 °C over the seawater ambient temperature.

Approximately 70 per cent of the seawater feed, increased in temperature, is discharged with the blowdown brine, which is loaded with other chemicals such as antiscalant, antifoam and trace metals, picked up from the distillation plant materials. As a result, it is possible that seawater might be contaminated by pre-chlorination at the seawater intake, and from the discharge of the hot concentrated brine at the outfall. Measurable quantities of copper, nickel and chromium, resulting from the attack on the distillation materials are also discharged at the outfall of the MSF plants. In addition, alterations in seawater chemistry at the outfall are possible, as a result of acid cleaning of the fouled MSF plants once or twice a year.

Similarly, antiscalants, namely, polyphosphate, act as a nutrient to algae, causing them to flourish at the outfall. Therefore, the marine environment is more likely to be affected at the outfall area rather than the in the open sea.

2. *Power generation activities*

Power generation also utilises seawater for cooling. The production of each MW requires some 110 to 85 m^3 per hour of seawater for cooling during summer and winter, respectively. Seawater utilized for cooling the steam exhaust from the steam turbines is injected with the same rate of chlorine, as for the MSF plants, namely, 2.5 mg/l of chlorine on a continuous basis. Hence, it is estimated that 210 to 270 tonnes of chlorine are injected daily into the cooling seawater feed entering the condensers of all power generation plants in the GCC countries.

C. ENVIRONMENTAL CONSIDERATIONS

The MSF process dominates desalination activities in the GCC countries. Other processes, such as RO are still not widely used for seawater. Hence, impact evaluation of the current power generation and water desalination activities on the marine environment is limited to the dual-purpose power/MSF cogeneration plants.

The power/MSF cogeneration plants are constructed according to properly conducted studies based on hydrographic oceanographic, geo-technical and aquatic biological investigations, including hydraulic design of the intake and the discharge channels and ecological and environmental impact assessment. However, during the construction phase, serious marine environmental impact occurs, mainly as a result of changes in the coastal areas of the constructed sites. During the operation of the MSF plants, a variety of chemicals control scale formation and biological growth. It is possible that utilization of seawater in such a process and chemical treatments would affect the marine environment in the following ways:

(a) Increase of chemical pollutants;
(b) Localized increase of the water temperature: thermal pollution;
(c) Changes or modifications in the marine biota.

The extent of damage depends on the chemical and thermal impact of discharged pollutants with regard to the coastal ecosystem. The marine environment could be affected by the chemical composition of the brine discharged, the thermal pollution, the additives and their by-products, and the corrosion products. Furthermore, thermal desalination also has other environmental impacts related to the emission load of the auxiliary boiler and ejected gases from the desalination plant.

D. CONCENTRATION IMPACTS

1. *Salinity*

Gulf countries produce some 8 million m^3 per day, which is equivalent to 2.92 km^3 per year of distillate.[8] The natural evaporation of Gulf seawater is between 335 to 1,195 km^3 of water per year. Hence, the total quantity of the produced distillate by the GCC countries ranges between 0.0024 and 0.008 of simultaneous natural evaporation.

In addition, there is usually no separate culvert for brine discharge. Nevertheless, this is mixed with other cooling waters from the MSF and power generation plants. For example, the Doha West Power and Distillation plant in Kuwait produces, at periods of peak demand 436,300 m^3 per day of distillate and has a capacity of 2400 MW. This level of production requires, on average, approximately 150,000 m^3 per hour of seawater for distillation and some 234,000 m^3 per hour for power generation, with a total amount of 384,000 m^3 per hour of seawater. The quantity of brine discharged amounts to 30,000 m^3 per hour. On the basis that the seawater concentration at this site is 45 g/m^3 and that the concentration of the discharged brine is 76.5 g/m^3, 1.7 concentration ratio, more than nine times the dilution of the brine occurs before reaching the outfall to the sea. Simple calculations show that the final concentration of discharged brine amounts to approximately 46 g/m^3, a normal concentration of Gulf seawater.

Individual organisms are not significantly affected by moderate salinity deviation from the conventional environment of the organisms.[9] Moreover, Morton states that discharged seawater has a density almost equal to the inlet seawater, since the density increase attributable to the higher brine concentration is nearly the same as the reduction related to temperature rise.[10] As the concentration and density of the final brine discharged is almost the same as the concentration and density of the inlet seawater, there is no significant effect ob the buoyancy of the brine discharged. Hence, the brine discharged from the MSF process is expected to have some effect on the area around the culvert of the discharged brine.

2. *Addition of chlorine*

Chlorine is continuously injected into seawater as a biocide to control biological growth inside the MSF plant. On average, this is in the range of 2.5 mg/l. The added concentration or their conversion products will eventually be discharged into the sea in different concentrations. It is a well-established fact that chlorine reacts against marine organisms and decays with time. Measurement of the residual chlorine at the outlet of Doha West Power/Desalination Plant in Kuwait, for example, indicates that the remaining concentration does not exceed 0.5 mg/l. Residual chlorine when exposed to sunlight, loses between 80 to 95

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[8] Klaus Wangnick, *1998 IDA Worldwide Desalting Plants Inventory*, Report No. 15, Wangnick Consulting GMBH, (Germany, 1998).

[9] J. V. Del Bene, G. Jirka and J. Largier, "Ocean brine disposal", *DESALINATION,* vol. 97, Nos. 1-3, (August, 1994), pp. 365-372.

[10] A. J. Morton, I.K. Callister and N.M. Wade, "Environmental impacts of seawater distillation and reverse osmosis processes", *DESALINATION*, vol. 108, (1996), pp. 1-10.

per cent of its active concentration within 30 minutes. Field measurements indicate that residual chlorine of 0.5 mg/l would be 0.05 mg/l at a distance of about 1 km from the discharge location.[11] This means that the residual chlorine impact on the marine environment is insignificant. However, Gulf seawater contains 1 to 2 mg/l of total organic compounds. It is expected to react with the chlorine to produce a variety of new compounds.[12] One of the main concerns is haloginated hydrocarbons. These seawater compounds follow the same pattern of dilution as the chlorine additions. Therefore, this would result in very minor to no significant impact, on marine life. MSF distillate is considered to be safe since it contains practically no detectable organic impurities that cause health hazards to humans. In fact, the drinking waters of many developed countries contain much higher concentrations of hazardous organic compounds than the drinking waters produced from the seawater distillation.

3. *Addition of antiscalants and antifoams*

For many years, scale formation inside the MSF desalination plants in the GCC countries was achieved using some 2.5 mg/l of polyphosphates as a threshold treatment. Hydrolysis of these polymeric compounds to orthophosphates and discharging to the sea acted as nutrients for all types of biological growth. In spite of the dilution factor, red and green algae that formed in the surrounding area of the outlet of the brine and discharged cooling water was discovered in the Shuaiba Plant area in Kuwait. Since the adoption of the polymeric additives that are based on maliec anhydride or polyacrylate, this problem has been eliminated. These additives are biodegradable and are certified as non-toxic. Similarly antifoams are also degradable and non-toxic.[13] Therefore, their impact on the marine environment is insignificant or negligible.

4. *Other concentrations*

Furthermore discharged brine contains low concentrations of metal ions resulting from corrosion, namely copper, nickel, chromium and iron. These concentrations are profoundly increased with acid cleaning of the plants, which occurs once or twice a year. The heavy metal ions affect marine organisms. Fortunately, the concentration of these elements in the brine blowdown of the MSF plants is very low, in the range of 50 times less than the requirements of the current drinking water standards.[14] Therefore, the impact of this type of discharge on the marine environment can also be considered to be minor.

E. THERMAL IMPACTS

The temperature of seawater feed is increased by 5° to 6 °C inside the heat rejection section of the MSF plant. Some 70 per cent of this heated seawater is sent back to the sea with the discharged brine, at the same temperature, but at approximately a 1.7 concentration ratio. In addition, the cooling stream of the power generation plant picks up a similar increase in temperature as the outfall. As a result and according to the temperature variations in the Gulf seawater, the increase in seawater temperature encourages biological activity for most of the year. Temporary lethal to sub-lethal impact on the marine life is possible for short periods during August and September near the discharge outlets of the water desalination and electrical power generation plants. Although the thermal impact has some adverse effect on the marine ecosystem for a very short period and in localized areas near the discharge outlets, the advantages of such practice outweigh the disadvantages.

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[11] N. Al-Ghadban and D. Al-Ajmi, "Environmental impact assessment: integrated methodology – a case study of Kuwait, Arabian Gulf", *Coastal Management*, vol. 21, (1993), pp. 271-298.

[12] P.C. Mayankutty, A.A. Nomani and T.S. Thankachan, "Monitoring of organic compounds in feed and product water samples from MSF plants in the eastern cost of Saudi Arabia", Proceedings of the Fourth World Congress on Desalination and Water Reuse, (Kuwait, 4-8 November 1989).

[13] A. J. Morton, I.K. Callister and N.M. Wade, "Environmental impacts of seawater distillation and reverse osmosis processes", *DESALINATION*, vol. 108, (1996), pp. 1-10.

[14] J.W. Oldfield and B. Todd, "Environmental aspects of corrosion in MSF and RO desalination plants", *DESALINATION*, vol. 108, (1996), pp. 27-36.

XIV.a. Total desalination capacity in the GCC countries

XIV.b. Desalination capacity by saline water resources

XIV.c. Technology share of desalination capacity

XIV.d. Desalination capacity by technology: world versus GCC countries