ECONOMIC AND SOCIAL COMMISSION FOR WESTERN ASIA (ESCWA)

ESCWA WATER DEVELOPMENT REPORT 3
ROLE OF DESALINATION IN ADDRESSING WATER SCARCITY

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ABBREVIATIONS AND EXPLANATORY NOTES

AF	acre feet
AF^2	square acre feet
CDM	Clean Development Mechanism
CER	certified emissions reductions
CO_2	carbon dioxide
ED	electrodialysis
EPC	engineering, procurement and construction
EU ETS	European Union Emission Trading Scheme
ft	feet
GCC	Gulf Cooperation Council
GDP	gross domestic product
hr	hour
IDA	International Desalination Association
IWRM	Integrated Water Resource Management
kg	kilogramme
km	kilometre
kWh	kilowatt hours
L	litre
m	metre
m^3	cubic metres
m^3/c/yr	cubic metres per capita per year
m^3/d	cubic metres per day
m^3/p/yr	cubic metres per person per year
MCM	million cubic metres
MED	multi-effect distillation
MJ	megajoules
MSF	multi-stage flash
O&M	operation and maintenance
pH	potential of Hydrogen as a measure of acidity
PPP	purchasing power parity
PV	photovoltaic
RO	reverse osmosis
s	second
s^2	second squared
SWP	State Water Project (California)
SWRO	seawater reverse osmosis
TDS	total dissolved solids
W	watt
yr	year

References to dollars ($) are to United States dollars, unless otherwise stated.

Executive summary

The water supply and demand balance of most countries in the ESCWA region is in serious deficit. Specifically, the average share of renewable freshwater in eight out of 14 ESCWA member countries is 500 cubic metres per capita per year (m^3/c/yr), which represents half the internationally accepted water poverty threshold of 1,000 m^3/c/yr. Furthermore, the regional average supply of freshwater per capita per year is significantly less than the world average.

Desalination has been practised for more than 50 years in the ESCWA region and has emerged as the primary response to water scarcity in several member countries. The region accounts for 44 per cent of the global desalination capacity, with four countries ranking among the world's top ten desalinating countries, namely, in descending order: Saudi Arabia, United Arab Emirates, Kuwait and Qatar. The countries of the Gulf Cooperation Council (GCC) have the largest desalination capacity in the region. Within that context, GCC members have been able to pursue desalination actively to overcome their severe renewable water resources constraints by drawing upon their large fossil fuel reserves to power their desalination plants.

While non-GCC countries in the ESCWA region are not as well endowed with oil reserves, they have also been increasing investment in desalination as a supply response to growing water scarcity. The energy demands required for desalination, however, have proven to be a constraint to expanding capacity in these countries. The three most common desalination technologies in the ESCWA region are multi-stage flash (MSF), reverse osmosis (RO) and multi-effect distillation (MED). MSF and MED are distillation-based plants, whereas RO uses membranes to separate salts from water.

Cost is a critical factor in deciding whether or not to pursue investments in desalination. While the cost of production is often the focus of this consideration, decision makers must also take into consideration transmission costs, namely, the cost of transporting desalinated water from the plant to the tap. While this does not represent a significant additional cost for coastal communities, transporting desalinated water from coastal installations to inland communities and elevated urban centres can dramatically increase the cost of desalination. Moreover, there are environmental considerations that can affect the cost of desalination, in addition to the impact of desalination processes on the environment. Accordingly, the full cost of desalination needs to be considered in a manner that incorporates the production and transportation of desalinated water as well as associated environmental externalities, including environmental costs associated with carbon emissions. Consequently, the nexus between water and energy consumption and production patterns emerges as a central factor when deciding on desalination investments as a means of addressing water scarcity in the ESCWA region.

Introduction

Desalination is very important to the ESCWA region. Almost half of the global desalination capacity is concentrated within the region and many countries rely almost exclusively on desalinated water for their freshwater supply in order to meet growing water demand in the face of increasingly scarce water resources.

Desalination capacity has grown substantially since 2001.[1] While investments in desalination have increased in the Gulf region, other ESCWA member countries have also pursued desalination as a means of complementing existing conventional water resources. Desalination capacity is concentrated in the middle- to high-income Gulf Cooperation Council (GCC) countries as a result of a combination of conditions, namely, extreme water scarcity coupled with an abundant endowment of fossil fuels. These conditions have encouraged decision makers to endorse investments in desalination. Specifically, Kuwait, Qatar and the United Arab Emirates are producing more desalinated water annually than is available from their national renewable water resources. Non-GCC countries in the ESCWA and Arab regions are also expanding their desalination capacity as water scarcity increases and desalination technologies become more efficient and less expensive. For example, Algeria, Jordan, Tunisia and Yemen have incorporated desalination into their water resource management strategies in order to satisfy growing water demand.

This report seeks to demonstrate the growing importance of desalination in the ESCWA region as a core component of water resource development plans in water scarce countries.[2] In doing so, it highlights the direct and indirect costs associated with providing desalinated water to growing cities and populations located across the region. Most private sector providers consider the cost of desalination as the sum of the capital, operating and maintenance costs of a desalination plant. However, the real cost of desalination must factor in the additional cost of delivering the water from the plant to the consumer's tap. The difference between these two costs can be substantial when water transport and environmental costs are taken into account. In some cases, water transport and environmental costs exceed desalination capital and operating costs combined. This report provides therefore an in-depth analysis of these costs in order to raise awareness of the substantial costs that can arise from desalination projects and the associated trade-offs involved in burning more energy to produce more water.

In order to expose more clearly the growing contribution of desalination to water supply in the region, the report also provides up-to-date information on the water supply and demand situations in ESCWA member countries. Additionally, it evaluates existing desalination capacities and practices in each country and presents a review of the most common desalination technologies employed in the region.

This baseline information is complemented with a review of the cost components of desalination, followed by guidance on how to reduce the cost of desalination. These options include reducing the energy demand of conventional desalination facilities and powering desalination plants using such alternative energy sources as solar, wind and nuclear energy. In addition, the reclamation and sale of salt from the desalination process is presented as a potential revenue source that can offset some of the cost of desalination.

Given the increasing water constraints being faced by ESCWA member countries, this report does not advocate or discourage desalination as a supply solution to water scarcity in the region. Rather, it endorses the need to provide decision makers with a complete picture of desalination and the full cost of desalination so that they can make more informed decisions

[1] ESCWA published its previous report on desalination in that year. See ESCWA, "Energy options for water desalination in selected ESCWA member countries" (E/ESCWA/ENR/2001/17).

[2] This report constitutes the third in a series of ESCWA water development reports, which are issued on a biennial basis. The first and second development reports, namely, "ESCWA Water Development Report 1: Vulnerability of the region to socio-economic drought" (E/ESCWA/SDPD/2005/9), and "ESCWA Water Development Report 2: State of water resources in the ESCWA region" (E/ESCWA/SDPD/2007/6), are both available at: www.escwa.un.org.

within the framework of Integrated Water Resource Management (IWRM). Certain cities and countries will find that desalination constitutes the best option for providing freshwater to their populations. Others will find that the full cost of desalination, including pumping and environmental costs, remains prohibitively expensive. Moreover, countries with a long history of desalination and a knowledgeable labour pool could decide that desalination is a proven management option; while others with little experience in desalination may decide that other water management approaches could prove more effective in the short term.

Chapters I and II examine the water supply and demand situation in the ESCWA region and provide a background on desalination capacities. Chapter III reviews the most common desalination technologies employed in the region. Chapter IV analyses the full cost of providing desalinated water from the plant to the consumer's tap. Chapter V reviews ways of reducing the cost of desalination and discusses the potential of using renewable and nuclear energy sources for desalination. Chapter VI concludes the report and provides some recommendations for decision makers and the desalination industry.

I. REVIEW OF WATER RESOURCES: SUPPLY AND DEMAND

The water supply and demand balance in most ESCWA member countries is in serious deficit. Countries in the region that are not already facing a water balance deficit are steadily heading towards that direction. The availability of conventional water resources is affected by growing water demands and the deterioration of surface and groundwater quality. Moreover, studies indicate that climate change pressures are further exacerbating the situation. In order to meet this deficit, ESCWA member countries can manage their existing water resources more efficiently through demand side management tools or by increasing their supply of freshwater through the development of conventional and non-conventional water resources. A combination of both water supply and demand side options is often pursued in order to fill the gap in the water balance.

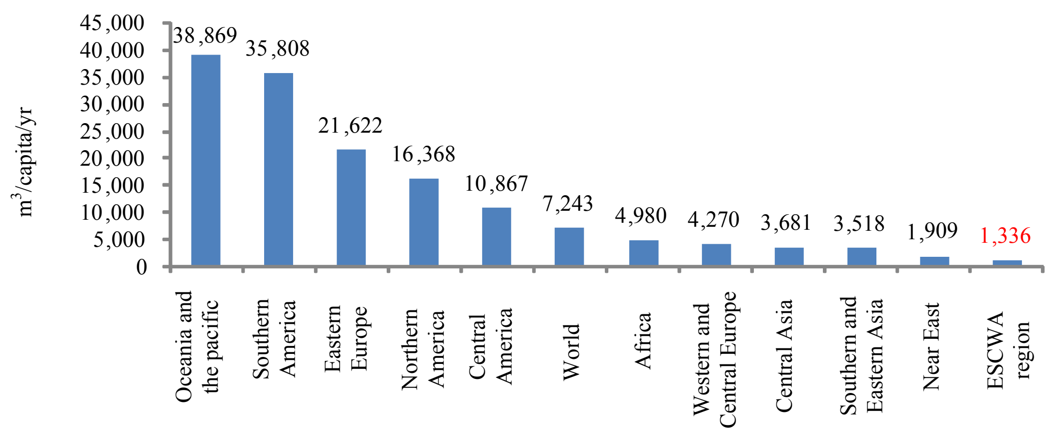
A. WATER SUPPLY

1. *Conventional water resources*

Conventional water supplies consist of fresh surface water and groundwater resources. Freshwater supplies can be disaggregated into renewable and non-renewable sources. The renewable amount of freshwater is the volume of water that is replenished on a yearly basis, and of both surface water and groundwater that is recharged. Non-renewable sources of water include non-renewable groundwater (fossil aquifers) and groundwater that is withdrawn at rates faster than recharge (overdraft).

The ESCWA region has the lowest per capita renewable freshwater supply compared to other regions (see figure 1). The average per capita share of renewable freshwater in the region is just slightly higher than the internationally accepted water poverty/scarcity threshold of 1,000 cubic metres per capita per year (m^3/c/yr), and is significantly lower than the world average of 7,243 m^3/c/yr.

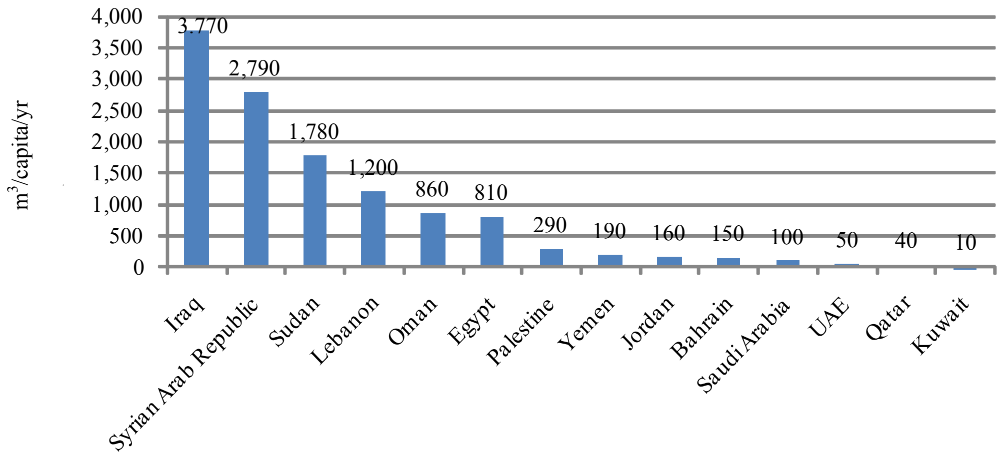
Figure 1. Renewable water resources
(*m^3/capita/year*)



Sources: ESCWA, "Vulnerability of the region to socio-economic drought" (E/ESCWA/SDPD/2005/9); and Food and Agriculture Organization (FAO), "AQUASTAT main country database", which is available at: http://www.fao.org/nr/water/aquastat/dbase/index.stm. For detailed figures, see annex table 5.

Figure 2 details the available renewable freshwater in each ESCWA member country. Specifically, eight out of the 14 member countries have an annual per capita share of less than 500 m^3 of renewable water resources. Out of these eight, seven have less than 200 m^3/c/yr, which consequently places them among the world's 15 poorest countries in terms of available water resources. On the other hand, four ESCWA member countries, namely, Iraq, Lebanon, the Sudan and the Syrian Arab Republic, have more than 1,000 m^3/c/yr of freshwater resources.

Figure 2. Total renewable water resources per capita
($m^3/c/yr$)



Source: Compiled by ESCWA based on data by the Food and Agriculture Organization (FAO), "AQUASTAT main country database", which is available at: http://www.fao.org/nr/water/aquastat/dbase/index.stm. See also annex table 5.

The major shared river basins serving Iraq and the Syrian Arab Republic, namely the Euphrates and Tigris, originate in Turkey. Equally, the Nile River headwaters originate outside the ESCWA region and serves as the primary source of freshwater for Egypt and the Sudan, the latter of which under-consumes its water allocation, thereby allowing additional supplies to flow to Egypt. While Lebanon shares several river basins with its neighbours, relatively high precipitation rates, short river courses and snowmelt generally provide the country with sufficient water supplies. Climate change is expected to have adverse impacts on these shared water resources.

2. *Non-conventional water resources*

As a result of limited conventional freshwater reserves in the region, a number of non-conventional water resources have been developed to offset the water gap. These include wastewater treatment and reuse, agricultural runoff reuse and desalination. Investments in desalination and the reuse of treated wastewater in the region have become so prevalent in some countries that there is even some doubt as to whether they can still be considered non-conventional water supply options.

(a) *Wastewater treatment and reuse*

Wastewater, drainage water and grey water that are treated and reused are non-conventional water resources. This type of practice promotes the use of water of varying qualities for different purposes. The reuse of these water sources is dependent upon whether it is treated at the primary, secondary or tertiary level. Treated wastewater for reuse supports crop production, the irrigation of green spaces and golf courses, groundwater recharge and industrial cooling. However, in order to expand developments in this sector, the adoption and enforcement of wastewater treatment standards for specific uses is essential. Its importance is evident when considering the use of wastewater in agriculture.

Many ESCWA member countries reuse wastewater and drainage water to complement limited conventional water resources in order to support agriculture. This deteriorates the quality of surface and groundwater and contaminates agricultural produce and vegetables, thereby resulting in negative implications for human health. The GCC countries, however, have invested in advanced technologies aimed at developing this water resource. This has included tertiary treatment to wastewater, including sand filtration and disinfection, prior to its reuse. This has allowed for the greenification and the development of greenbelts around several cities in the Gulf aimed at both protecting existing groundwater resources and reducing land degradation and desertification. In a few cases, wastewater is also used in these countries to recharge groundwater through recharge pits and deep-well injection. Six countries in the region reuse over 10 m^3/c/yr of wastewater, namely: Qatar and the United Arab Emirates, which reuse over 50 m^3/c/yr; and Egypt, Jordan, Kuwait and Syrian Arab Republic, which reuse 20-40 m^3/c/yr of wastewater.[3] The treatment of wastewater for reuse has therefore become a mainstay of national water resource management plans in most countries in the ESCWA region.

(b) *Agricultural runoff*

Agricultural runoff is defined as water that flows off farmed areas after crops have been watered. The runoff is reused by diluting it in large surface water bodies in order to provide more water to downstream cropping systems and users. With the exception of Egypt and the Syrian Arab Republic, agricultural runoff is not used significantly by countries in the region. In Egypt, almost 100 m^3/c/yr of agricultural runoff is mixed with water from the Nile and reused. Similarly, the Syrian Arab Republic reuses approximately 100 m^3/c/yr of agricultural runoff. However, this practice has progressively increased the salt and pesticide content in downstream river segments. Furthermore, agricultural runoff in the region often contains untreated domestic and industrial effluents. The practice of blending agriculture runoff with freshwater resources is degrading water quality to varying degrees with such contaminants as toxic trace metals, micro-organics, pathogens, pesticides, trace nutrients and biodegradable organic loads. In addition to adversely affecting downstream ecosystems, this practice increases heavy metal concentrations in downstream fisheries and agricultural produce.

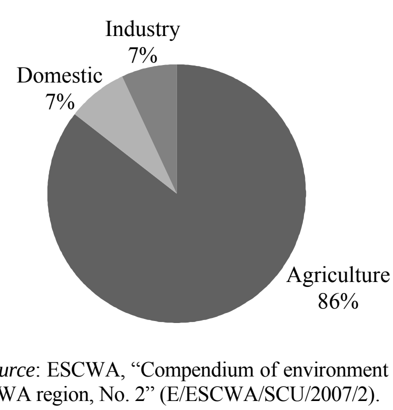
(c) *Desalination*

Water scarcity and increasing water demands have prompted the region to become a global leader in water desalination. Desalination fills a significant portion of the shortfall in water supply in ESCWA member countries. Without desalination, many of these regions would be uninhabitable. Within that context, the GCC countries produce approximately half the world's desalinated water; and Jordan, Palestine and Yemen are incorporating the desalination of seawater and brackish in their water strategies in order to augment their water supplies. Large-scale investments are already under way in Jordan and Yemen, and small household desalination units can be found in the Gaza Strip. However, some adverse environmental impacts are associated with desalination, including the discharge of hot and concentrated brine into coastal marine environments, the entrapment of aquatic creatures in plants intakes, and the production of carbon dioxide (CO_2). The maintenance of household desalination units in the Gaza Strip has also become prohibitively expensive, which has reduced their performance and drinking water supplies.

B. WATER DEMAND

Water demand can be categorized into three sectors, namely, agriculture, domestic and industry, with the service sector normally accounted for in the latter two. Figure 3 shows the percentage of water used by each sector in the ESCWA region. Most countries in the region fit very closely to these averages, with a few exceptions. Bahrain and Palestine use just under 50 per cent of their water resources for agriculture, reserving most of the remaining 50 per cent for domestic use. Jordan, Kuwait, Lebanon and Qatar use between 50-70 per cent of their water for agriculture, with most of the remaining water being used in domestic consumption.

Figure 3. Water demand by sector in the ESCWA region



Source: ESCWA, "Compendium of environment statistics in the ESCWA region, No. 2" (E/ESCWA/SCU/2007/2).

[3] ESCWA, "Compendium of environment statistics in the ESCWA region, No. 2" (E/ESCWA/SCU/2007/2).

1. *Agricultural demand*

On average, the agricultural sector in the region consumes more than 80 per cent of freshwater resources. The annual amount of water used in agriculture is expected to increase by 40 per cent by 2020.[4] Moreover, the economic productivity of agriculture is low in most countries in the region, accounting for less than 10 per cent of gross domestic product (GDP), with the exception of the Syrian Arab Republic where it accounts for approximately 25 per cent of GDP; and Egypt and Yemen, where agriculture contributes to some 15 per cent of GDP.

Agricultural economic efficiency, which is defined as agricultural GDP divided by the agricultural work labour force has remained less than 1.0 since 1995 in most ESCWA member countries.[5] Consequently, these countries are finding that there are higher returns to labour in industry rather than in agriculture. Consequently, these countries are finding that there are higher returns to labour in industry than in agriculture, and that self-sufficiency is not necessarily the best approach for achieving food security. This represents a significant shift from traditional policies aimed at achieving food security through self-sufficiency.[6] Nevertheless, population pressures and the need to promote rural development through agriculture-based employment and income generation projects have maintained the agricultural sector as a central component of socio-economic development planning in most countries in the region.

Historically, political concerns regarding food security have driven many ESCWA member countries to purse food self-sufficiency policies, which resulted in the production of large quantities of grains and livestock that required significant amounts of water and resulted in low economic returns. Geopolitical instability and the suffering endured by some conflict-stricken populations in the region have justified ongoing policies with regard to food security and the need for self-sufficiency. Given these concerns, the production of staple foods in many countries of the region was given a high priority regardless of their contribution to GDP or the volume of water consumed in their production. In the ESCWA region, this also resulted in a high proportion of available water resources being devoted to irrigation and to subsidized agricultural production. In turn this situation led some countries to accumulate substantial water deficits as a result of mining underground aquifers for water with which to produce their own cereals.

In recent years, however, several of these countries have begun revising their water consumption patterns owing to increasing water scarcity. In Saudi Arabia, this has resulted in the elimination of many agricultural subsidies as well as the reduction in the number of permits issued for drilling groundwater wells for agricultural purposes. As an alternative, water scarce countries of the GCC are purchasing agricultural land and investing in agricultural production in other countries, including the Sudan, Malaysia and the Philippines, where water is more plentiful and where preferential trade and investment agreements can be forged aimed at facilitating agricultural trade and achieving food security goals.

2. *Domestic demand*

Higher standards of living are generally associated with higher water consumption rates, given the correlation between domestic water consumption per capita and GDP per capita. As illustrated in figure 4, the four wealthiest GCC countries with the highest levels of GDP per capita in the region are using substantial quantities of water for sustaining their high standards of living. Relatively poorer countries including Palestine, the Sudan and Yemen, have less domestic consumption of water per capita, despite differences in their freshwater availability.

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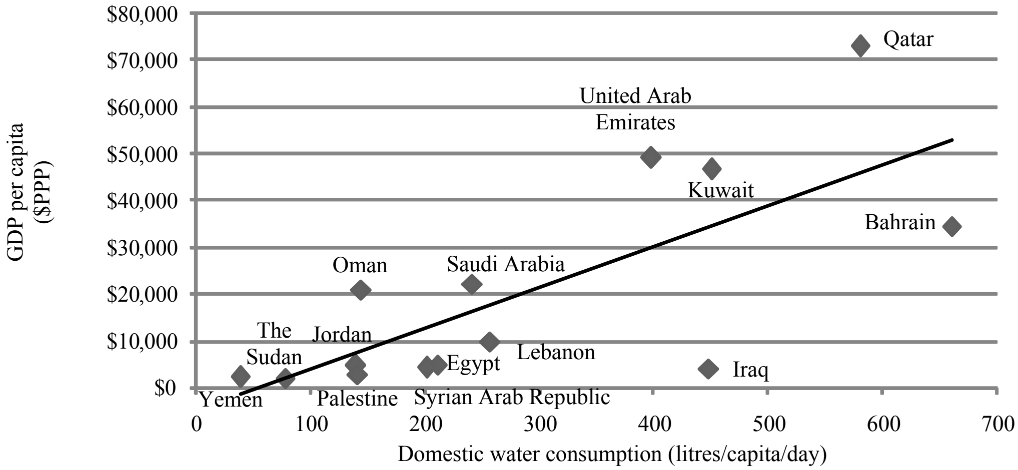
[4] ESCWA, "ESCWA Water Development Report 2: State of water resources in the ESCWA region" (E/ESCWA/SDPD/2007/6).

[5] Arab Monetary Fund (AMF), Arab Fund for Economic and Social Development (AFESD), League of Arab States and Organization of Arab Petroleum Exporting Countries (OAPEC), *Joint Arab Economic Report* (in Arabic) (September 2006), p. 271.

[6] See Food and Agriculture Organization (FAO), *Crops and Drops* (2002), for discussion of water use efficiency and productivity associated with different crops.

Figure 4. Domestic water consumption versus GDP per capita



Sources: Domestic water consumption: Food and Agriculture Organization (FAO), "AQUASTAT main country database", which is available at: http://www.fao.org/nr/water/aquastat/dbase/index.stm; and GDP per capita: United Nations Population Division (UNPD), "World Population Prospects: The 2008 Revision", which is available at: http://esa.un.org/unpp/.

3. *Industrial demand*

While industrial water demand in the region has been low in past decades compared to other economic sectors and regions, the industrial sector has been growing in recent years. The major use of water in the industrial sector is for cooling purposes, particularly in power generation. The water requirement for cooling purposes represents a quarter to a half of the total volume of water used in industry.

The water quality required by industry varies according to type of production. In general, industry requires moderately clear, non-turbid soft water, with low concentrations of suspended solids or silica. Petroleum production usually requires water of moderate quality, with low concentrations of suspended solids and an acidity range of 6-9 pH. Paper production requires water with low suspended solids, while textile and soap production requires relatively soft water with no heavy metals or trace elements that will cause staining or push products outside of health-related norms.[7] Certain sensitive industries, including pharmaceuticals and food production, require water of excellent quality; and pre-treatment is sometimes required to achieve the desired water specifications.

In general, surface and groundwater usually meet the quality requirements for most industries. However, in the GCC countries, the groundwater is highly saline and often fails to meet industrial water quality requirements. Secondary wastewater treatment is then usually pursued and adequate for industrial cooling purposes. In several GCC countries, industrial effluent from large industrial zones is also usually treated prior to being discharged.

4. *Service sector demand*

The service sector has emerged as an increasingly important consumer of water in the Arab region. Consequently, it needs to be incorporated into development planning, with special consideration given to the sector's seasonal pressures on freshwater resources. This sector is often accounted for in various statistical databases under domestic or industrial demand, despite its importance for policymaking as a stand-alone sector. The key service sub-sectors that are imposing new demands on limited freshwater resources are tourism and leisure, and real estate development. These economic activities are introducing new population

[7] A. Hamza, "The role of industry in the development and conservation of water resources in the Arab region: Challenges and prospects", which was presented at the Workshop on the Role of Industry in the Development and Rational Use of Water Resources in the Middle East and North Africa (Amman, 13-15 May 1996).

pressures on urban and urbanizing areas, as well as coastal areas that are already facing water constraints.

The tourism sector is a water-intensive sector and is driving water consumption up in most Arab countries, including those in the ESCWA region. Heavy investments in tourism in the GCC countries and in remote coastal areas along the Mediterranean Sea and Red Sea encompass water parks, golf courses, large-scale hotel and beachfront developments. Expansion in the sector has therefore required the incorporation of new water supply and demand-side strategies aimed at meeting growing water needs, particularly during peak periods associated with population influxes experienced on a seasonal basis. In the United Arab Emirates, for instance, decision-making on desalination investments has been driven principally by tourism and real estate development. Similarly, beachfront developments along the Red Sea have resulted in increased desalination capacity in Egypt in areas far removed from the country's main freshwater resource.

II. DESALINATION CAPACITY AND FUTURE PROSPECTS

Desalination has been practised on a large scale for more than 50 years in the ESCWA region. During this time, there have been continual improvements in desalination technology, and the most commonly used technologies are now mature, efficient and reliable. Desalination represents the largest source of non-conventional water for ESCWA member countries, especially where renewable freshwater is extremely limited. Population growth, socio-economic development and climate change have led to an increase in water demand, and desalination constitutes one way for countries to bridge the gap between water demand and supply.

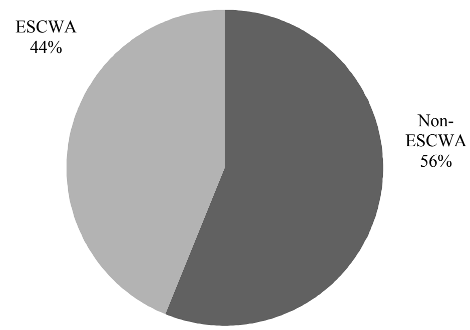
A. DESALINATION CAPACITY

The total global capacity of desalinated water is an estimated 61 million cubic metres per day (m^3/day). The ESCWA region has an estimated capacity of 27 million m^3/day, or 44 per cent of global capacity, which is expected to increase in the coming years (see figure 5).

The three principal desalination technologies used in the ESCWA region are multi-stage flash (MSF), which accounts for about 54 per cent of installed capacity; reverse osmosis (RO), which accounts for approximately 28 per cent of installed capacity; and multi-effect distillation (MED), which accounts for some 9 per cent of installed capacity (see figure 6). A comparative analysis of these technologies is presented in chapter III.

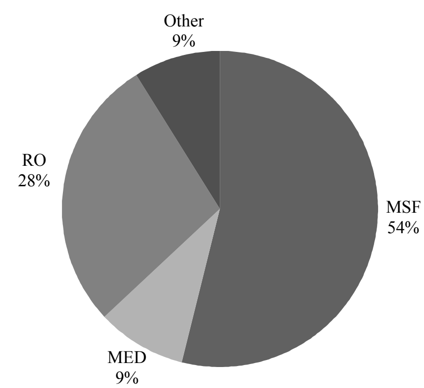
Table 1 below shows the leading position of some ESCWA member countries in the desalination industry, with four countries, namely, Kuwait, Qatar, Saudi Arabia and United Arab Emirates, among the top 10 producers of desalinated water in the world. The prominence of these four countries in the desalination field owes to their limited renewable freshwater resources and wealth in fossil fuel resources.

Figure 5. Global desalination capacity



Source: ESCWA.

Figure 6. Desalination technology usage in the ESCWA region



Source: DesalData.com, which is available at: http://desaldata.com/.

Note: These data reflect online plants, presumed online plants and plants under construction before 2008.

It is important to note that all the major plants constructed or under construction in non-oil rich countries in the Mediterranean basin have used membrane technologies, which requires electrical power as the only source of energy. Where energy prices are low (or perceived to be low), thermal technologies are used. Countries in the region that have significant domestic fossil fuel energy sources usually subsidize the provision of fossil fuel to power plants, thereby subsidizing the cost of electricity and steam used for thermal-based desalination technologies. Energy subsidies thus distort the choice of processes in favour of more energy-intensive technologies. However, even in countries where thermal technologies dominate, reverse osmosis is making inroads into the market.

TABLE 1. TOP 10 DESALINATING COUNTRIES

Country	Capacity (m^3/day)	Share of global production (*percentage*)
1. Saudi Arabia	10 598 000	17
2. United Arab Emirates	8 743 000	14
3. United States of America	8 344 000	14
4. Spain	5 428 000	9
5. China	2 553 000	4
6. Kuwait	2 390 000	4
7. Qatar	2 049 000	3
8. Algeria	1 826 000	3
9. Australia	1 508 000	2
10. Japan	1 153 000	2

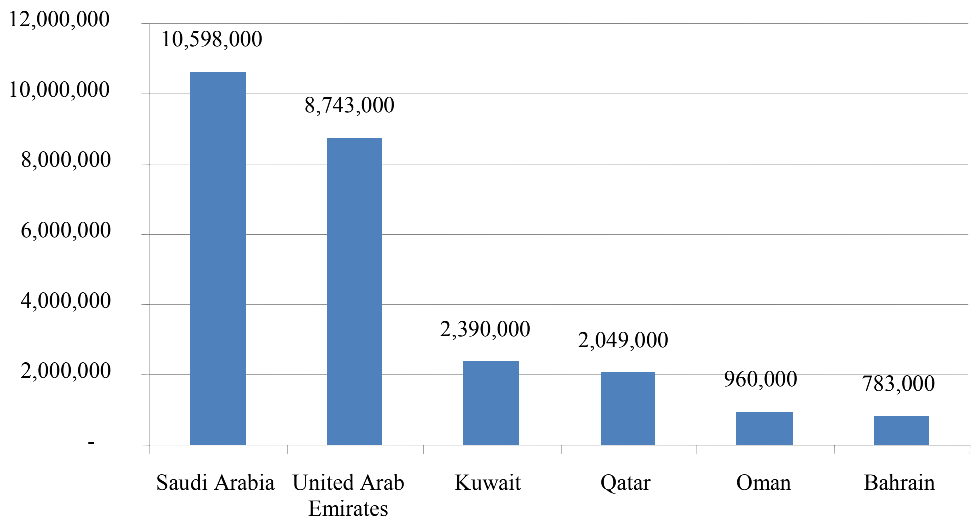
Source: DesalData.com, which is available at: http://desaldata.com/.

Note: These data reflect online plants, presumed online plants and plants under construction before 2008.

1. *ESCWA member countries in the Gulf subregion*

Water production per capita from desalination plants differs across the Gulf subregion according to production capacity and water needs, and as a function of available conventional water resources. The total installed desalination capacity of plants operating in the GCC in 2008 was approximately 26 million m^3/day. This amount supplied more than 90 per cent of the water needs of the GCC.[8] Figure 7 displays the desalination capacity of each GCC country.

Figure 7. Desalination capacity of ESCWA member countries in the Gulf subregion
(m^3/d)



Source: DesalData.com, which is available at: http://desaldata.com/.

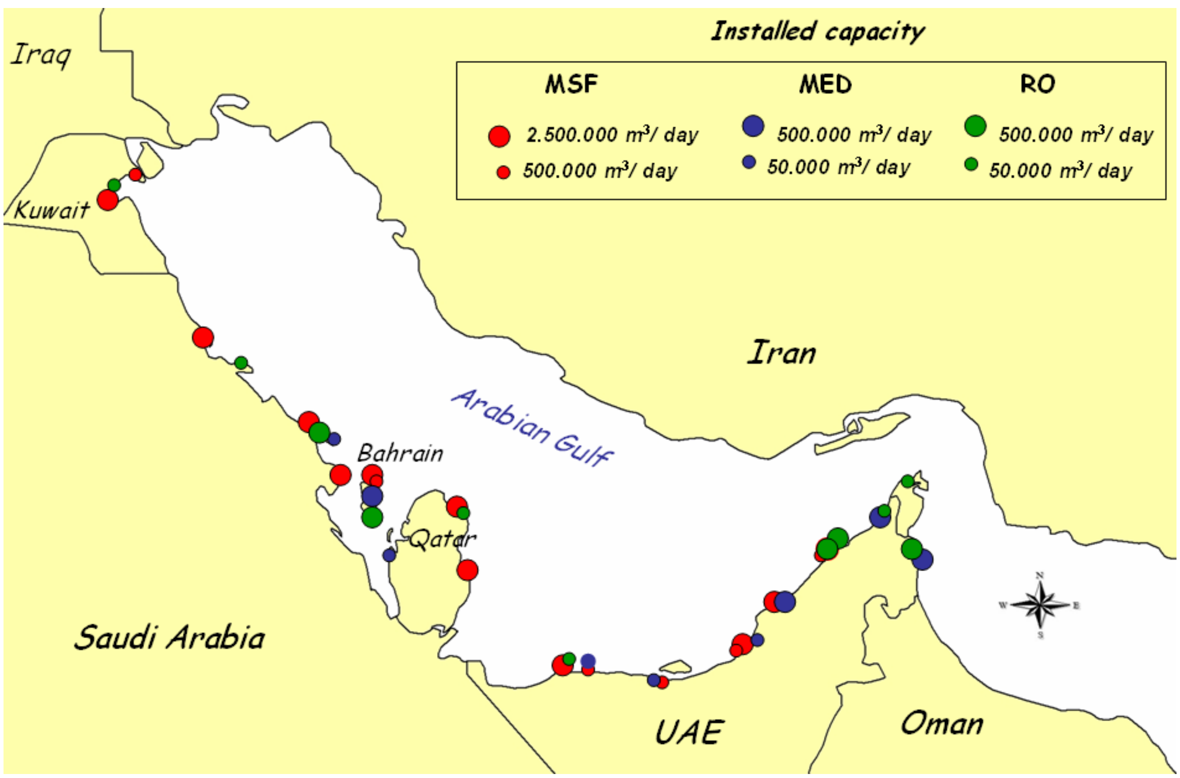
Note: These data reflect online plants, presumed online plants and plants under construction before 2008.

[8] M. el-Kady and F. el-Shibini, "Desalination in Egypt and the future application in supplementary irrigation", *Desalination*, vol. 136 (2001), pp. 63-72.

The Gulf subregion has the greatest density of desalination plants in the world, as shown in figure 8. The coast of the Arabian Gulf is shared by seven ESCWA member countries, of which six are members of the GCC. Given that the Arabian Gulf is the only source of seawater for most GCC countries, with the exception of Oman and Saudi Arabia, the largest desalination plants are located near major cities that have direct access to the coast.[9]

Specifically, the largest plants in the GCC are as follows: (a) al-Jubail in Saudi Arabia, at 2.01 million m^3/day; (b) Jabal Ali on the coast of Dubai, at 1.17 million m^3/day; and (c) al-Taweelah, Um An Nar and Shuweihat on the coast of Abu Dhabi, at, respectively, 1.06 million, 0.86 million and 0.45 million m^3/day.[10]

Figure 8. Major desalination plants in the Gulf subregion



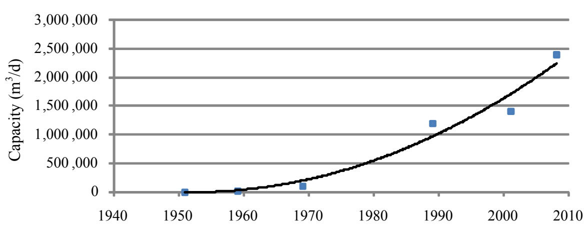
Source: Modified by ESCWA based on H.H. al-Barwani and A. Purnama, "Evaluating the effect of producing desalinated seawater on hypersaline Arabian Gulf", *European Journal of Scientific Research*, vol. 22, No. 2 (2008), pp. 279-285; and Global Water Intelligence, "IDA Desalination Plants Inventory", which is available at: http://desaldata.com.

[9] These include, for example, Abu Dhabi, Dammam, Doha, Dubai, Kuwait City and Manama.

[10] H.H. al-Barwani and A. Purnama, "Evaluating the effect of producing desalinated seawater on hypersaline Arabian Gulf", *European Journal of Scientific Research*, vol. 22, No. 2 (2008), pp. 279-285.

Kuwait was the first country in the GCC region to invest in desalination when the Kuwait Oil Company erected a small seawater desalination plant at Mina Al-Ahmadi in 1951, with a capacity of 36 m^3/day, and piped part of the water to Kuwait City. Kuwait's first desalination plant based on MED technology went online in 1953 and had a capacity of 9,200 m^3/day.[11] Kuwait slowly ramped up its desalination capacity from 1950 to 1970 (see figure 9). The introduction of MSF desalination in the early 1970s increased Kuwait's uptake of desalination, reaching some 2.4 million m^3/day in 2008.

Figure 9. Historical growth of desalination capacity in Kuwait



Source: Compiled by ESCWA.

Saudi Arabia is the largest producer of desalinated water in the world, accounting for 17 per cent of global desalinated water capacity. In the 1970s, the Government of Saudi Arabia established the Saline Water Conversion Corporation, which represents the largest desalination enterprise in the world, aimed at managing two desalination plants on opposite coasts at the Red Sea and Arabian Gulf. By 1985, Saudi Arabia had 24 desalination plants, including 17 plants on the western coast along the Red Sea and 7 plants on the east coast along the Arabian Gulf. These plants were producing 1.82 million m^3/day and 3,630 MW of electric power.

By the end of the 1990s, six co-generation plants were added, thereby resulting in a total production yield of 2.17 million m^3/day and 4,080 MW. More than 70 per cent of that country's water needs are provided by desalination, and its plants currently generate more than 4,600 MW of electric power. The facility at al-Jubail is the world's largest desalination plant and produces some 2 million m^3/day of desalinated water. In 2008, the total amount of desalinated water produced by Saudi Arabia was an estimated 10.6 million m^3/day.

In the United Arab Emirates, the ever increasing demand for water is met by an extensive desalination programme that has made the country the second largest producer of desalinated water in the world. Desalination provides for the majority of domestic water supply. Recently, an RO desalination plant was completed in Fujairah with a desalination capacity of 450,000 m^3/day. This helped to satisfy the needs of growing development in the Northern Emirates. Moreover, the construction of a new desalination plant in al-Taweelah in Abu Dhabi, with a capacity of 315,000 m^3/day, has increased the yield of the complex to a total of 1.36 million m^3/day, which represents almost one-sixth of national water production.

Qatar has two major desalination complexes and a large desalination plant at a third site. The two largest complexes are Ras Abu Fontas and Ras Laffan. These two complexes consist of mostly MSF plants and together produce some 77 per cent of the 2 million m^3/day of desalinated water in Qatar. The third large desalination plant serves Mesaieed Industrial City and has a capacity of 0.18 million m^3/day.[12]

The history of major desalination plants in Oman goes back to early 1970s when the Government was faced with growing demand for domestic water as a result of population pressures and a rapid rise in living standards. The Government decided to build the Ghubrah power and desalination plant in the Governorate of Muscat. Five states or *wilayas* out of six in Muscat depend mainly on desalinated water for their daily water supply, with desalinated water for domestic use accounting for 59 per cent of total desalinated water production.[13] The installation capacity of the Ghubrah plant, which comprises seven MSF units, is approximately 190,000 m^3/day. The Sohar complex, comprising a large MSF plant and smaller RO and MED

[11] Global Water Intelligence, "IDA Desalination Plants Inventory", which is available at: http://desaldata.com.

[12] DesalData.com, which is available at: http://desaldata.com/.

[13] Ibid.

plants, produces approximately 208,000 m^3/day. The cumulative desalination production in Oman in 2008 reached 960,000 m^3/day.[14]

Bahrain lacks abundant water sources and is dependent on groundwater and desalination to provide for its largely urban population and industrial facilities. The first MSF distillation plant was introduced in Bahrain in 1976. The total installed capacity of this plant was 22,730 m³/d in 1981, which represented 15 per cent of total demand. The first RO desalination plant at Ras Abu Jarjur, located 25 km south of Manama, was commissioned in 1984 and had an installed capacity of 45,000 m³/day; it stood as the world's largest RO plant with seawater membranes during the 1980s. during 2008, Bahrain had a cumulative production capacity of 780,000 m^3/day.[15]

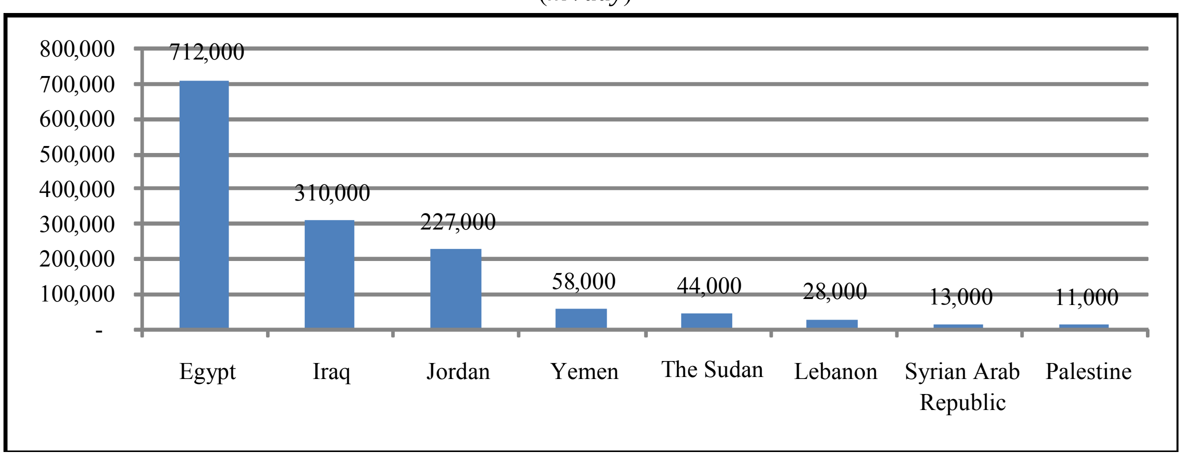
2. *ESCWA member countries outside the Gulf subregion*

Demand for water has also increased rapidly in ESCWA member countries outside the Gulf subregion. This increase has been spurred by a decline in the precipitation rate combined with an increase in population in major urban centres. In addition, the development of tourist sites, such as those along the Mediterranean and Red Sea coasts, has prompted many countries to seek out desalination to complement existing water resources. Climate change is expected to exacerbate this situation.

Consequently, ESCWA member countries outside the GCC have been developing their desalination capacity, albeit on a smaller scale compared to their Gulf counterparts (see figure 10). This difference in desalination production can be attributed to several factors, namely: (a) greater availability of renewable water resources in some non-GCC countries of the region; (b) limited availabilty of financial resources for investment in desalination plants; (c) development of other lower cost non-conventional water resources; (d) geographic and topographic constraints whereby some countries have limited access to coastlines for the purpose of building desalination plants; and (e) highly volatile political and security situation, which inhibit desalination planning and investment.

Figure 10. Desalination capacity of ESCWA member countries outside the Gulf subregion

(m^3*/day*)



Source: DesalData.com, which is available at: http://desaldata.com/.

Note: These data reflect online plants, presumed online plants and plants under construction before 2008.

[14] Ibid.

[15] Ibid.

Iraq, which has a narrow coastline of less than 25 km on the Arabian Gulf, produces a modest amount of seawater desalination. Accordingly, investment has been primarily in river and brackish water desalination. River water desalination is used to improve the poor quality of water flowing from the Tigris and Euphrates rivers. Out of approximately 310,000 m^3/day of total desalination capacity in 2008, some 40 per cent was dedicated to river desalination and almost 30 per cent to brackish water desalination. Iraq is the only country in the ESCWA region that has witnessed a decrease in its total desalination capacity over the period 2000-2008, owing, most probably, to the effect of the conflict in Iraq.[16]

In Egypt, desalination began in the mid-1970s in remote areas and deserts and subsequently expanded to urban centres, notably along coastal areas and inland tourist sites.[17] In 2008, the cumulative capacity of desalination plants in Egypt stood at approximately 710,000 m^3/day, 80 per cent of which was generated from small RO plants averaging some 1,500 m^3/day.[18]

Yemen had a desalination capacity of almost 58,000 m^3/day in 2008, and is expected to expand its desalination capacity along the coastline.[19] The main source of desalinized water is seawater, with some brackish water desalination in inland aquifers. Approximately 72 per cent of total production is used for domestic purposes. Among the challenges facing desalination in Yemen is the transportation of desalinated water from the coast to the high altitudes around the capital city of Sana'a.

In Palestine, demand for freshwater currently exceeds its availability. While plans aimed at installing new desalination plants in the Gaza Strip are underway to meet growing water demand, the deterioration of the political situation is limiting the ability of donors to install these much needed plants, despite the availability of financial resources to support these investments. The dependency on energy imports also constrains investment in the sector.

As a result, the last desalination plant went online in 2000 before the second popular uprising, or intifada, while other plants have remained in the planning stage. When in operation, the total current capacity of desalination in Palestine stands at 11,000 m^3/day.[20] As an alternative, households in the Gaza Strip have turned to small desalination units, which run on solar energy, in order to supplement other sources of water that have become increasingly expensive and decreasingly low quality. However, according to the World Bank, the usage of these household desalination units is constrained by two factors, namely, the high cost of the initial investment given the low income levels in the Gaza Strip; and the inability to secure replacement filters and parts for these units after purchase owing to resource and customs constraints.[21] Using desalination as an option for overcoming water scarcity in Palestine therefore remains a challenge.

Jordan has suffered from extreme bouts of water scarcity in recent years, particularly in the growing city of Amman, which has welcomed a significant number of refugees from Iraq in recent years. The need for water has led Jordan to consider seriously a proposal to link the Red Sea to the Dead Sea aimed at replenishing the latter and using the drop in elevation near the Dead Sea to generate hydroelectric power to support desalination. Moreover, Jordan is considering investing in nuclear energy in order to fuel its need for water through desalination. Jordan has increased its desalination capacity significantly over the past decade by investing mostly in RO plants using brackish water. While starting from a small base in 2000, Jordan produced 230,000 m^3/day of desalinated water by 2008.[22]

The Syrian Arab Republic has demonstrated an interest in desalination, which

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[16] Ibid.

[17] A. Lamei, P. van der Zaag and E. von Münch, "Impact of solar energy cost on water production cost of seawater desalination plants in Egypt", *Energy Policy*, vol. 36, No. 5 (May 2008), pp. 1748-1756.

[18] DesalData.com, which is available at: http://desaldata.com/.

[19] Ibid.

[20] Ibid.

[21] The World Bank, "Report on Gaza Strip post-December 2008" (2009).

[22] DesalData.com, which is available at: http://desaldata.com/.

resulted in the establishment of the Scientific National Commission aimed at studying the most suitable techniques for water desalination for that country.[23] The Commission has recommended sites for brackish water desalination in Hamah, al-Badia and al-Jezirah, and has recommended the installation of several smaller scale, low-cost plants in order to provide water in various other regions. Projects are underway to purse seawater desalination on medium scale coastal industrial sites. In 2008, the Syrian Arab Republic had a capacity of 13,000 m^3/day, which was entirely produced from RO technology and fed primarily by brackish water.[24]

In the Sudan, the growing demand for clean water and the inadequacy of existing supplies within the city of Port Sudan has led that country to purse desalination despite the significant freshwater supplies that it receives from the Nile River.[25] As such, the Sudan initiated a sea water desalination project on the Red Sea in 2006. The project uses RO technology and will be used for sanitation and potable purposes. The total desalination production of the Sudan in 2008 was 44,000 m^3/day.[26]

Lebanon uses large quantities of desalinated water to provide feedwater for thermal power plants. Desalinated water is used in order to avoid the corrosion of turbine equipment, which would otherwise result from using groundwater along its caustic coastline that suffers from saltwater intrusion. The national electricity provider, Electricité du Liban, operates these desalination plants, with a combined capacity of approximately 15,000 m^3/day. A limited amount of additional desalination is conducted in the country, typically for private consumption, such as by bottling plants.

B. Trends and future prospects for desalination

The ESCWA region has increased its desalination capacity by approximately 150 per cent over the past eight years, as shown in table 2. This increase can be attributed to increased investments in both GCC and non-GCC countries, albeit with investments growing from a much smaller base in the case of the latter.

TABLE 2. DESALINATION CAPACITY AND ITS INCREASE IN THE ESCWA REGION

ESCWA country	Installed capacity (*thousands of m^3/day*) 2000	2008	Capacity increase (*percentage*)
Saudi Arabia	5 153	10 598	106
United Arab Emirates	2 669	8 743	228
Kuwait	1 153	2 390	107
Qatar	511	2 049	301
Bahrain	409	783	91
Iraq	343	310	-10
Oman	173	960	455
Egypt	253	712	182
Yemen	43	58	35
Lebanon	26	28	9
Jordan	14	227	1 549
Syrian Arab Republic	12	13	17
Palestine	11	11	0
The Sudan	2	44	1 841
Total	**10 771**	**26 927**	**150**

Source: Calculated and compiled by ESCWA based on DesalData.com, which is available at: http://desaldata.com/.

Looking into the future, all ESCWA member countries have plans to increase their production capacity over the coming five years. However, capacity is increasing at a lower rate over the period 2006-2010, compared to the expected rate increase over 2011-2015 (see figure 11). According to a report issued by the International Desalination Association (IDA), capacity in the region should increase by some 40 per cent over the period 2006-2015.

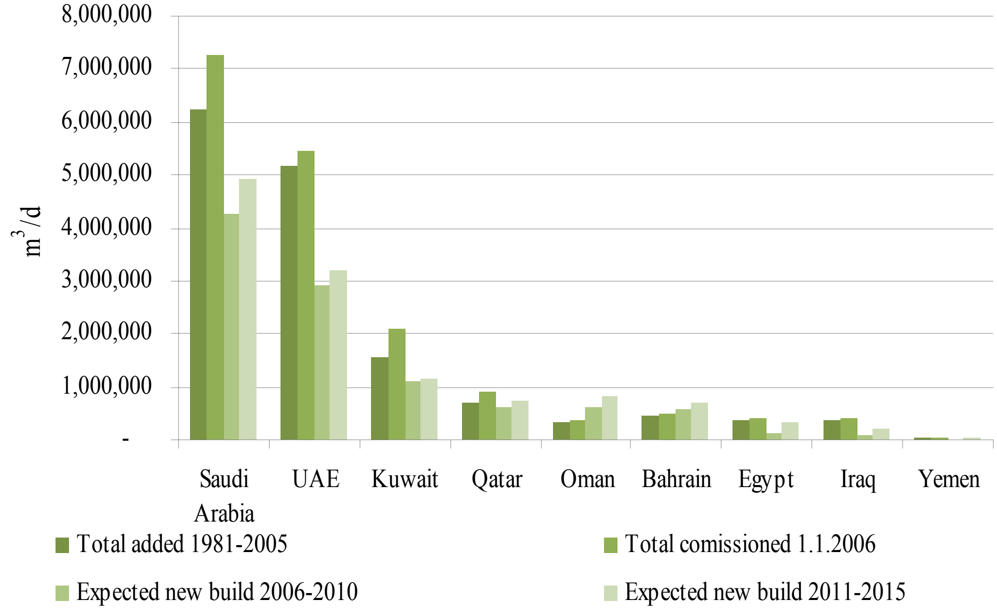
[23] S. Wardeh, H.P. Morvan and N.G. Wright, "Desalination for Syria".

[24] DesalData.com, which is available at: http://desaldata.com/.

[25] *AsiaPulse News*, "Water specialist Metito awarded $2.3 million Sudan contract" (18 September 2006).

[26] DesalData.com, which is available at: http://desaldata.com/.

Figure 11. Actual and projected increase in capacity, 1981-2015



Source: Compiled by ESCWA based on various data by the Global Water Intelligence (GWI), including *Desalination Markets* (GWI, 2007).

Table 3 lists the largest planned desalination units. As mentioned above, the most common technology used in the region is MSF. However, the market share for RO is increasing, especially with the introduction of the hybrid system plants that rely on both MSF and RO for water and electricity production. The largest such plant is located in Fujeirah in the United Arab Emirates and generates 650 MW of power, 295,100 m^3/day of MSF desalinated water and 170,000 m^3/day of RO desalinated water.[27]

TABLE 3. PLANNED DESALINATION UNITS IN THE COUNTRIES OF THE GCC

Country	Location	Capacity (*m^3/day*)	Operation year
United Arab Emirates	Jabal Ali	600 000	2011
United Arab Emirates	Jabal Ali	300 000	2013
Qatar	Ras Laffan	227 000	2009
Saudi Arabia	Shuaibah	150 000	2009
United Arab Emirates	Fujariah	136 000	2009
Kuwait	Shuwaikh	136 000	2010
United Arab Emirates	Dubai	64 000	2008
Qatar	Pearl	35 000	2008
Oman	Qarn Aram	25 000	2008

Sources: Toray Industries, which is available at: http://www.toray.com/news/water/nr080918.html; and K. Wangnick, "IDA Worldwide Desalination Plants Inventory Report" (2005).

[27] Global Water Intelligence, *Desalination Markets* (2007).

III. OVERVIEW OF DESALINATION TECHNOLOGIES

This chapter reviews the most widely used desalination technologies and assesses their regional and global use as a viable and reliable option to prevailing water shortages.

A. Brief introduction to desalination technology

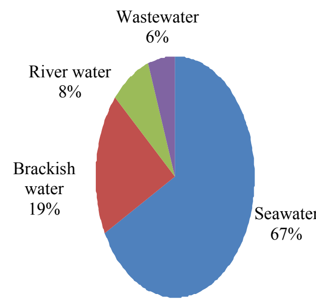
Desalination is a technology that removes dissolved salts and other minerals from seawater or brackish water, thereby producing one stream of water with a low concentration of salt (the product stream) and another with a high concentration of remaining salts (the brine or concentrate). The product stream is then used to provide water for domestic, municipal or irrigation purposes. For domestic purposes, the improved water is blended with current drinking water supplies and distributed directly to users.

Commercially available desalination plants consist mainly of thermal (distillation) and electric (membranes) driven processes. The distillation process is based on the principle of heating feedwater and evaporating it to separate the dissolved minerals, thereby creating the desired separation of salts and freshwater. The most commonly used thermal processes are multi-stage flash (MSF) and multi-effect distillation (MED). The membrane process involves the use of special physical membranes in which the salt or solvent is transferred across the barrier by hydraulic pressure or electric current.

Common membrane processes are reverse osmosis (RO) and electrodialysis (ED). Other minor desalination processes used include freezing and solar- or wind-driven mechanisms.[28] The selection of which desalination technology to pursue depends primarily on such factors as site location, total capacity needs, types of available energy inputs, salt content of the feedwater, end-use considerations, availability of support services and investment costs.

Globally, the total installed capacity of desalination plants was 61 million m^3 per day in 2008. Seawater desalination is the most common, accounting for 67 per cent of production, followed by brackish water, at 19 per cent; river water, at 8 per cent; and wastewater, at 6 per cent (see figure 12).

Figure 12. Worldwide feedwater quality used in desalination



Source: DesalData.com, which is available at: http://desaldata.com/.

Note: These data reflect online plants, presumed online plants and plants under construction before 2008.

The most prolific users of desalinated water are located in the Arab region, namely, Saudi Arabia, Kuwait, United Arab Emirates, Qatar, Oman and Bahrain, which uses more than 40 per cent of worldwide capacity.

B. History of desalination

Prior to the mid-1950s, desalination was undertaken only on a relatively small scale and was entirely based on distillation. Desalination technology developed largely for steam ships that required freshwater to operate their boilers. The simple distillation technology employed on ships reached its peak usage in the mid-1950s, with plants that had relatively high capital costs.[29] Two events around that time changed the course of desalination development, namely: (a) the introduction of the MSF distillation process, which significantly reduced the capital costs of large plants; and (b) the advent of government-backed research and development programmes in desalination technology that led to

[28] These processes are discussed further in chapter V.

[29] W.T. Hanbury, "Trends in desalination technology", *Desalination Market Trends* (2008).

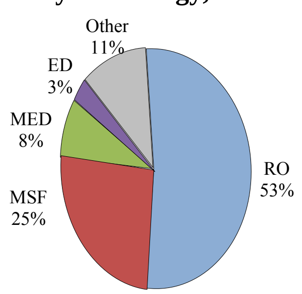
the development of RO as a cost effective desalination process.[30]

The subsequent fifty years witnessed a refinement in the MSF distillation technology in terms of materials, unit sizes and scale prevention techniques. Membrane technology that employed reverse osmosis was developed initially for desalted brackish water. Improvements in membrane durability and stability in addition to very significant reductions in energy requirements gave rise to seawater reverse osmosis (SWRO) during this period. Subsequently, RO has emerged as the dominant desalination technology owing in part to the development of better membranes, reductions in energy consumptions and improved pretreatments.

C. Desalination technologies

The two most commonly used desalination technologies are MSF and RO systems. As the more recent technology, RO has become dominant in the desalination industry. While, in 1999, approximately 78 per cent of global production capacity comprised MSF plants and RO accounted for a modest 10 per cent, by 2008, RO accounted for 53 per cent of worldwide capacity while MSF consisted of almost 25 per cent (see figure 13). While MED is less common than RO or MSF, it still accounts for a significant percentage of global desalination capacity. ED is used only on a limited basis.

Figure 13. Global desalination plant capacity by technology, 2008



Source: DesalData.com, which is available at: http://desaldata.com/.

Note: These data reflect online plants, presumed online plants and plants under construction before 2008.

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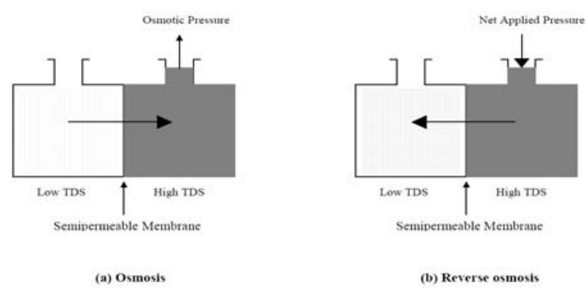
[30] Within that context, the Office of Saline Water in the United States of America played a pioneering role in terms of developing reverse osmosis.

1. *Membrane desalination: reverse osmosis*

Osmosis is defined as the diffusion of water through a semi-permeable membrane from a solution with low total dissolved solids (TDS) to a solution with high TDS. In reverse osmosis, saline feedwater, a high TDS solution, is pumped at high pressure through permeable membranes to produce a solution with low TDS, thereby separating salts from the water and producing freshwater (see figure 14). The feedwater is usually pretreated to remove particles that would clog the membranes. The quality of the water produced depends on the pressure applied, concentration of salts in the feedwater and the type of membranes used. Product water quality can be improved by passing the water through membranes a second time.

Improvements in RO efficiency have led to reduced energy consumption and cheaper processing costs. Moreover, the increased lifespan of the membranes has resulted in increased cost effectiveness of RO.

Figure 14. Diagram of the RO process



The main advantages of RO plants include the following:

(a) Low energy consumption;

(b) Low thermal impact of discharges;

(c) Fewer problems with corrosion;

(d) High recovery rates (about 45 per cent for seawater);

(e) Removal of unwanted contaminants (such as trihalomethane-precursors, pesticides and bacteria);

(f) Plant footprint is smaller than other desalination processes;

(g) Flexible to meet fluctuations in water demand.

The main disadvantages of RO plants include the following:

(a) Sensitivity to feedwater quality;

(b) Membrane fouling calls for frequent chemical cleaning of the membrane and loss of productivity;

(c) More complex to operate;

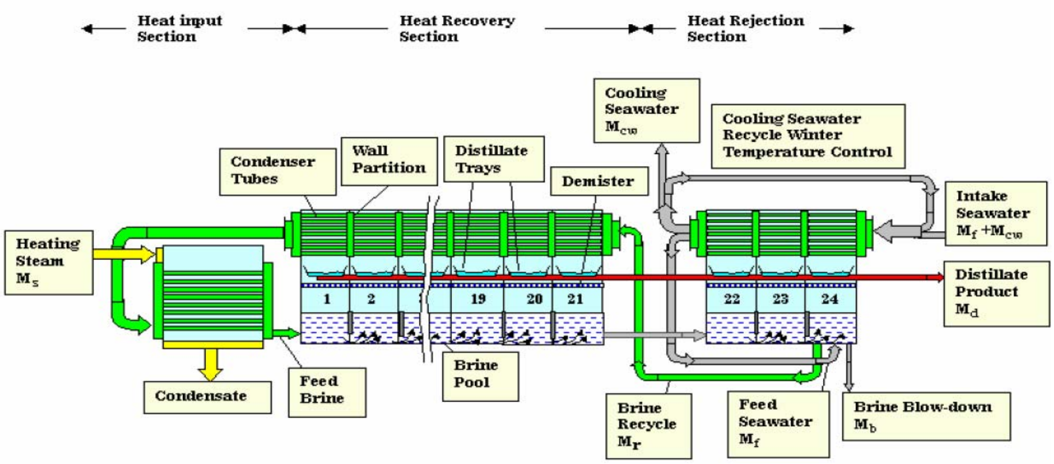
(d) Lower product water purity.

2. *Thermal distillation*

(a) *Multi-stage flash*

In the MSF process, water is made to boil at temperatures below the normal boiling temperature, which is referred to as the "flashing effect". Feedwater is heated in a vessel, called the brine heater, before being allowed to flow into a series of vessels, known as "stages", which constitute the "evaporator" in the MSF unit. Most stages are maintained at reduced pressure relative to atmospheric pressure so that the sudden introduction of heated feedwater into these vessels causes rapid boiling, or "flashing". Steam generated by flashing is converted to freshwater by condensation at each stage on tubes and is collected separately from the brine. The tubes are cooled down by incoming feedwater on its way to the brine heater. This has the effect of warming up the feedwater such that the amount of thermal energy needed to raise its temperature in the brine heater is reduced. Freshwater flowing from stage to stage is taken out as product water from the last stage. It may then be chemically treated to adjust its acidity (pH) and hardness prior to storage or usage (see figure 15).

Figure 15. Diagram of the MSF desalination process



Most MSF plants operate in a dual-purpose or cogeneration mode that incorporates both power generation and water desalination. Waste or extracted heat produced in electricity generation units is used to preheat feedwater, thereby resulting in high thermal efficiencies and cheaper operating costs.[31] The most significant progress made over the past decade is the increase in the reliability of operation owing to improvements in controlling scale occurrence, automation and controls, and improved materials of construction and availability of skilled labour. In addition, an increase in the size of the basic unit has produced economies of scale in capital costs.

The main advantages of MSF include the following:

(a) Simple to operate;

(b) Generates high quality water;

(c) Marginal costs drop significantly at larger capacities;

(d) Can be semi-operational during cleaning or replacement of equipment periods, thereby limiting down time;

(e) Few pretreatment requirements;

(f) Does not generate waste from backwash of pretreatment filters.

[31] ESCWA, "Water desalination technologies in the ESCWA member countries" (E/ESCWA/TECH/2001/3).

The main disadvantages of MSF include the following:

(a) High energy consumption compared to RO;

(b) Creates a large amount of air pollution (primarily from high-energy consumption);

(c) Slow response to water demand fluctuations;

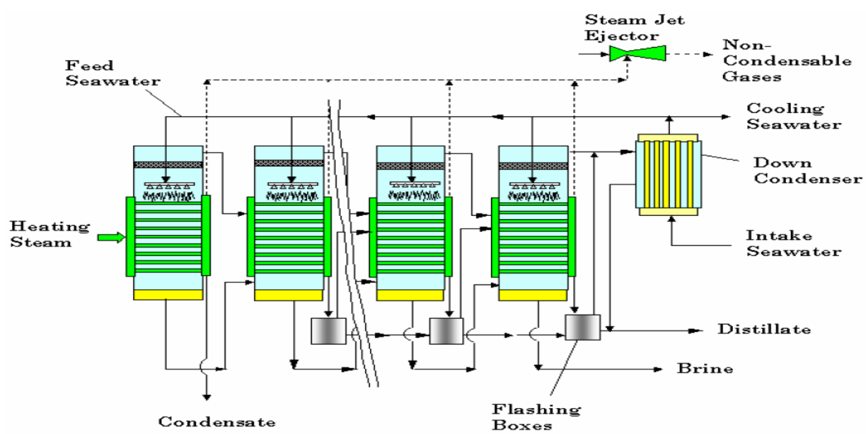
(d) High rate of scaling in tubes.

(b) *Multi-effect distillation*

In MED, the feedwater passes through a number of evaporators in series. Vapour from one series is used to evaporate water in the next series. This approach reuses the heat of vaporization by placing evaporators and condensers in series. Vapour produced by evaporation can be condensed in a way that uses the heat of vaporization to heat salt water at a lower temperature and pressure in each succeeding chamber, thereby permitting water to undergo multiple boils without supplying additional heat after the first “effect”.

In MED plants, the feedwater enters the first effect and is heated to boiling point. Salt water may be sprayed onto heated tubes or may flow over vertical surfaces in a thin film in order to promote rapid boiling and evaporation. Only a portion of the salty water applied to the tubes in the first effect evaporates. The rest moves to the second effect where it is applied to another tube bundle heated by the steam created in the first effect. This steam condenses to freshwater, while giving up heat to evaporate a portion of the remaining salty water in the next effect. The condensate from the tubes is then recycled (see figure 16).

Figure 16. Diagram of the MED desalination process



MED is one of the oldest desalination technologies and dates back to the nineteenth century. In the past few years, however, interest in the MED process has been renewed and MED appears to be gaining market share.[32] This can be attributed to the fact that MED may have lower capital costs, lower power requirements and higher thermal performance than conventional MSF.[33]

[32] H. Cooley, P.H. Gleick and G. Wolff, “Desalination, with a grain of salt: A California perspective” (Pacific Institute, June 2006).

[33] The World Bank “Seawater and brackish water desalination in the Middle East, North Africa and Central Asia: A review of key issues and experience in six countries” (December 2004).

The main advantages of MED include the following:

(a) Wide selection of feedwater;

(b) High quality of product water with high reliability;

(c) Less energy consumption than MSF;

(d) Requires lower temperature operation (reduces scaling and energy costs).

The main disadvantages of MED include the following:

(a) Higher energy requirements than RO;

(b) Slow response to water demand fluctuations;

(c) Lower capacity than MSF.

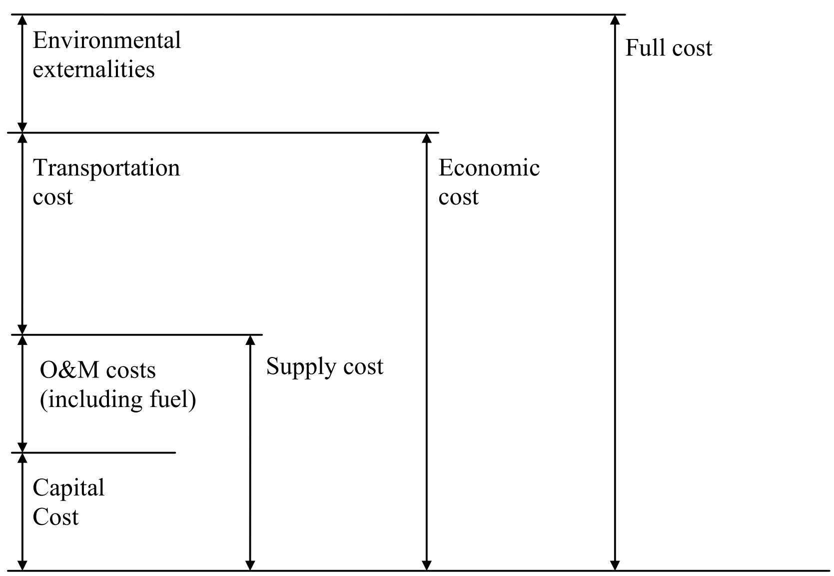
IV. EXAMINING THE FULL COST OF DESALINATION

Desalination is one of the supply side options that decision makers should consider when balancing water supply and demand. Cost is a critical factor in deciding whether or not to pursue desalination, and the cost considered must be the cost of desalinated water delivered to the consumer's tap. Too often only the capital cost and operation of the desalination plant, that is the supply cost, is considered without regards to the cost encountered to bringing the water to the consumer. Supply cost is only part of the overall cost of desalination.

To consider the full cost of desalination, two other costs must be added to the supply cost, namely, water transportation costs and environmental externalities. The transportation cost is the cost of transporting water from the desalination plant to the municipal distribution network. Adding transport cost to the supply cost gives the economic cost of desalination.

Environmental externalities include any positive or negative effect on the environment created by the desalination process. Overwhelmingly, the environmental effects of desalination are negative, particularly in terms of effluents pumped into the sea or into the air. In this chapter, the focus is on CO_2 emissions from desalination plants. Other environmental externalities, including environmental costs from effluent deposits, chemicals and saline brines or sludges, or the pumping of effluents into the sea are more difficult to estimate and often depend on local factors. Adding the environmental externalities to the economic cost provides the full cost of desalination. Figure 17 provides a graphical representation of the cost components of a desalination plant. It is this full cost that must be considered when weighing the benefits and costs of desalination.

Figure 17. The full component costs of desalination



Source: Adapted from P. Rogers, R. de Silva and R. Bhatia, "Water is an economic good: How to use prices to promote equity, efficiency, and sustainability", *Water Policy*, No. 4 (2002), pp. 1-17.

Note: The figure is not to scale.

A. SUPPLY COST OF DESALINATION

The supply cost of desalination comprises capital costs and operation and maintenance (O&M) costs. The capital cost is the cost of a physical plant and the land it occupies, from plant conception until the first moment of operation. The O&M costs relate to ongoing operational and maintenance activities associated with the plant, including labour, energy and part replacement costs.

Determining an accurate supply cost of desalination is difficult, owing primarily to the lack of global standards for cost reporting. Reported costs of desalinated water per cubic metre are usually given in a summary form. However, summary costs do not specify what is included in the cost and may or may not contain such cost factors as land acquisition and regulatory costs or contingency factors that can significantly influence the cost of desalination.

Moreover, many of the published summary costs do not reflect government subsidies (either direct subsidies or fuel subsidies). A large review of published desalination costs shows a range of $0.27/m^3 to $6.56/m^3 for seawater desalination and $0.18/m^3 to $0.70/m^3 for brackish desalination for various technologies.[34]

Consequently, it is difficult to create an accurate model for desalination costs based on reported costs and including such key plant variables as capacity, feedwater, age of plant and desalination technology. A number of multi-variable models were developed at ESCWA that provide a cost estimate for a desalination plant based on the key variables (see annex I for model results).

However, the most accurate model developed had a very wide range of cost estimates for plants, owing primarily to the lack of standardized cost structures available in the database. Typical estimates from the model ranged widely from $0.06/m^3 to $2.22/m^3 of desalinated water (at the 95 per cent confidence intervals of the model). Similar academic attempts at creating a model for desalination costs had a range from $0.00/m^3 to $1.68/m^3 (at the 95 per cent confidence interval).[35]

1. *Reported cost estimation: $1.15/m^3 desalination cost*

Two options are available to overcome these difficulties and estimate a plausible supply cost for desalination. The first is to use a simple average supply cost of desalination of $1.15/m^3 as a working estimate for the supply cost of desalination. This figure is based on a benchmarking exercise of 51 seawater RO desalination plants[36] that led to a similar average supply cost and on previous studies that have taken an estimation approach to supply costs.[37] The supply cost is irrespective of technology type and feedwater because reported costs are not tractable.

Another method to calculate costs is desirable because the reported costs lack a methodological approach. The second method for calculating cost is to use an energy cost based method.

2. *Energy cost estimation: the price of oil and $1.50/m^3 desalination cost*

There are two types of energy sources for desalination plants depending on the type of plant technology used. The first is electric energy that is produced from a large number of fuel sources, including coal, oil, natural gas, nuclear fuel, photovoltaic solar and wind energy.[38] RO plants use only electrical energy, while MSF and MED use some electrical energy.

The second energy source for desalination plants is thermal energy. Thermal energy can be derived from many of the same fuel sources as electrical energy, including oil and natural gas, or from such alternative sources as solar thermal.[39] MSF and MED plants primarily use thermal energy, while RO plants do not use any thermal energy.

[34] J.E. Miller, "Review of water resources and desalination technologies" (Sandia National Laboratories, March 2003), which is available at: http://www.sandia.gov/water/docs/MillerSAND2003_0800.pdf.

[35] M. Dore, "Forecasting the economic costs of desalination technology", *Desalination*, vol. 172 (20 February 2005), pp. 207-214. The figures have been inflated to 2008 United States dollars.

[36] J.H. Kim, "Benchmarking SWRO water costs", *Water Desalination Report*, vol. 44, No. 33 (15 September 2008).

[37] Y. Zhou and R. Tol, "Evaluating the costs of desalination and water transport", *Water Resources Research*, vol. 41, No. 3 (9 December 2004).

[38] The carbon based fuels are burned to heat water and create steam. The steam is used to push and rotate a turbine which converts rotational energy into electrical energy. Electrical energy is generally denoted in watt-hours, or more commonly kilowatt hours (kWh).

[39] For carbon based sources, the fuel is burned to heat water, just as in an electrical plant. However, this is the final product for thermal energy. No conversion to electricity is needed given that a thermal desalination plant, such as MSF or MED plants, uses thermal energy directly. See also chapter V for a discussion on alternative thermal sources.

MSF and MED plants can run either as stand-alone plants or as part of a more efficient cogeneration plant. Determining the energy used in stand-alone plants is easier than in cogeneration plants, given the dual use of fuel for electricity generation and steam. Some attempts have been made at decoupling the fuel energy that goes towards electricity production and desalination. A previous ESCWA report on desalination quoted the energy attributable to desalination in a cogeneration plant as 162 MJ/m^3 for MSF plants.[40] Another study calculates the energy costs attributable to cogeneration desalination for MSF and MED as 170 MJ/m^3 and 96 MJ/m^3, respectively.[41] Table 4 shows the energy amount and type required by RO, MSF and MED plants (stand-alone and cogeneration).

TABLE 4. ENERGY USED IN SELECTED DESALINATION TECHNOLOGIES

Desalination technology	Electric energy (*kWh/m^3*)	Thermal energy - stand-alone (*MJ/m^3*)	Thermal energy - cogeneration (*MJ/m^3*)
MSF	3.5-5	250-300	160-170
MED	1.5-2.5	150-220	100
RO (sea)	5-9	none	none
RO (brackish)	0.5-2.5	none	none

Sources: Compiled by ESCWA based on a presentation by F. Banat, "Membrane desalination driven by solar energy" (2007), which is available at: www.dicpm.unipa.it/nato/25Feb/Banat.pdf; and M.A. Darwish, "Desalting fuel energy cost in Kuwait in view of $75/barrel oil price", *Desalination*, vol. 208, Nos. 1-3 (5 April 2007), pp. 306-320.

Figure 18 shows how the energy cost per cubic metre of desalinated water varies with the price of oil based on the energy values of table 5. While oil is used for illustration purposes, other fuels can also be used to power desalination. The minimum energy required for each process is used in the figure and includes both thermal and electric energy.

The price of oil in 2008 peaked at above $140 per barrel and dropped below $40 per barrel. In 2009, prices rose again towards $80 per barrel. Figure 18 shows representative prices for energy for desalination given certain oil costs. The prices at the top of the arrows represent an average cost of desalination given the technology profile of the region using only more efficient cogeneration energy needs.[42] The cost is derived by assuming conservatively that energy accounts for 75 per cent of the supply cost of desalination. At $40 per barrel, the supply cost is $1.20/$m^3$; at $80 per barrel the cost rises to $2.40/$m^3$; and at $120 per barrel the cost is $3.59/$m^3$.

The prices of energy for the distillation technologies is very high in this example, giving the impression that RO should be the preferred technology in all cases where oil is above $20/barrel. However, the energy figures for MSF and MED cogeneration are derived from a single plant in Kuwait operating at a capacity of 300 MW and 60,000 m^3/d. Larger capacity distillation plants may use energy more efficiently than this particular plant. More data is needed from various sizes and types of plants to better determine the energy required for desalination. Figure 18 represents only a particular example of energy costs.

An arbitrarily rounded cost of $1.50/$m^3$ is attained if the cost of oil is $50 per barrel. This amount is larger than the amount calculated using reported costs of desalination discussed above. Consequently, a range of $1.15/$m^3$ to $1.50/$m^3$ needs to be considered owing to limited available information with regard to real production costs.

[40] ESCWA, "Energy options for water desalination in selected ESCWA member countries" (E/ESCWA/ENR/2001/17).

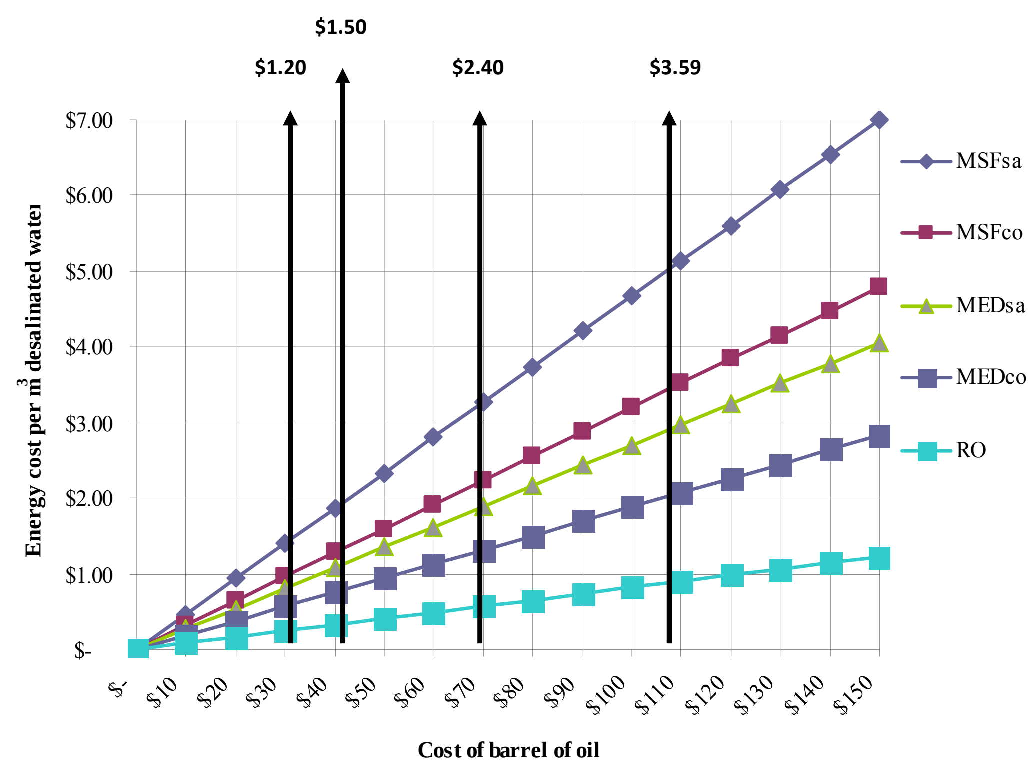
[41] M.A. Darwish, "Desalting fuel energy cost in Kuwait in view of $75/barrel oil price", *Desalination*, vol. 208, Nos. 1-3 (5 April 2007), pp. 306-320.

[42] As illustrated by figure 6 in chapter II, the technology profile of the region can be categorized as follows: MSF, at 54 per cent; RO, at 28 per cent; MED, at 9 per cent; and other, at 9 per cent.

A note on opportunity cost

World market prices of oil are used to calculate energy costs. Naturally, this cost is incurred for both oil importers and oil exporters/producers. The cost of the oil producer represents an opportunity cost. A barrel of oil can be sold for dollars or burned for water. In that context, at least, dollars and water can therefore be considered interchangeable and equivalent.

Figure 18. The energy cost of desalination in relation to the cost of oil



Source: Compiled by ESCWA based on the energy values of table 4.

Notes: Plant capacity for the cogeneration figures are based on a 300 MW and 60,000 m^3/d seawater plant. Plants with different capacities may use more or less energy.

The price of oil in 2008 fluctuated from a low of $40 per barrel to more than $140 per barrel. The cost figures at certain price points at the top of the graph represent the supply cost of desalination assuming that energy accounts for 75 per cent of the supply cost.

MSFsa denotes multi-stage flash stand-alone; MSFco denotes multi-stage flash cogeneration; MEDsa denotes multi-effect distillation stand-alone; and MEDco denotes multi-effect distillation cogeneration.

3. *Capacity, research and development, and cost*

Observations point to economies of scale of desalination plants. Larger desalination plants generally tend to have lower costs per cubic metre. Desalination plants with a capacity less than 10,000 m^3/day tend to exhibit a large variation in supply costs. Plants with capacities larger than this exhibit a smaller, more consistent range in their supply cost. Generally, smaller plants tend to have a higher supply cost per cubic metre than larger plants.

A distinct trend in desalination supply cost has been the decreasing cost of desalination over time. Research and development in the desalination field has led to many improvements in energy efficiency in all desalination technologies. In the 1950s and 1960s, supply costs frequently exceeded $5/$m^3$. While costs began to dip below the $5 mark in the 1970s, it was not until around 1990 that costs of $1/$m^3$ began to be observed.

4. *The International Desalination Association Inventory*

The largest source for desalination costs comes from the International Desalination Association (IDA) Inventory, which contains information on more than 14,000 plants worldwide.[43] The Inventory provides information on the country of operation, technology, capacity, feedwater, contract date, and the engineering, procurement and construction (EPC) cost of the plant. It is the largest and most comprehensive inventory of empirical data on desalination plants available.

However, as a collection of information on desalination plants, the Inventory does not standardize its data across plants. Out of the 14,000 plants, only some 10,000 have cost data associated with them. Moreover, out of these 10,000 remaining plants, the majority are very small, with capacities of less than 600 m^3/day. The costs of these very small plants vary widely and their impact on the incurred cost of desalination is not nearly as great as those of larger plants. Furthermore, the Inventory does not standardize cost data; there is a lack of guidelines for reporting cost; the Inventory only collects capital costs (O&M costs are not reported); and the cost data varies widely and inconsistently.[44]

B. TRANSPORT AND INFRASTRUCTURE COSTS

Water transportation costs are not widely available in the published literature.[45] This section isolates the cost of transporting water with a breakdown between distance as well as altitude, with a further breakdown into capital, pumping and maintenance costs.

1. *Determining transportation cost*

The most often cited work on water transportation costs is Kally (1993).[46] The cost calculations in that study are based on a transfer of water from the Suez to the Negev. The transport costs are broken into capital costs (\$0.13/m^3), energy costs for pumping (\$0.10/m^3), operation and maintenance (\$0.06/m^3), and the cost of water at the source (\$0.07/m^3).[47] Excluding the cost of water at the source, the total cost for capital, pumping, and operation and maintenance is \$0.29/m^3 for a Suez-Negev transfer. The distance of this transfer is 200 km with an increase in elevation of 75 metres. A disaggregated cost of horizontal transfer and lifting costs of water is not explicitly made.

One method to disaggregate the horizontal and vertical costs of water transport is to calculate the cost of lifting water. A common way to lift water is to use diesel engines to pump water through a series of pipes. In this case, the cost of lifting water consists of a capital cost (the cost of purchasing the pump and pipes) and an operating cost (diesel fuel and pump maintenance). The energy required to pump water is a function of flow rate, total volume being pumped, pumping height and the pump efficiency (see annex II for the water lifting calculations). For this energy estimate, the minimum flow rate required to lift all the water produced by a plant is assumed.[48] The calculated amount of energy needed to lift water is approximately 0.36 kWh/m^3/100 m.

To translate the energy required to lift water into a cost estimate, two steps are needed, namely: (a) the average fuel efficiency for pumps, which is here assumed to be 0.25 L/kWh;[49] and (b) the cost

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[43] Global Water Intelligence, "IDA Desalination Plants Inventory", which is available at: http://desaldata.com.

[44] For these reasons, a cost envelope had to be created using the two methods highlighted above in subsections 1 and 2 of this chapter.

[45] Zhou and Tol refer to this when they note that "an extensive search of the scientific literature revealed little that has been published on the costs of transporting water". Y. Zhou and R. Tol, "Evaluating the costs of desalination and water transport", *Water Resources Research*, vol. 41, No. 3 (9 December 2004), p. 10.

[46] According to Zhou and Tol, ibid. See E. Kally, *Water and peace: Water resources and the Arab-Israeli peace process* (1993).

[47] Inflated to 2008 United States dollars.

[48] This assumption is conservative since a flow rate higher than the minimum may be desired in cases of peak flow or to ensure an engineering factor of safety. The energy required to lift water is independent of plant size due to the minimum flow rate assumption.

[49] P. Smith, "Agfact: Is your diesel pump costing you money?" Department of Primary Industries, New South Wales, Australia (July 2004), which is available at: http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0004/165217/cost-diesel-pump.pdf.

of a litre of diesel fuel. Within the context of the latter, in countries that do not subsidize diesel fuel, such as Lebanon and the United Arab Emirates, the cost of a litre of diesel is approximately $1.00/litre.[50] The cost in other countries where subsidies exist varies from $0.09/litre in Saudi Arabia to $0.24/litre in the Syrian Arab Republic to $0.44/litre in Jordan.[51] A subsidy represents a real cost that, while not borne directly by the consumer, is paid for indirectly by the public through government expenditures. Therefore, $1/litre is used in the water lifting calculations. Accordingly, the cost of diesel fuel required to pump a cubic metre of water 100 metres in altitude is approximately $0.09 (when using 0.36 kWh/m^3/100 m). This figure does not include the capital cost or maintenance of the pumps. This figure will also change if the price of oil, and therefore of diesel fuel, changes significantly.

2. *Comparison to other cost calculations*

This cost is lower than the cost incurred by the water transportation authority of Canal de Provence in France, which is approximately $0.13/m^3/100m.[52] An analysis of 17 pumping stations in the California State Water Project (SWP), which pumps water from Northern California to the southern coastal cities, shows a range of energy used for pumping from 0.31 to 0.79 kWh/m^3/100m (see annex III for details).[53] On average, the pumping energy used in SWP amounts to 0.37 kWh/m^3/100m, or $0.09/m^3/100m, which is nearly identical to the calculated cost. Another estimate for pumping costs provides that 6 kWh is sufficient to lift one cubic metre of water over 1,800m, or approximately 0.33 kWh/m^3/100m, which translates to $0.08/m^3/100m.[54]

Table 5 summarizes the various estimates for vertical pumping costs. The calculated estimate of $0.09 is approximately the average of these four estimates.

TABLE 5. ESTIMATING VERTICAL PUMPING COSTS

	Pumping costs (*\$/m^3/100 m*)
Calculated	0.09
Canal de Provence	0.13
California SWP	0.09
Schiffler (2004)	0.08

Sources: Compiled by ESCWA based on sources cited above.

Applying the figure of $0.09/m^3/100 m to Kally's total of $0.29/m^3 for the Suez-Negev transfer above, the cost of lifting water 75 m would be $0.07/m^3. This leaves $0.22/m^3 for the 200 m horizontal transport of water, or $0.11 per 100 m. Disaggregating the horizontal cost into capital, operation and maintenance, and pumping costs on the basis of Kally's figures yields the following:[55]

(a) Capital: $0.06/m^3/100 km;

(b) Operation and maintenance: $0.03/m^3/100 km;

(c) Pumping horizontal: $0.01/m^3/100 km;

(d) Pumping vertical: $0.09/m^3/100 m.

[50] For more information on this, see also IRIN, "Palestinians protest exclusion as government moots minimum wage" (1 May 2008), which is available at: http://www.alertnet.org/thenews/newsdesk/IRIN/8fe0845e1c396ea59b873782d1a11604.htm; and K. Himendra, "Dubai oil retailers lower diesel price", *Gulf News* (12 November 2008), which is available at: http://www.gulfnews.com/business/Oil_and_Gas/10258959.html.

[51] See M. Singh, "Smuggling clamp hits causeway", *Gulf Daily News* (7 February 2008), which is available at: http://www.gulf-daily-news.com/1yr_arc_articles.asp?Article=207952&Sn=BNEW&IssueID=30324&date=2-7-2008; CC TV International, "Syria to raise diesel price to restructure oil subsidies" (27 August 2007), which is available at: http://www.cctv.com/program/bizchina/20070827/102136.shtml.; and *International Herald Tribune*, "Jordan's finance minister resigns amid government decision not to boost fuel prices" (21 August 2007), which is available at: http://www.iht.com/articles/ap/2007/08/21/africa/ME-GEN-Jordan-Minister-Resigns.php.

[52] This section is based on personal communication with an engineer at Canal de Provence. The amount of energy required to lift one cubic metre of water 100 metres was quoted at 0.53kWh/m3/100 m. However, this figure is only a mean average and depends heavily on local conditions.

[53] California Department of Water Resources, "Management of the California State Water Project", *Bulletin 132-06* (December 2007), which is available at: http://www.water.ca.gov/swpao/bulletin.cfm.

[54] While this cost is very similar to the calculated cost, does not cite any source for his figure. M. Schiffler, "Perspectives and challenges for desalination in the 21st century", *Desalination*, vol. 165 (15 August 2004).

[55] See E. Kally, *Water and peace: Water resources and the Arab-Israeli peace process* (1993).

-or-

Transport Cost = 0.10x + 0.09y

Where:

x = horizontal transfer distance (100 km)
y = vertical distance (100 m)

Some examples of transport costs for cities around the region are shown in table 6. Transportation costs are significantly large for all the cities except for coastal cities.

TABLE 6. SEA-TO-CITY COSTS OF WATER TRANSPORTATION

City	Distance from sea (*km*)	Elevation (*m*)	Sea-to-city water transport (*$/m³*)	Lifting cost from sea level to city (*$/m³*)	Total transport cost (*$/m³*)
Sana'a	130	2 250	0.13	2.03	2.16
Amman	270	890	0.27	0.80	1.07
Riyadh	360	600	0.36	0.54	0.90
Damascus	180	680	0.18	0.61	0.79
Gaza City	0	35	0.00	0.03	0.03
Muscat	0	15	0.00	0.01	0.01

Source: Compiled by ESCWA.

C. ENVIRONMENTAL EXTERNALITIES

Desalination contributes directly to environmental pollution in two ways, namely: fossil fuel energy consumption and brine plus chemical discharge. The energy required for desalination is most often obtained by burning fossil fuels, which contributes to air pollution and greenhouse gas emissions. The impacts of brine and chemical discharges on the environment are more dubious. Brine impact on the environment is mixed and varies considerably from location to location. Therefore, owing to the complex nature of brine and chemical impacts on the environment, they are not included as a component of desalination costs in this publication. However, it is recommended that these costs should be considered as part of future studies in the desalination sector and in planning individual desalination plants.

Energy and CO_2 emissions

The most straightforward way of calculating air emissions costs is to consider just one emission product, namely, CO_2, for the following two reasons: (a) there is a large market for CO_2 that can be used to calculate costs; and (b) the effects of CO_2 on the environment are global and have no association with their point of origin, thereby allowing pricing of CO_2 without regard to location.

There are two major markets for carbon. The first is the European Union Emission Trading Scheme (EU ETS), which represents the largest market-based cap and trade mechanism of carbon in the world. In 2008, EU ETS was worth approximately $50 billion tons annually, with more than 2 billion tons CO_2 traded annually. The cost of carbon emissions on EU ETS was an estimated $27 per ton CO_2 in 2007.[56]

The second market consists of certified emissions reductions (CER) based on the Clean Development Mechanism (CDM). CERs are carbon reductions that take place in non-annex I countries, which include all the countries in the ESCWA region. Spot contracts for CERs cost about $20 per ton CO_2 in 2007.[57] Very few CDM projects take place in the ESCWA region.[58]

[56] The World Bank, "State and trends of the carbon market 2008" (May 2008), which is available: http://wbcarbonfinance.org/docs/State_Trends_FINAL.pdf.

[57] For the purpose of this calculation, 1 euro is equivalent to $1.21 United States dollar.

[58] The notable exception is Egypt, where cost estimates from the CDM projects are similar to $20 per tonne. I. Elmassry, "CDM/energy efficiency projects Egypt: Group II", which was presented at the Jerba CDM Investment Forum (Tunis, 22-24 September 2004) and is available at: http://www.cd4cdm.org/North_per_cent20Africa_per_cent20and_per_cent20Middle_per_cent20East/Region/Jerba_per_cent20Investment_per_cent20Forum/29-EgyptEnergyEfficiency_Elmassry.ppt.

The price of carbon, however, has been volatile in these two markets. In addition to the market price, some efforts have been made to identify the societal cost of carbon. The Stern Review, which is among the best known reviews of carbon economics, puts the price of carbon at $85 per ton.[59] Moreover, a report by the National Research Council in the United States of America reviewed a number of carbon pricing studies and found an average cost of approximately $30 per ton.[60] This study uses the CDM figure of $20 per ton to allow for more conservative cost estimates.

Table 7 presents the energy used by each desalination technology and calculates the abatement cost for each cubic metre of desalinated water. MSF and MED plants use both thermal and electric energy, whereas RO plants use just electrical energy. As is evident from the table, the abatement costs are significant, especially for energy intensive MSF plants.

TABLE 7. COST OF CO_2 EMISSIONS FOR DIFFERENT DESALINATION TECHNOLOGIES

Desalination technology	Electric energy (*kWh/m³*)	Thermal energy (*MJ/m³*)	kg-CO_2/m^3	CO_2 abatement (*$/m³*)
MSF	3.5-5	250-300	20.4-25.0	0.41-0.50
MSF_{cogen}	3.5-5	160-170	13.9-15.6	0.28-0.31
MED	1.5 -.5	150-220	11.8-17.6	0.24-0.35
MED_{cogen}	1.5-2.5	100	8.2-8.9	0.16-0.18
RO (sea)	5-9	none	3.4-6.0	0.07-0.12
RO (brackish)	0.5-2.5	none	0.3-1.7	0.01-0.03

Sources: Energy requirements from F. Banat, “Membrane desalination driven by solar energy” (2007), which is available at: 1; and cogeneration energy requirements from M.A. Darwish, “Desalting fuel energy cost in Kuwait in view of $75/barrel oil price”, *Desalination*, vol. 208, Nos. 1-3 (5 April 2007), pp. 306-320.

TABLE 8. COST OF CO_2 EMISSIONS FOR WATER TRANSPORTATION

Pumping	Energy (*kWh/m³/(distance)*)	kg-CO_2/m^3/(distance)	CO_2 abatement (*$/m³/(distance)*)
Vertical (per 100 m)	0.36	0.24	0.0048
Horizontal (per 100 km)	0.040	0.027	0.00053

Source: Compiled by ESCWA.

TABLE 9. COST OF CO_2 EMISSIONS FOR WATER TRANSPORT FOR SELECTED CITIES

City	Distance from sea (*km*)	Elevation (*m*)	Energy (*litres-diesel/m³*)	kg-CO_2/m^3	CO_2 abatement (*$/m³*)
Sana’a	130	2 250	2.0	5.4	0.11
Amman	270	890	0.83	2.2	0.04
Riyadh	360	600	0.58	1.5	0.03
Damascus	180	680	0.63	1.7	0.03
Gaza City	0	35	0.03	0.08	0.00
Muscat	0	15	0.01	0.04	0.00

Source: Compiled by ESCWA.

Note: Details on abatement calculations are available in annex IV.

[59] N. Stern, “Stern review on the economics of climate change” (2006), which is available at: http://www.hm-treasury.gov.uk/sternreview_index.htm.

[60] National Research Council, “Hidden costs of energy: Unpriced consequences of energy production and use” (prepublication copy, 2009), which is available at: http://books.nap.edu/openbook.php?record_id=12794&page=R1.

Transportation of water also consumes energy and therefore releases CO_2. Vertical pumping requires 0.36 kWh/m^3/100 m (derived in the transport section). Horizontal pumping requires much less energy, typically of the order of 0.04 kWh/m^3/100 km. The energy, CO_2 emissions and abatement costs from the vertical and horizontal pumping components are presented in tables 8 and 9. The vertical component dominates the energy required for pumping. In fact, for all practical purposes, the horizontal pumping can be ignored in a CO_2 abatement cost calculation in the region since pumping horizontally 2,000 km would represent a sea-to-city distance greater than exists in any country in the ESCWA region, and would result in an abatement cost of only $0.01. Overall, the amount of energy used and, consequently, of CO_2 produced for water transport is considerably less than the energy used in the desalination process. However, in cities at very high altitudes, such as Sana'a, the vertical pumping component does become significant. For Sana'a, the CO_2 abatement cost for water transported from sea-to-city would be $0.11/m^3, about the same cost as is needed to abate for the desalination process itself. Table 9 lists the CO_2 abatement costs for water transport for the six cities highlighted in the previous transport section.

D. Putting costs together: supply transport and externality costs

This chapter presented the cost of desalination in three parts, namely: (a) the supply cost of desalination; (b) the sea-to-city transportation cost of water; and (c) an environmental externality cost of CO_2 emissions. The six cities that have been used as examples throughout this chapter are redeployed in table 10 showing the full cost components of desalination.

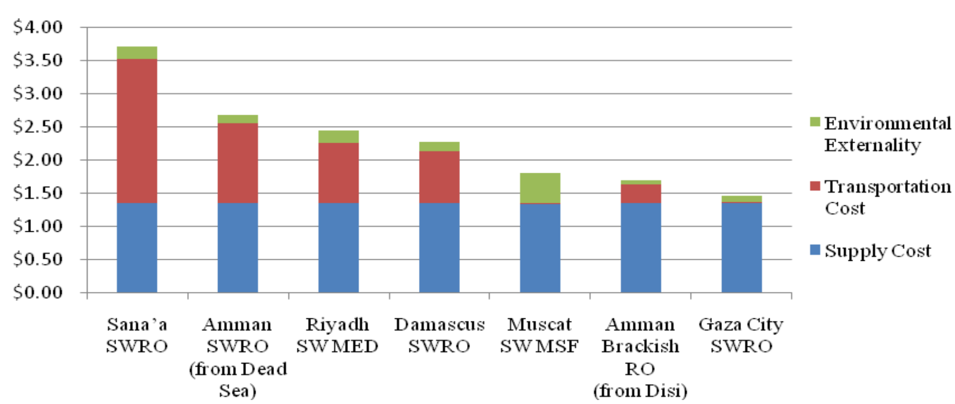
TABLE 10. FULL COST OF DESALINATION FOR SELECTED CITIES

City	Desalination unit technology type	(a) Supply cost of desalination (*\$/m^3*)	(b) Sea-to-city transport cost (*\$/m^3*)	(c) Environmental cost[3] (CO_2) (*\$/m^3*)	Full cost: [(a)+(b)+(c)] (*\$/m^3*)
Sana'a	Seawater RO	1.35	2.16	0.20	3.71
Amman	Seawater RO (from Dead Sea)	1.35	1.20	0.13	2.68
Amman	Seawater RO	1.35	1.07	0.14	2.56
Riyadh	Seawater MED (cogeneration)	1.35	0.90	0.20	2.45
Damascus	Seawater RO	1.35	0.79	0.13	2.27
Muscat	Seawater MSF	1.35	0.01	0.45	1.81
Amman	Brackish RO (from Disi Aquifer)	1.35	0.28	0.06	1.69
Gaza City	Seawater RO	1.35	0.02	0.10	1.47

Source: Compiled by ESCWA.

Notes: These are approximate costs indicative of what the actual full cost of desalination would likely be in these cities. The equations used to derive these figures are as follows (calculation details are in the respective sections of this chapter):

$(a) = 1.35$, approximate average of \$1.15 and \$1.50 $(b) = 0.10x + 0.09y$ and $(c) = 0.02 * \frac{kg\text{-}CO_2}{m^3}$.



The graphical representation of the table above illustrates the comparative cost of desalination in selected cities of the ESCWA region. The cities are ordered from the most expensive in which to provide desalinated water to the least expensive. Cities that are very high above sea level, including, for example, Sana'a, are predicted to be very expensive locations to provide desalinated seawater. Coastal cities and nearby brackish water fields are situations where cheaper desalination will take place.

Sana'a provides one of the starkest examples of the difference between supply cost and total cost of desalination, a difference in this case of 175 per cent. On the other end of the spectrum, Gaza City, which represents a coastal, low-lying city, has a difference between supply and total cost of merely 9 per cent. Transportation is a significant component of the total cost of desalination in every case except for the coastal cities or brackish desalination, especially so for such high altitude cities as Sana'a and Amman. Environmental costs account for a large percentage of the costs of MSF plants, accounting for 25 per cent of the cost in Muscat.

V. REDUCING THE COST OF DESALINATION

Reducing the cost of desalination could greatly benefit the water-stressed countries of the ESCWA region in addition to providing those countries that are already using desalination with significant savings. Cheap and abundant desalination has been a long standing goal of science and society, and measures up to many of the greatest scientific objectives and accomplishments of humanity. While the vision of cheap desalination has not yet been achieved, the cost of desalination can be reduced in many ways. Some of these options are explored in this chapter, focusing on the supply cost of desalination. It is important to note that while these options are not intended as a silver bullet to solve completely the issue of cost, desalination has gone from being prohibitively expensive to merely costly. In the future, some of the suggestions or technologies discussed in this section could mature enough to become a reality.

A. ENERGY

Energy is a major cost incurred in the operation of a desalination plant. There are two ways to reduce energy costs, namely: (a) by increasing the energy efficiency in the desalination process; and (b) by using a cheaper energy source.

1. *Increasing energy efficiency*

One method of increasing energy efficiency is to couple a desalination plant with a power plant, thereby creating a cogeneration desalination-power unit. In such a setup, hot exhaust gases from a power plant are used either to desalinate water in a distillation plant or to heat incoming feedwater. As noted in chapter IV, cogeneration desalination plants can be more energy efficient than stand-alone plants. Higher temperature feedwater reduces the amount of energy needed to desalinate water. Cogeneration is usually used in combination with distillation desalination, though RO plants can also operate more efficiently with higher temperature feedwaters.[61]

[61] O.A. Hamed, "Overview of hybrid desalination systems – current status and future prospects", *Desalination*, vol. 186, Nos. 1-3 (30 December 2005), pp. 207-214.

Another method of increasing energy efficiency is to combine a thermal desalination unit and a single pass RO unit into a hybrid plant. The single pass RO unit is used as opposed to the more common multi-pass RO plant given that a single pass unit uses less energy than a multi-pass. The single pass RO is made possible in this configuration by blending its output with the output from the thermal desalination unit. The blended water is then potable and allows for a less energy-intensive operation of the RO plant.[62]

A hybrid plant is cost effective and efficient when implemented as a retrofit on an old thermal plant by adding an RO unit.[63] For new plants, some reservations have been made regarding the improved efficiency of hybrid systems, as evidence has shown that hybrid plants do not necessarily increase energy efficiency per cubic metre. In addition, hybrid designs tend to be less flexible than single technology systems.

2. *Cheaper energy sources*

In the Gulf subregion, desalination plants have been developed to take advantage of the variation in demand for electrical power. Energy demand spikes during the hot summer months given the need for additional power for air conditioning. Energy demand in winter is substantially lower, thereby leading to a surplus of generating capacity during the winter. Various plants have been designed to take advantage of this cheap surplus capacity to produce more water during the winter. This water can then be stored for later use.

Moreover, alternative energy sources can be used for desalination and can reduce the cost of desalination. Specifically, renewable solar energy can be used as an alternative fuel for electric or thermal plants; and renewable wind energy and nuclear energy can be used to generate electricity for use in desalination plants. The alternative energy sources and their application are explored below.

[62] Ibid.

[63] I. Kamal, "Myth and reality of the hybrid desalination process", *Desalination*, vol. 230, Nos. 1-3 (30 September 2008), pp. 269-280.

3. *Renewable energy*

Renewable energy can potentially provide less expensive energy in certain desalination applications. Renewable energy sources have been explored for desalination primarily in research settings. No large scale renewable desalination is currently taking place in the ESCWA region. This owes largely to the high, albeit declining, cost of renewable energy. The Red-Dead Sea project, which aims to channel water from the Red Sea to the lower altitude Dead Sea, represents arguably the first very large desalination scheme in the region that would be driven by a renewable energy source, hydropower.[64] While still in the design phase in 2009, the project has the potential to produce up to 850 million m^3/year of potable water.

Renewable desalination plants do not produce CO_2, which is a main advantage of such plants that translates into cost savings of up to \$0.50/m^3 of water (see chapter IV for details on the cost of CO_2 emissions and environmental externalities).

(a) *Solar energy*

The ESCWA region, which is rich in solar energy, receives more than 4 kWh/m^2/day (electric equivalent) of solar energy, with very few cloudy days.[65] Combining the two characteristics of water poverty and sun wealth could be a boon to the region. However, development in solar desalination is still primarily restricted to research prototypes and small-scale systems designed for remote and rural areas.[66] Research and development in solar desalination is promising, and the solar energy available for harnessing is abundant.

Two types of solar power can be harnessed, namely, solar photovoltaic (PV) and solar thermal. Solar PV uses a silicon-based system to produce electricity from solar rays. As such, solar PV can be used primarily for RO plants or to provide some of the electrical power required by thermal plants. Solar PV is currently very expensive and does not compete with other forms of electricity generation. Solar PV may also be used in remote or off-grid locations to satisfy small scale RO demands.

Solar thermal can be used to produce both thermal and electrical energy that is capable of powering a desalination plant. Thermal energy is created by concentrating or collecting solar radiation and generating heat. Generally, solar thermal takes the form of a collector that concentrates solar rays onto a liquid medium, usually oil, water or molten salt, thereby creating a hot fluid. For desalination, this hot fluid can be used to provide direct thermal energy needed for thermal plants, namely, MED or MSF, or it can be used to create steam to generate electricity. For direct thermal energy purposes, the liquid medium used is often oil or water, while for electricity generation molten salt is often used owing to its higher temperature profile.

Some of the thermal energy created during daylight can be stored so that energy can continue to be provided throughout the night. Traditional energy sources can also be used to augment solar thermal in order to ensure continuous power output.

Additionally, solar thermal energy can be used to desalinate water directly without going through a conventional desalination plant. Within that context, the simplest setup is a solar still whereby water is evaporated by solar thermal energy and is condensed and collected separately from the brine. Multiple-effect dehumidification is a more sophisticated version of a solar still, and uses multiple temperature evaporation and condensation cycles to reduce the overall amount of energy used. However, direct solar desalination often requires significant land areas and is less productive than solar thermal coupled with conventional desalination plants.[67]

[64] This project is aimed at replenishing the shrinking Dead Sea and producing hydroelectric power by virtue of the drop in altitude.

[65] See ESCWA, "Energy options for water desalination in selected ESCWA member countries" (E/ESCWA/ENR/2001/17).

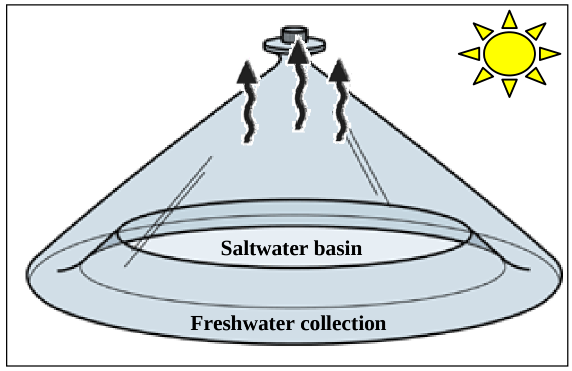
[66] H.M. Qiblaway and F. Banat, "Solar thermal desalination technologies", *Desalination*, vol. 220, Nos. 1-3 (1 March 2008) pp. 633-644.

[67] Ibid.

Currently, both solar PV and solar thermal do not provide any cost savings over traditional fuel sources for desalination. Solar power is being used only for research or such niche uses as in remote areas that are unconnected to the electricity grid or on a micro-scale for users who do not have access to other sources of water. Moreover, while several small-scale solar PV/RO plants exist in the ESCWA region and across the world, most of those in the region are ageing. One fairly modern PV/RO plant in Brazil produces water at approximately $3.60/m^3.[68] One study on solar thermal desalination in the region predicts that solar thermal desalinated water is set to cost $3/m^3 in 2010 and will drop quickly to approximately $1.15/m^3 by 2020, and $0.65/m^3 by 2030.[69] At these costs, solar thermal would be very competitive with conventionally fuelled plants, particularly in view of oil price volatility.

On a much smaller scale, solar micro-desalination may be used in remote areas where little or no freshwater exists. Micro-desalination units use solar thermal energy to desalinate water and are capable of producing some 1.5 litres of freshwater every day. A typical unit has a capital cost of about $26.50, with an operational lifetime of approximately two years.[70] Figure 19 displays a typical micro-desalination unit marketed as Watercone.[71] At such a cost, the unit could produce water for about $24/m^3.[72] This is much higher than traditional desalination plants, owing to the micro-scale of the unit. However, it can provide a reasonable alternative in areas that lack access to freshwater. For instance, such units can be used by various groups, including, among others, travellers in remote regions or fishermen out at sea for extended periods. For any permanent settlements, it would be less expensive to provide remote areas with water from a conventional desalination plant. In Palestine, the ongoing uncertainty and insecurity has also encouraged investment in these micro-desalinization units, particularly in the Gaza Strip.

Figure 19. Micro-desalination unit: Watercone



(b) *Wind energy*

While wind power can provide electricity for a desalination plant, it cannot directly provide thermal energy. As such, the future of wind power for desalination is in providing electric energy for RO plants. Consequently, the focus of wind power for desalination relies mainly on reducing the cost of wind per kWh of electricity, thereby competing with other electricity generation methods.[73]

Wind power is becoming more competitive with conventional electric power sources, particularly in windy areas. Generally, wind power is competitive in areas where wind speeds are at least 6 m/s.

More work needs to be done to identify locations in the ESCWA region that have high winds speeds that are capable of supporting large-scale wind power. The most promising areas for wind power production in the ESCWA region are the east coast of Egypt; some sites in Jordan,

[68] A. al-Karaghouli, D. Renne and L.L. Kazmerski, “Solar and wind opportunities for water desalination in the Arab regions”, *Energy Reviews*, vol. 13, No. 9 (December 2009).

[69] F. Trieb and H. el-Nokrashy, “Concentrating solar power for seawater desalination”, which is available at: http://www.solarec-egypt.com/resources/CSP+for+Desalination-IWTC_2008.pdf.

[70] IRIN, “Using small devices to desalinate water” (11 May 2009), which is available at: http://www.irinnews.org/Report.aspx?ReportId=84329.

[71] More information on Watercone is available at: http://www.watercone.com/product.html.

[72] This assumes that there are no additional costs, including operation and maintenance, transport and environmental externalities.

[73] While there are methods to power mechanically an RO system directly with wind energy, such a system is currently only experimental.

including Ras Munif, Mafraq and Aqaba;[74] and some of the coastal regions in the Gulf subregion.

Within that context, while the ESCWA region has not been studied in detail, there are many areas with wind speeds that are sufficiently high to support wind power generation.[75] A study completed for Abu Dhabi stated that no reliable wind data existed for the Emirate and that the available data suggested a low average with regard to annual wind speeds, despite modestly higher wind speeds along the coast.[76] Nevertheless, the first wind-powered desalination plant in the Gulf subregion began operations in Abu Dhabi in October 2004 on Sir Bani Yas Island, which is an ecological and animal reserve off the coast of Abu Dhabi. The plant, which was established as a demonstration project for wind desalination, produces 850 kW of electricity and a maximum of 1,000 m^3/day of freshwater.[77] The capital cost of the wind power plant alone was an estimated $2.5 million.[78] The cost of water produced by the desalination unit attached to this wind plant can be estimated at roughly $3/$m^3$, excluding transport cost (given the small size of the island) and environmental externalities. Of course, some economies of scale could be achieved if a larger wind turbine and desalination plant were used.

(c) *Nuclear energy*

Nuclear desalination is achieved through a cogeneration unit that couples a desalination plant with a nuclear reactor, which is used as the source of energy. Nuclear reactors can be coupled with thermal plants to provide steam for desalination processes, or with membrane plants to generate electricity to drive the desalination process. Generally, small- or medium-sized reactors are best suited for desalination when the reactor is used solely for desalination purposes.[79] While nuclear desalination does not produce greenhouse gases, which constitutes a main advantage, the disposal of nuclear waste and the threat of nuclear proliferation are unresolved issues that need to be considered.

Nuclear power has witnessed renewed interest as concerns over climate change and interruptible supplies of fossil fuel have led to the construction of new plants across the world. In the United States of America, the construction of nuclear plants is being realistically considered for the first time since 1979.[80] In the ESCWA region, Egypt has explored several options for nuclear desalination and Jordan is exploring nuclear power options. The renewed interest in nuclear power comes along with new standardized plant designs that could theoretically reduce the cost of nuclear power. As practical construction experience increases, the cost of commissioning nuclear power plants and, by extension, of nuclear desalination facilities will decrease. While estimated costs vary, in general, nuclear power is considered to be cost competitive with fossil fuel sources when subsidies and opportunity cost are accounted for.[81]

The cost of nuclear desalination is based on the cost of nuclear power. Consequently, such site-specific parameters as construction costs, fuel price and interest rates determine whether nuclear desalination is an economical alternative. Initially, construction costs for nuclear plants could be higher owing to the region's inexperience in managing nuclear power plants. However, as

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[74] B.A. Akash, R.O. al-Jayyousi and M.S. Mohsen, "Multi-criteria analysis of non-conventional energy technologies for water desalination in Jordan", *Desalination*, vol. 114, No. 1 (1 December 1997), pp. 1-12.

[75] C.L. Archer and M.Z. Jacobson, "Evaluation of global wind power", *Journal of Geophysical Research – Atmospheres* (2005), which is available at: http://www.stanford.edu/group/efmh/winds/global_winds.html.

[76] J. Kaufler, "Experiences in Morocco and Abu Dhabi (UAE)", which was presented at Win-win Potential and Export Opportunities for German Companies (Berlin, 22-23 November 2007) and is available at: http://www.umwelt-dienstleistungen.de/vortraege/AG1_5_Joachim_Kaeufler.pdf.

[77] W. Sawahel, "Gulf's first wind power plant is opened" (Science and Development Network, 2 November 2004).

[78] Ibid.

[79] B.M. Misra and J. Kupitz, "The role of nuclear desalination in meeting the potable water needs in water scarce areas in the next decades", *Desalination*, vol. 166 (15 August 2004), pp. 1-9.

[80] This was the year of the nuclear incident known as the Three Mile Island accident.

[81] D. Milborrow, "Electricity generation costs: little to choose between the options?" *Power UK*, No. 173 (July 2008), which is available at: www.claverton-energy.com/?dl_id=314.

experience is gained, construction costs should fall in line with international costs. High fossil fuel prices favour nuclear power development, while high interest rates favour less capital-intensive, fossil fuel power sources for desalination.[82]

Nuclear proliferation or the perceived threat of nuclear proliferation is a real concern that impedes the commissioning of new nuclear power plants, especially in the ESCWA region. However, the League of Arab States has agreed to launch training sessions on nuclear energy planning and legislative frameworks and is set to organize a meeting on nuclear energy prospects in the Arab region in 2010.[83]

B. OPERATION AND MAINTENANCE

The operation and maintenance (O&M) of a plant can have significant effects on desalination cost. Two ways that O&M can affect cost are through the robustness of the desalination plant and the extent of experience of the labour force.

1. *Technology*

While there are many factors to be taken into account when considering which desalination technology to select for a particular application, one selection criterion needs to be the robustness of a selected desalination technology. Thermal technologies tend to be more robust than RO technology. It takes many years of poor operation to destroy a thermal plant; by contrast, an RO plant can have its membranes ruined in a day or two. If labour is inexperienced, the maintenance costs of an RO plant increase the cost of a cubic metre of desalinated water. Consequently, a plant operator may choose a thermal plant if the operator has inexperienced labour force or is highly averse to risks.

2. *Labour costs*

The quality of staff, their practical experience in desalination operation and access to technical assistance affect cost, as illustrated in the example above on the comparative robustness of thermal and RO technologies. Costs can be reduced by employing highly skilled operators, and downtime can be reduced by following the maintenance schedule. Evidence from the region bears this out. Properly trained staff can improve the uptime of a plant. Specifically, while most plants are designed to operate at 90-95 per cent capacity, plants in the region operate closer to 80 per cent.[84] This is partly due to untrained staff. Moreover, few universities in the region have undergraduate courses in desalination and only a limited number of institutions conduct capacity-building in this sector.

C. DESALINATION BY-PRODUCTS

Another method of reducing the cost of desalination is to make economic use of desalination by-products, namely salt. Brine discharge from a desalination plant contains a large volume of salt that can be harvested and sold at a profit. To produce salt, brine discharge is pumped into large, shallow evaporation ponds. The climate in the Gulf subregion is particularly suitable for the production of salt in ponds, given its dry climate, low precipitation, large tracts of available land and proximity to shipping ports for transportation of the final product salt.

An operating dual-purpose SWRO plant can produce 30-40 kg of salt per cubic metre of freshwater capacity (10,000 m^3/d capacity plant).[85] Salt of various qualities can be obtained from the brine. High purity salt is used as a food additive, while lower quality salt can be used as a de-icing agent. Most salt is used as a feedstock to the chemical industry.[86] In the United States of

[82] B.M. Misra and J. Kupitz, "The role of nuclear desalination in meeting the potable water needs in water scarce areas in the next decades", *Desalination*, vol. 166 (15 August 2004), pp. 1-9.

[83] Pursuant to a resolution adopted at the eighth session of the Council of Arab Ministers Responsible for Electricity (Cairo, 20 May 2009).

[84] K. Quteishat, "MENA Region: Capacity building needs in desalination", which was presented at the World Bank Water Week 2004 (Washington DC, 25 February 2004).

[85] A. Ravikzy and N. Nadav, "Salt production by the evaporation of SWRO brine in Eilat: a success story", *Desalination*, vol. 205 (5 February 2007), pp. 374-379.

[86] O. Kilic and A.M. Kilic, "Recovery of salt co-products during the salt production from brine", *Desalination*, vol. 186 (30 December 2005), pp. 11-19.

America, salt is sold for approximately \$57/ton on average, with low grade road and chemical salt priced at about \$34/ton and high quality table salt sold at approximately \$200/ton.[87] Salt sales from a dual-purpose SWRO plant can amount to more than \$8 million annually, which represents a revenue stream of more than \$2/m^3 of capacity. A significant offset to the total cost of desalination can therefore be realized by salt harvesting as long as the capital and maintenance costs of salt harvesting are less than \$2/m^3. Further feasibility studies on salt harvesting need to be conducted in the region.

There are also environmental externalities associated with desalinization by-products that are not properly disposed. For instance, brackish water released by desalinization plants increases the salinity of coastal waters and inland streams. This can adversely affect local fish populations and marine biodiversity if appropriate measures are not put in place. The temperature of coastal waters is also generally higher in areas neighbouring desalinization facilities, which also presents potential implications for local biodiversity.

D. TRAINING, RESEARCH AND DEVELOPMENT

The capital and operating costs for desalination have decreased over time given technological improvements, economies of scale associated with larger plants, and improved project management and experience. Improvements in RO technology provide a good example of reduced costs arising from research and development. Membrane performance has increased dramatically and has moved RO from a niche, small-scale technology into a mainstream choice for desalination across the world.

A number of centres, programmes and associations exist within the ESCWA region that conduct research on desalination and provide courses or training programmes on desalination operations. For example, the Middle East Desalination Research Centre has been funding research on desalination since its inception in 1996 and is currently focused on finding ways to reduce the cost of desalination.[88] The Kuwait Institute for Scientific Research also conducts research on desalination issues, including technical standards and technical and economic assessments of various desalination technologies. Equally, the Water Science and Technology Association supports research and training in GCC countries on water and science issues, including a significant amount of research on desalination. Saudi Arabia holds an annual exhibition and prizes for new research and technologies for desalination; while Oman has established a new university desalination research facility that involves undergraduate students as well as postgraduate programmes and short courses.[89]

However, a great deal of desalination research is conducted outside of the ESCWA region. This is striking given that the region has more desalination capacity than any other region in the world. More research can be done on desalination technology improvements specific to the region. Some avenues of research that can be followed include identifying alternative energy locations in the region, including solar or wind energy as described above. Future research on conventional desalination can focus on some of the following areas:[90]

(a) For RO plants: (i) increase the efficiency of pumps and power recovery; (ii) improve robustness of membranes and increase their tolerance for increased pressure, temperature and pollutants often found in seawater; (iii) increase the lifetime of these

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[87] Salt Institute, "US salt production/sales" (2008), which is available at: http://www.saltinstitute.org/Production-industry/Facts-figures/US-production-sales.

[88] M. Alian, "Middle East centre to tackle desalination research" (Science and Development Network, 7 July 2006), which is available at: http://web.scidev.net/en/new technologies/south-south-cooperation/news/middle-east-centre-to-tackle-desalination-research.html.

[89] M.F.A. Goosen, H. al-Hinai and S. Sablani, "Capacity-building strategies for desalination: activities, facilities and educational programs in Oman", *Desalination*, vol. 141, No. 2 (15 December 2001).

[90] These recommendations are drawn from J.E. Blank, G.F. Tusel and S. Nisanc, "The real cost of desalted water and how to reduce it further", *Desalination*, vol. 205, Nos. 1-3 (5 February 2007), pp. 298-311; and A.D. Khawaji, I.K. Kutubkhanah, and J-M. Wie, "Advances in seawater desalination technologies", *Desalination*, vol. 221, Nos. 1-3 (1 March 2008), pp. 47-69.

membranes to 10 years by reducing befouling; and (iv) create maintenance free pre-treatment systems that require a minimum amount of additives and chemicals;

(b) For thermal plants: (i) improve the heat transfer coefficient to allow for cheaper production of freshwater; (ii) reduce the cost of plant materials, such as evaporators, heat transfer materials and intakes; and (iii) develop alternative energy sources;

(c) For all desalination technologies: (i) standardize plant sizes and design to reduce the need to design unique units for each site;[91] and (ii) assess and reduce the environmental impacts of brine discharge.

The suggestions above are not meant to be prescriptive. Future avenues of research are sure to become available, which could be complementary to the above suggestions or could even push research and development into radically different directions. However, the above suggestions are examples of the kind of research that can and must be conducted in the ESCWA region. Desalination is a vital technology in the region, and research and training dollars need to be spent on this priority area.

[91] Maintenance training and parts replacement can then be standardized, and experiences can be shared with other plant operators. This can also open opportunities for South-South cooperation.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The ESCWA region has a great deal of experience and capacity with desalination. The cost of providing desalinated water can be high in certain cities, especially cities far from the coast. For example, the cost of delivering desalinated water to Sana'a, which is a city that is far from the coast and at a high altitude, is approximately \$3.71/m^3. On the other hand, the cost of providing desalinated water to Gaza City, which is a low-lying coastal city, is approximately \$1.47/m^3.[92] These costs vary considerably depending on the type of desalination technology employed and the cost of energy.

The cost figures are only approximate given the limited availability of public data and information on desalination. It is therefore difficult to determine precisely the cost of desalination, and the cost figures provided in this report are conservatively estimated in order to provide a floor price of the real cost of desalination.

B. RECOMMENDATIONS

The recommendations relate to the following three categories: (a) cost considerations; (b) water management options; and (c) areas for further research.

1. *Cost considerations*

Decision makers need to look at the full cost of desalination when considering whether to pursue desalination as a supply side water management choice. The full cost of desalination includes the supply cost, water transportation costs and environmental externalities. The water transportation cost to cities that are far from a sea coast can be very high. Moreover, the cost of environmental externalities needs to be included in the desalination cost as well, and must be monetized. The production of CO_2 is set to have an impact on the region, even if that impact currently remains uncertain.

Furthermore, the desalination industry needs to set up standards for reporting supply costs of desalination so that decision makers are better informed with regard to all the costs associated with desalination. The desalination costs need to include a range of realistic energy prices in the cost estimates given that future prices are hard to predict.

2. *Water management options*

Governments need to consider demand side management alternative aimed at augmenting available freshwater supplies before pursuing desalination investments, especially given the high cost of desalination. Demand side management initiatives can provide cost-effective and environmentally sound alternatives for addressing the region's water scarcity challenges when addressed within the IWRM framework.

3. *Areas for further research*

Researchers need to generate more research and data regarding the energy usage of desalination plants, especially cogeneration plants. Very few studies have disaggregated energy usage in terms of electricity and desalination in cogeneration plants. This report made use of one study on cogeneration energy usage that was limited to one plant in Kuwait. Other plants could produce different energy usage results.

More research and training on desalination needs to be conducted in the region rather than being imported from abroad. The sheer quantity of desalination facilities in the region represents a unique opportunity for hands-on study and training, as well as a sector for generating skilled employment opportunities for the region's burgeoning youth population.

Researchers and governments need to pursue renewable energy desalination on a large scale. While a number of small-scale studies have been conducted on renewable energy desalination, primarily solar, these studies are insufficient to give an overall picture of the potential of desalination in the region. Given the abundant solar energy resources of the region, a large-scale pilot study on this issue must be conducted.

[92] Albeit the ability to achieve this cost in the Gaza Strip depends on the ability to operate plants efficiently within the current security context.

Annex I

MODELS PRODUCED FOR ESTIMATING DESALINATION COST

ESCWA produced a model to calculate desalination costs based on a large database of desalination plants available from the International Desalination Association (IDA). The intended goal of the model was to produce an equation with which an estimate of the cost of desalination could be made using simple inputs such as capacity, online date, feedwater and technology. As noted in chapter IV, the model developed did not succeed given data gaps and inconsistencies. Therefore, other methods to calculate desalination costs have been used in the main text. The following are the details of the model presented for completeness and transparency of the process used by ESCWA.

The model developed is a least squares linear regression. The table below displays regression models 1, 2 and 3 that were used to estimate desalination cost. The parameters used in the model are on the left hand side of the table. The coefficients (beta) of the model are displayed below each model followed by the coefficient's 95 per cent confidence interval (shown as a +/-). The model equations follow the general equation:

$$y = \alpha + \beta_i * x_i + \varepsilon$$

Where *y* is the cost/m^3, α is a constant, β_i are the various coefficients in the table (under columns 1, 2 and 3), and x_i are the variables in the first column of the table. The regression used data from the IDA Inventory.

All the parameters used in the regression are taken directly from the IDA Inventory with the exception of cost. The Inventory does not contain a cost variable. Rather, it contains an engineering, procurement and construction (EPC) cost. EPC is the capital cost of the plant. To obtain a supply cost, the EPC cost must be amortized and the operation and maintenance cost must be estimated. The amortization equation is:

$$Amortized\_Cost = \frac{EPC * i * (1+i)^t}{(1+i)^{t-1}}$$

Where *i* is the interest rate and *t* is the lifetime of the plant. The interest rate is assumed to be 7 per cent and the plant lifetime is assumed to be 30 years.

To estimate operation and maintenance costs, as they are not included in the Inventory, an assumption is made that operations and maintenance account for 60 per cent of the supply cost of a plant. The assumption follows the convention that amortized capital costs are assumed to be 40 per cent of the supply cost of a plant and operating costs are assumed to be 60 per cent of the annual cost.[93] Therefore, the total supply cost of the plant is the amortized cost divided by 40 per cent.

The last assumption made is that desalination plants must incur some amount of downtime due to periodic maintenance. This downtime is assumed to be 10 per cent of the operational time of the plant. The total capacity of a plant is therefore only 90 per cent of the rated capacity.

[93] J.H. Kim, "Benchmarking SWRO water costs", *Water Desalination Report*, vol. 44, No. 33 (15 September 2008).

ANNEX TABLE 1. THREE MODELS FOR ESTIMATING DESALINATION COST

	Model 1		Model 2		Model 3	
Capacity	-2.71e-6*	+/- 1.09e-6	-2.28e-6*	+/- 1.1e-6	-5.53e-6*	+/- 1.03e-6
Technology						
RO					0.06	+/- 0.09
MSF					1.78*	+/- 0.14
MED					0.77*	+/- 0.13
Feedwater	2.11*	+/- 0.09	2.15*	+/- 0.09	1.47*	+/- 0.10
Ln (on-line date)	-3.80*	+/- 0.11	-3.80*	+/- 0.11	-3.17*	+/- 0.11
GCC			-.209*	+/- 0.09		
Constant (á)	14.97*	+/- 0.43	15.00*	+/- 0.43	12.65*	+/- 0.43
Num of Obs		4 896		4 896		4 896
Adj R^2		0.61		0.61		0.67

Source: ESCWA.

Notes: capacity = cubic metres per day (90 per cent of rated capacity).
RO/MSF/MED = 1 for plants of a particular technology, 0 else.
Feedwater = 0 for pure or river water.
0.3 for wastewater.
0.5 for brackish water.
1 for seawater or brine.
on-line date = on-line date of plant (1946 is subtracted out because the oldest plant in the data began operations in 1947). Natural log of online date is used in regression.
GCC = 1 if country is a GCC country, 0 for others.

* Significant to the 95 per cent confidence level.

Annex II

WATER LIFTING CALCULATIONS

To calculate the energy required to lift water, the following equation is used:

$$W = \rho * flow * head * g * pump_{efficiency}$$ [94]

Where:

W = watts
ñ = density of water = 1,000 kg/m^3
flow = flow rate (m^3/s)
head = hydraulic head (m)
g = acceleration of gravity = 9.8 m/s^2
pump efficiency = assumed to be 75 per cent

The calculation is intended to provide a minimum threshold. Therefore, *head* is assumed to be exactly the lifting height with no additional pressure needed. This assumption assumes that friction is negligible and that no additional pressure at the pipe end is needed. *Pump efficiency* is assumed to be 75 per cent, which is an average efficiency for a medium-sized pump. *Flow* is calculated to be the amount of water produced at a desalination plant. This is very much a minimum assumption because a higher flow rate (and hence more energy) may be desirable to ensure that any variation in water output can be accommodated.

The following equation transforms watts into kWh/m^3:

$$\frac{kWh}{m^3} = \frac{W}{1000} * \frac{hr}{yr} * \frac{1}{capacity}$$

Where:

hr/yr = hours per year = 8,760 hr/yr
capacity = total capacity of the plant

The capacity of the plant is a loose term. More rigorously, it should be the total flow out of the plant because, due to plant inefficiencies, the total flow out of the plant will be a percentage of the capacity (often around 85 per cent).

The amount of energy needed to lift one cubic metre of water 100 metres is 0.36 kWh. This is irrespective of plant capacity due to the minimum flow assumptions.

For this calculation, it is assumed that a diesel pump will be used. This is often the case in remote areas far from the electricity grid. It also has the advantage of not requiring any electric infrastructure (which may add to the cost of pumping). The average amount of energy in a litre of diesel is 0.25 kWh.[95] Therefore, the following equation is used to obtain the cost of pumping:

$$\frac{\$}{m^3} = \frac{L}{kWh} * \frac{kWh}{m^3}$$

The cost of lifting one cubic metre of water 100 metres is $0.09.

[94] P. Smith, "Agfact: Is your diesel pump costing you money?" Department of Primary Industries, New South Wales, Australia (July 2004), which is available at: http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0004/165217/cost-diesel-pump.pdf.

[95] Ibid.

Annex III

WATER LIFTING CALCULATIONS FOR THE CALIFORNIA STATE WATER PROJECT

The State of California transports large amounts of water from Northern California to the southern cities in the State. California publishes an annual bulletin on the management of the State Water Project (SWP) responsible for this water transportation.

The table below shows the energy and volume details of a number of the pumping stations along the transport route, ordered from largest to smallest station. The average pumping energy from these plants, along with other sources, is used to arrive at a water transport cost in chapter IV.

ANNEX TABLE 2. ENERGY AND VOLUME DETAILS OF SELECTED PUMPING STATIONS

Pump Plant Name	Normal Static Head (ft)[1/]	kWh/AF[2/]	kWh/m^3	$kWh/m^3/100$ m	$\$/m^3/100$ m
Edmonston	1 926	2 236	1.81	0.31	
Crafton Hills	613	1 087	0.88	0.47	
Greenspot	382	871	0.71	0.61	
Devil's Den	521	705	0.57	0.36	
Bluestone	484	705	0.57	0.39	
Polonia Pass	533	705	0.57	0.35	
Pearblossom	540	703	0.57	0.35	
Chrisman	518	639	0.52	0.33	
H.O. Banks	244	296	0.24	0.32	
Teerink	233	295	0.24	0.34	
Oso	231	280	0.23	0.32	
Buena Vista	205	242	0.20	0.31	
Cherry Valley	75	224	0.18	0.79	
Barker Slough	108	223	0.18	0.55	
Badger Hill	151	200	0.16	0.35	
Dos Amigos	116	138	0.11	0.32	
Las Perillas	55	77	0.06	0.37	
Total	**6 935**	**9 626**	**7.80**	**(Avg.) 0.37**	**$0.09**
1,233.48	AF = 1 m^3				

Source: California Department of Water Resources, "Management of the California State Water Project", *Bulletin 132-06* (December 2007), which is available at: http://www.water.ca.gov/swpao/bulletin.cfm.

1/ Page 8.
2/ Page B16.

Annex IV

CALCULATION OF CARBON ABATEMENT COSTS

In order to obtain the cost of carbon emissions per m^3 of desalinated water, three pieces of information are needed, namely: (a) the thermal and electric energy consumption of various desalination processes (MJ/m^3 thermal and kWh/m^3 electric); (b) the amount of carbon emitted per unit energy (in order to estimate carbon emissions per m^3); and (c) the cost per kg CO_2.

Pumping calculations are similar except that kg-CO_2 per litre of diesel is needed.

Equation for CO_2 cost: $$\frac{energy}{m^3} \ast \frac{kg - CO_2}{unit_{energy}} \ast \frac{\$}{kg - CO_2} = \frac{\$}{m^3}$$

The table below presents the amount of CO_2 generated by fossil fuel source. The average numbers are used because data on the types of fuel used specifically for desalination power do not exist (electric or thermal). The table below shows the calculated abatement costs based on the aforementioned equation.

ANNEX TABLE 3. CO_2 EMISSIONS PER UNIT ENERGY FROM VARIOUS FUEL SOURCES

Fuel	Electric kg-CO_2/kWh*	Thermal kg-CO_2/MJ	Diesel Fuel kg-CO_2/L
Coal	0.86	0.092	
Oil	0.79	0.072	
Gas	0.62	0.052	
Average	**0.67**	**0.072**	**2.7**

Sources: Compiled by ESCWA based on the Organisation for Economic Co-operation and Development (OECD), "IEA CO_2 emissions from fuel combustion – Emissions per kWh and electricity and heat output vol. 2009 release 01", which is available at: http://oberon.sourceoecd.org/vl=876123/cl=48/nw=1/rpsv/ij/oecdstats/16834291/v335n1/s4/p1; Oak Ridge National Laboratory, "Quick-reference list of conversion factors", which is available at: http://bioenergy.ornl.gov/papers/misc/energy_conv.html; and United States Environmental Protection Agency, "Emission facts: Average carbon dioxide emissions resulting from gasoline and diesel fuel" (February 2005), which is available at: http://www.epa.gov/otaq/climate/420f05001.htm.

* The figures include all ESCWA member countries, with the exception of Egypt, Palestine (as separate from Israel) and the Sudan; in addition to Iran and Israel.

Annex V

COUNTRY PROFILES

ANNEX TABLE 4. KEY SOCIO-ECONOMIC DEVELOPMENT INDICATORS

Country	Total population	Annual population growth rate (*percentage*)	GDP per capita (*current $*)	Agricultural share of GDP (*percentage*)	Industrial share of GDP (*percentage*)
	2007	**2007**	**2007**	**2007**	**2007**
Bahrain	761 000	2.5	26 000	0	35
Egypt	72 798 000	1.8	1 510	16	31
Iraq	29 682 000	2.0	2 400	8	62
Jordan	5 723 000	3.5	2 700	3	22
Kuwait	2 411 000	1.7	38 600	0	56
Lebanon	3 760 000	1.9	6 000	6	12
Oman	2 744 000	3.7	15 500	1	56
Palestine	3 762 000	2.0	1 360	8	15
Qatar	1 448 000	3.5	76 000	0	64
Saudi Arabia	23 679 000	2.5	14 600	3	57
The Sudan	36 297 000	2.3	1 200	32	19
Syrian Arab Republic	19 172 000	2.6	1 900	22	27
United Arab Emirates	4 229 000	5.0	38 800	2	49
Yemen	21 220 000	3.5	970	11	42

Source: Compiled by ESCWA based on data provided by the Statistical Economic and Social Research and Training Center for Islamic Countries (SESRIC).

ANNEX TABLE 5. KEY WATER RESOURCES INDICATORS

Country	Total renewable water resources per capita[a/] (*m^3/p/yr*)	Total water withdrawal per capita (*m^3/p/yr*)	Dependency ratio[d/] (*percentage*)	Water stress index[e/]	Agricultural water withdrawal as percentage of total withdrawal[a/] (*percentage*)	Domestic water withdrawal as percentage of total withdrawal[a/] (*percentage*)
Bahrain	150	480	97	64	44	50
Egypt	810	990	97	13	80	
Iraq	3 770	2 500	53	4	87	
Jordan	160	160	27	61	65	31
Kuwait	10	370	100	1 430	54	44
Lebanon	1 200	320	1	9	60	29
Oman	290	520	0	18	89	10
Palestine	860	110	3	46	45	40
Qatar	40	540	3	142	59	39
Saudi Arabia	100	980	0	101	88	9
The Sudan	1 780	1 100	77	6	96	2
Syrian Arab Republic	2 790	860	72	12	88	9
United Arab Emirates	50	940	0	283	83	15
Yemen	190	180	0	103	90	8

Source: Compiled by ESCWA based on data by the Food and Agriculture Organization (FAO) unless otherwise noted.

a/ 2007. ESCWA, "Compendium of environmental statistics in the ESCWA region, No. 2" (E/ESCWA/SCU/2007/2).

b/ 1998-2002.

c/ 2007.

d/ Dependency ratio is the ratio of renewable water resources originating outside the country to the total renewable water.

e/ This indicator is calculated by dividing 10,000 by the per capita annual share from renewable water resources.

ANNEX TABLE 6. KEY DESALINATION INDICATORS
(A) CURRENT DESALINATION PROFILE
(*Percentages*)

Country	Bahrain	Kuwait	Oman	Qatar	Saudi Arabia	United Arab Emirates	Yemen	Egypt	Iraq
More than 50,000 m^3/d	44	88	56	83	68	81	0	0	0%
10,000m3/d - 49,000 m^3/d	37	8	28	10	14	14	49	17	56%
1,000m3/d - 9,999 m^3/d	12	3	12	6	12	5	21	59	37%
100m3/d - 999 m^3/d	6	0	4	1	6	1	30	24	7%
MSF	57	82	82	82	57	78	6	9	2%
MED	10	1	6	3	2	10	62	6	0%
RO	30	17	11	2	37	11	16	71	75%
ED	4	0	1	0	1	0	8	9	22%
EDI	0	0	0	0	0	0	0	0	0%
Unknown	0	0	0	14	2	0	9	5	0%
Seawater	85	83	95	99	76	98	78	74	1%
Brackish Water	15	2	4	1	23	2	22	24	53%
River Water	0	0	0	0	1	0	1	0	44%
Pure Water	0	0	0	0	0	0	0	1	0%
Wastewater	0	15	0	0	1	0	0	0	3%

Source: DesalData.com, which is available at: http://desaldata.com/.

(B) CURRENT CAPACITY DATA

Country	Bahrain	Kuwait	Oman	Qatar	Saudi Arabia	United Arab Emirates	Yemen	Egypt	Iraq
Total capacity m^3/d	497 000	2 081 000	367 000	920 000	7 246 000	5 456 000	58 000	395 000	427 000
Current membrane capacity m^3/d	**167 000**	**361 000**	**45 000**	**140 000**	**2 936 000**	**665 000**	**19 000**	**335 000**	**416 000**
< 2,000 m^3/d	11 000	2 000	2 000	1 000	164 000	5 000	6 000	80 000	31 000
2,000 m^3/d-10,000 m^3/d	20 000	11 000	5 000	8 000	356 000	34 000	4 000	198 000	154 000
10,000m^3/d+	136 000	348 000	37 000	131 000	2 415 000	626 000	9 000	57 000	231 000
Seawater	85%	83%	95%	99%	76%	98%	78%	74%	1%
Brackish/river	15%	17%	5%	1%	24%	2%	22%	24%	100%
Pure	0%	0%	0%	0%	0%	0%	0%	1%	0%
< 2,000m^3/d	6%	0%	4%	1%	6%	1%	30%	24%	7%
2,000m^3/d-10,000m^3/d	12%	3%	12%	6%	12%	5%	21%	59%	37%
10,000m^3/d+	82%	96%	84%	93%	82%	94%	49%	17%	56%
Current thermal capacity m^3/d	**330 000**	**1 720 000**	**322 000**	**780 000**	**4 310 000**	**4 791 000**	**39 000**	**60 000**	**11 000**
Large Project MSF capacity >10,000 m^3/d	249 000	1 654 000	262 000	715 000	3 480 000	4 262 000	10 000	8, 00	6 000
Large Project MED capacity >10,000 m^3/d	20 000	0	0	11 000	66 000	250 000	0	0	0
Medium projects (assumes all MED) m^3/d	6 000	8 000	16 000	1 000	19 000	27 000	22 000	18 000	1 000
Small projects m^3/d	55 000	58 000	44 000	52 000	745 000	252 000	7 000	34 000	5 000
Large MSF	76%	96%	81%	92%	81%	89%	27%	14%	53%
Large MED	6%	0%	0%	2%	2%	5%	0%	0%	0%
Medium MED	2%	1%	5%	0%	1%	1%	56%	30%	8%
Small projects	17%	3%	14%	7%	17%	5%	18%	56%	39%
Thermal MED	15%	1%	6%	3%	4%	11%	92%	42%	10%
Electricity $/kWh	0.025	0.025	0.025	0.025	0.025	0.025	0.050	0.050	0.050
Labour factor	0.45	0.45	0.45	0.45	0.45	0.45	0.35	0.45	0.75

Source: Compiled by ESCWA.

(C) PROFILE OF FORECASTED CAPACITY GROWTH, 2006-2015

	Bahrain		Egypt		Iraq		Kuwait		Oman		Qatar		Saudi Arabia		United Arab Emirates		Yemen	
Years	**06–10**	**11–15**	**06–10**	**11–15**	**06–10**	**11–15**	**06–10**	**11–15**	**06–10**	**11–15**	**06–10**	**11–15**	**06–10**	**11–15**	**06–10**	**11–15**	**06–10**	**11–15**
Production by desalination technology (MCM/d)																		
Membrane	0.17	0.31	0.09	0.28	0.08	0.21	0.38	0.54	0.18	0.37	0.2	0.34	1.7	2.57	0.86	1.4	0	0.03
MED	0.23	0.26	0.01	0.03	0	0	0.15	0.16	0.12	0.15	0.12	0.13	0.85	0.93	0.46	0.49	0	0.02
MSF	0.18	0.14	0	0	0	0	0.59	0.45	0.32	0.32	0.32	0.27	1.67	1.44	1.58	1.31	0	0
Total production	0.58	0.71	0.1	0.31	0.08	0.21	1.11	1.15	0.62	0.84	0.64	0.74	4.25	4.94	2.9	3.2	0.01	0.05
Production by type of feedwater (MCM/d)																		
Seawater	0.49	0.6	0.08	0.23	0	0	0.92	0.95	0.59	0.8	0.63	0.73	3.21	3.73	2.84	3.14	0.01	0.04
Brackish water	0.09	0.11	0.03	0.08	0.08	0.21	0.19	0.2	0.03	0.04	0.01	0.01	1.04	1.2	0.06	0.06	0	0.01
Pure water	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Production by plant size																		
Plants < 2,000	5%	4%	19%	14%	5%	2%	0%	0%	3%	2%	0%	0%	4%	4%	0%	0%	27%	24%
Plants 2,000–10,000	11%	10%	54%	49%	34%	32%	3%	3%	11%	10%	6%	5%	11%	10%	5%	4%	18%	15%
Plants > 10,000	84%	86%	27%	37%	61%	66%	97%	97%	86%	88%	94%	95%	84%	86%	95%	96%	55%	61%

Source: Compiled by ESCWA.