CHAPTER 18

The economics of desalination for various uses

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ABSTRACT: Water scarcity is a major problem that needs to be efficiently solved to ensure water availability for future generations. Desalination is an alternative technology for water production based on salt separation from water. Reverse osmosis (RO) and multi stage flash (MSF) are by far the most prevalent desalination processes. Desalination operating costs depend on several factors such as pre-/post-treatment requirements, selected technology, feed water quality, plant location, energy availability and brines disposal. These costs are usually lower for RO than MSF, moreover, MSF has been stated to be at its technological limit whilst RO can be developed and improved in the future. Despite its higher cost compared to conventional water sources, desalination can play an important role when developing a full-cost assessment of the integrated water cycle as it avoids some of the resource costs incurred when demand cannot be met. The aim of this study is to give a general overview on available desalination technologies and market, desalination for water reuse applications, desalination costs (capital, operation, resource and environmental) and economic instruments available to integrate desalination into water cycle economics.

Keywords: desalination costs, desalination technologies, desalination in water treatment, full-cost assessment, economic instruments

1 INTRODUCTION

Water supply for domestic, agricultural and industrial uses comes from many different conventional sources such as rivers, lakes and aquifers. This water often needs to be treated and purified at a treatment plant in order to meet quality requirements depending on its final use.

When conventional water resources become chronically scarce, as happens in many parts of the world, governments usually respond by 1) restricting water demand; 2) using existing resources more effectively; and/or 3) exploiting non-conventional water supplies such as desalination and water reuse. Non-conventional resources are well recognized as being able to potentially contribute to mitigate quantitative and qualitative stress on conventional water resources, especially in arid regions. This can be achieved by supplying water that can be used after proper treatment for different purposes such as agricultural irrigation, industrial uses, recreational activities, environment enhancement and aquifer recharge. An illustration of the water supply cycle is shown in Figure 1.

Among non-conventional water supplies, desalination has become an efficient alternative resource to mitigate water shortage in many countries throughout the world. The world production

Figure 1. Diagram of the global water cycle (ACA, 2009).

of desalted water, which includes desalted sea and brackish water, was 48 Mm^3/day (enough for supplying potable water to 240 million people) in 2006 and about 65 Mm^3/day in 2008 (AEDyR, 2009). Desalted water production is expected to keep growing in the near future as water demand increases. A production of desalted water of 95 Mm^3/day for 2011 and 140–160 Mm^3/day for 2025 has been predicted (AEDyR, 2009).

The aim of this chapter is to present both the current situation and the future challenges of water desalination. For this purpose, aspects such as desalination technologies, the desalination market and uses of desalted water (including water reuse) are analyzed. The chapter includes a full-cost assessment of desalination considering capital and operating costs of the selected technology as well as the effects of the introduction of desalted water on the water cycle, in terms of resource and environmental costs. Furthermore, the document outlines how the economic instruments associated should be readdressed when introducing non-conventional water supplies.

2 AVAILABLE DESALINATION TECHNOLOGIES

There are several desalination technologies able to technically fulfill the water quality standards required for its final use. Table 1 shows the most common desalination processes organized by the source of energy used (electrical and/or thermal) and the separation mechanism involved in (according to whether water is separated from salts or viceversa).

Table 1. Classification of desalination processes (AEDyR, 2009).

Separation mechanism	Energy	Process	Name
Water separation	Thermal + Electrical	Evaporation	Multi Stage Flash (MSF) Multi Effect Distillation (MED) Thermal Vapor Compression (TVC) Solar Desalination (SD)
		Crystallization	Freezing Formation of hydrates
		Evaporation and filtration	Membrane Distillation (MD)
	Electrical	Evaporation	Mechanical Vapor Compression (MVC)
		Ionic filtration	Reverse Osmosis (RO)
Salt removal	Electrical	Ionic migration	Electrodialysis (ED)
	Chemical	Others	Ion Exchange (IX) Solvent Extraction (SE)

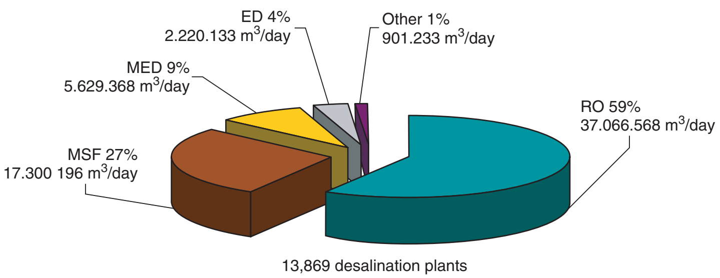

Figure 2. Distribution of desalination technologies by total installed capacity (GWI DesalData/IDA, 2008).

Selection of the appropriate technology has to be done considering several factors. Site-specific conditions such as energy and labor costs, available area, electric power cost and availability, impact of brines disposal, feed water salinity and desalted water quality will influence the desalination technology choice (Fritzmann *et al*., 2007).

Reverse osmosis (RO) and multi stage flash (MSF) processes together account nowadays for more than 85% of the total installed desalination capacity, as shown in Figure 2. It has been predicted that most large-scale desalination plants over 40,000 m^3/day built during the next quarter of the century will be based on these technologies (Blank *et al*., 2007).

MSF is by far the most robust desalination technology. Like any thermal evaporation process, it essentially consists of heating a saline solution to generate water vapor, which is then condensed to liquid water with lower salt concentration. Though a small percentage of the feed water is converted into vapor and condensed, MSF is capable of producing significant amounts of high-purity desalted water. The main disadvantage of MSF is that it is very energy intensive. For this reason, MSF is the preferred choice in the Middle East, where local energy costs are low. In other parts of the world, where oil and other fossil fuels cost is much higher and thermal processes are expensive, other desalination technologies such as RO are preferred.

RO, like any membrane process, consists in selectively restricting the passage of certain ions (including salts) through a membrane, resulting in a desalted water stream (permeate) and a waste stream containing the salts left behind (brine or concentrate). RO technology can be used for the removal not only of salts but also of non-saline contaminants (e.g. organic matter, bacteria, viruses, etc.).

Table 2. General features of MSF and RO (adapted from Blank *et al.*, 2007; Reddy & Ghaffour, 2007; Nisan & Benzarti, 2008).

	MSF	RO
Physico-chemical principle	Flash evaporation	Solution-diffusion
Energy consumption (including auxiliaries)	Electrical: 2.5–5.0 kW·h/m^3 Thermal: 40–120 kW·h/m^3	Electrical: 3.5–4.5 kW·h/m^3 Thermal: None
Total capital costs	High	Low
Operation costs	High	Low at 250 mg/L TDS product High at 10 mg/L TDS product
Replacement parts requirement	Low-Medium (large special pumps)	High (large pumps, membrane replacement)
Maintenance requirements	Medium	High
Chemical consumption	High	High
Conversion rate*	0.1–0.2	0.3–0.5
Potential for further requirements	Low (at technological limit)	High
Most needed R&D areas	Low-cost materials Low-cost and more efficient heat transfer materials	Pre-treatment, high-durable membranes, low-fouling/-energy materials

* Conversion rate: ratio between product to total feed water flow.

Water can also be desalted through many other processes, as shown in Table 1 and Figure 2. None, however, has achieved the commercial success of MSF and RO. Given that other technologies different from MSF and RO account all together for less than 15% of the total installed capacity, and that they are not expected to be installed in large-scale desalination plants (Blank *et al.*, 2007), these technologies will not be further discussed in this study.

The differences between MSF and RO are grouped in Table 2. As shown in the table, operating principles, process limitations, costs and perspectives are significantly different between MSF and RO.

The main advantage of MSF is the available knowledge of the technology. However, it is probably at its technological development limit. Due to this limitation, together with the expected development for RO, it can be estimated that MSF will probably not continue growing and being improved like RO will apparently do. In fact, it is foreseen that research into new pre-treatments, high-resistant elements manufacture, low-fouling/-energy materials formulation, together with the increase of the RO knowledge and transfer to plant operation levels, will enable the RO technology to be further adapted to specific water sources and operation constraints. Nevertheless, vast efforts still need to be invested in developing the RO process further in order to achieve a more efficient and cost-effective desalination technology.

3 DESALTED WATER AND RECLAIMED WATER USES

3.1 *Desalted water sources and uses*

The quality of the water to be desalted is a crucial parameter which determines its final use. Figure 3 shows the typical water resources being desalted and their final use. As the figure shows, seawater represents 62% of total desalted water, followed by brackish water (19%). With regards to the final use, more than 65% of desalted water is used for municipal purposes followed by industrial applications (around 20%), while irrigation only accounts for 2% of the total.

Desalted water use is conditioned by the quality standards specified in water quality regulations. Hence, for instance, the high percentage of municipal uses of desalted water is justified by the fact that RO technology is best suitable for the production of drinking water within the chemical

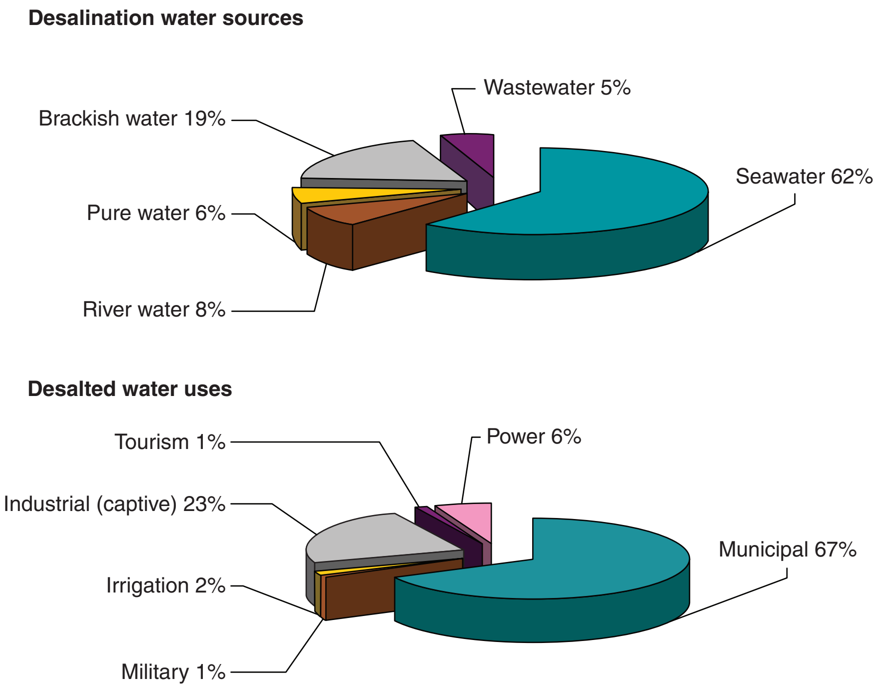

Figure 3. Sources and uses of desalted water in the world (GWI Desaldata/IDA, 2008).

and microbiological quality standards according to the European Directive 2000/60/CE (Water Framework Directive). However, two operational aspects have to be taken into account. The first is related to the pH of drinking water, which needs to be between 6.5 and 9.5. As RO permeate has an acidic pH, it has to be accordingly adjusted to satisfy the standards. The second limitation is related to boron presence in drinking water, whose concentration cannot be beyond 1 mg/L. Seawater typically contains an average of 4.6 mg/L boron. When desalting seawater with RO (one-step operation), boron concentration in permeate ranges between 0.8 and 1.5 mg/L. Hence, the system works close to the limits of the drinking water quality standards. Two possible solutions can help avoid this situation. One is based on increasing the pH up to 9.5–10 so that boron is in the form of borate and accordingly almost completely retained by RO in one-step operation. The other option consists in the installation of two RO steps. This process configuration allows fulfilling the drinking water quality standards in terms of boron concentration because the first-step permeate is purified in a subsequent RO step. Two-step operation is more adequate than pH adjustment because the latter could precipitate some of the ions present in the feed water causing membrane fouling (AEDyR, 2009).

3.2 *Water reclamation technologies and uses*

The possible uses of reclaimed water are related to their qualities and depend on the user country. For instance, in Spain, the Royal Decree 1620/2007 dictates the quality levels required for reclaimed water depending on its final use. The possible uses have been classified as industrial, agricultural, urban, recreational and environmental. Each group has specific subcategories and the legislation defines the quality standards of each subcategory.

The minimal quality standards can be organized in three main groups: microbiological parameters (*Ancylostoma*, *Escherichia Coli*, etc.), physico-chemical parameters (turbidity, suspended solids,

Table 3. Quality of tertiary effluents in function of the membrane technology installed (Prats Rico, 2009).

	Tertiary effluent quality			
	SS (mg/L)	Turbidity (NTU)	*E. Coli* (UFC/100 mL)	Nematodes (eggs/10 L)
MF	<7	<1	<1,000	Absence
UF	<5	<1	Absence	Absence
UF+RO	0	<0.3	Absence	Absence
EDR	<5	<2	10	Absence

etc.) and specific quality parameters for certain uses (*Legionella spp*., total phosphorous, etc.). There are several technologies capable of treating wastewater and rendering it able to be used for a certain application. However, primary (generally flocculation/coagulation) and secondary treatments (aerobic oxidation) are installed in wastewater treatment plants. Nevertheless, for reuse applications, a tertiary treatment is required.

Three main tertiary treatment processes can be distinguished to achieve efficient water regeneration: conventional treatment, advanced treatment and membrane treatment. Conventional treatment is based on the elimination of suspended solids and turbidity followed by disinfection. This treatment is most common for treating water from the secondary treatment where the effluents present a good quality (<10 mg/L SS, <5 NTU, <10 UFC *E. Coli*/100 mL, absence of nematodes eggs/10 L). Advanced treatments are efficient for the elimination of biorefractory organic compounds contained in the secondary treatment effluent. They include adsorption and advanced oxidation processes (Fenton, ozonation, etc.). Finally, membrane technologies can also be satisfactorily used as tertiary treatment. For instance, microfiltration (MF) and ultrafiltration (UF) can be installed after secondary treatment to obtain higher-quality product water. However, when residual waters have a high salt content, RO is also needed to reduce it. Thus, desalination processes are frequently present in water reclamation processes and will gain relevance to satisfy water sustainability criteria in terms of water regeneration and reusability. In order to decrease membrane fouling, which is a common drawback in membrane processes, RO is generally preceded by UF pre-treatment (e.g. Wastewater Treatment Plants of Rincón de León and Benidorm in Spain).

Table 3 shows that the final quality of reclaimed water depends upon the membrane technology. Thus, the final water use dictates the right membrane filtration range (or a combination of them) to be installed as tertiary treatment (Prats Rico, 2009).

Apart from the previous membrane technologies, membrane bioreactors (MBR) can also be employed as simultaneous secondary and tertiary treatment. MBR are based on the use of a biological treatment coupled to membrane filtration (MF or UF). With the intensified technology, the decanter after the secondary treatment is not required. Hence, it can be stated that MBR are not only able to treat wastewater achieving the required discharge limits but also to simultaneously reclaim treated wastewater achieving the quality standards required for reusing it. It has to be pointed out that, as MBR are based on MF or UF membranes, the systems are unable to decrease water salinity. In order to reduce salts content, an additional RO unit would be required.

4 WORLD DESALINATION INDUSTRY

The evolution of the installed and contracted global desalination capacity is shown in Figure 4. As can be observed, overall desalination capacity has been continuously growing during the last twenty years and, as stated above, it is not expected to stabilize in the near future. Nowadays, the contracted capacity of desalted water in the world is around 65 Mm^3/day (installed capacity: 52 Mm^3/day). The geographical distribution of the desalination capacity on a worldwide basis is

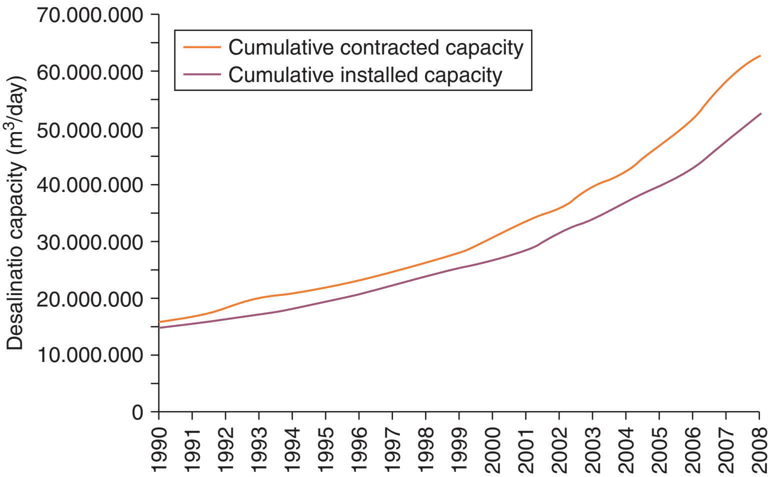

Figure 4. Installed and contracted desalination capacities evolution (GWI Desaldata/IDA 2009).

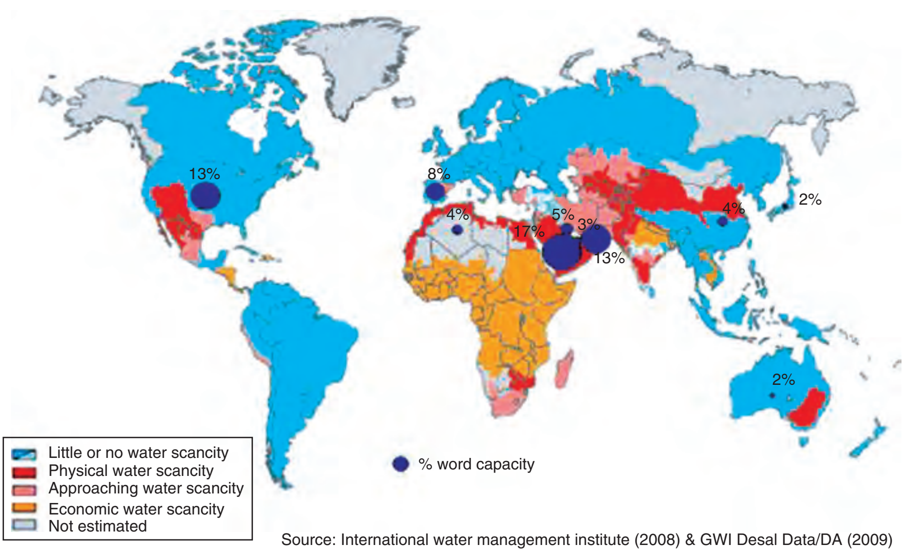

Figure 5. Major desalted water producing countries (IWMI, 2006; GWI DesalData/IDA, 2009).

presented in Figure 5. As can be observed, Saudi Arabia is the largest desalted water producer (17% of the global water production), followed by United Arab Emirates (UAE) and USA (13% of the desalted water production each) and Spain (8%).

Spain's pioneering involvement with desalination spans several decades. The installation of the first desalination plant on the island of Lanzarote in the Canary Islands dates back to 1964. Since then, a growing number of other plants have been installed to such an extent that nowadays the desalted water capacity in Spain is 8% of the global desalination capacity while its population represents only 0.6% of the world population (AEDyR, 2009). The Spanish Mediterranean coast currently hosts the largest desalination plants in Europe, for both drinking water (in Barcelona with a capacity of 200,000 m^3/day) and water for irrigation (in Torrevieja with a capacity of

Table 4. Largest desalination plants for potable water production from seawater (GWI DesalData/IDA, 2009).

RO		MSF	
Plant	Capacity (m^3/day)	Plant	Capacity (m^3/day)
Ashkelon (Israel)	326,144	Jebel Ali (UAE)	529,000
El Hamma (Algeria)	200,000	Shoaiba (Saudi Arabia)	524,000
Barcelona(Spain)	200,000	Fujairah 1 (UAE)	454,000

220,000 m^3/day). In some coastal regions in Spain, desalted seawater accounts for between 30 and 50% of water consumed (GWI Desaldata/IDA, 2009).

The desalination plants with largest capacities in the world are summarized in Table 4. As discussed above, desalination plants using MSF operate at higher capacities than those using RO and are geographically more concentrated around the Persian Gulf. Desalination plants using RO usually have lower production capacities and are geographically more distributed throughout the world.

5 ECONOMIC ELEMENTS OF DESALINATION FULL COST ASSESSMENT

Water supply costs have traditionally been defined as operating and maintenance costs (O&M) and capital costs. However, as more knowledge is gathered in this field, other water cycle costs need to be considered.

In order to improve the efficiency and sustainability of integrated water resources management (IWRM), policy-makers and actors in the water sector should account not only for capital and operation costs but also for environmental and resource costs (Rogers *et al.*, 2002; WATECO, 2003; OECD, 2009), as schematized in Table 5.

From a holistic approach of the whole water cycle, beyond the production plant, total costs are quite variable among different locations. Therefore, it is difficult and not reliable to compare unit operating costs from locations which do not share the same characteristics. Overall, the most important drivers of cost heterogeneity are:

- Availability of water resources, and more specifically, their quantity, quality and proximity to final users.
- Desalination technology and plant capacity.
- Environmental and energy cost.
- Special levies from water sector regulation.
- Efficiency in delivery service.
- Investments in network maintenance. It must be noted that recent networks do not require significant expense in maintenance, but on the other hand, higher amortization allowances must be faced as the value of the asset is significant.

In the following sections, desalination costs, introduced below in Table 5, are presented according to the whole water cycle approach.

6 CAPITAL AND OPERATING COSTS

6.1 *Desalination cost evolution*

The operating costs of producing desalinated water have steadily decreased during the last few decades thanks to continuous technological advances. Though still a costly water supply option compared to natural water resources such as ground- or surface water, desalination may soon be

Table 5. General principles for the cost of public water supply service. (adapted from Rogers *et al*., 2002)

Capital charges	Full supply cost	Full use cost (= Economic cost)	Full cost
Operating and maintenance costs			
Resource costs			
Environmental cost			

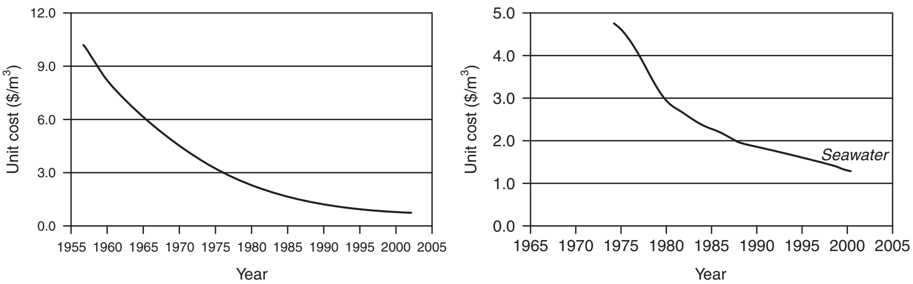

Figure 6. Evolution of the unit desalted water cost by: a) MSF; and b) RO, over the last decades (adapted from Reddy & Ghaffour, 2007).

a competitive alternative even in non-water stressed regions. It is important to note that costs for conventional water sources are expected to increase, while costs for desalting are expected to decrease as technology improves (Reddy & Ghaffour, 2007).

Figure 6 shows the evolution of desalination costs over the past few decades for both MSF and RO. As can be seen, costs for MSF in the early 1960s were between 7 and 9 US$/m^3, while they dropped down to below 1 US$/m^3 by 2000. A similar trend is observed for RO-desalted water, whose cost was between 3 and 5 US$/m^3 in the 1970s and is currently less than 1 US$/m^3. Recent examples for MSF and RO installations are Abu Dhabi's Taweelah (United Arab Emirates) desalination plant and Israel's Ashkelon desalination plant, which produce water at 0.7 US$/m^3 and 0.53 US$/m^3, respectively.

This sharp cost reduction has occurred in the three main cost areas: capital, energy and operation and maintenance. For desalination technology as a whole, the reduction of unit water cost is due mainly to:

– Technological developments.
– Increasing size of plants.
– Lower interest rate and energy costs.
– Changes in managing enterprise performance.
– Intense competition between equipment suppliers worldwide.

Specific improvements that have contributed to the cost reduction, among many others, have been optimization of process design (with regards to equipment and configurations) and thermodynamic efficiency, use of newer materials with better heat transfer properties, and development of new construction and transportation techniques for MSF; technological improvements of membranes (with higher surface per unit volume, higher salt rejection factors and fluxes, and extended life-span), optimization of pre-treatment options and use of energy recovery devices for RO (Fritzmann *et al*., 2007; Reddy & Ghaffour, 2007).

Figure 7 illustrates desalination technological improvements by representing the evolution of the energy consumption necessary per m^3 of desalted seawater in Spain during the last 40 years. The figure clearly shows how the energy needed has been reduced from 22 kW·h/m^3 to less than 3 kW·h/m^3,

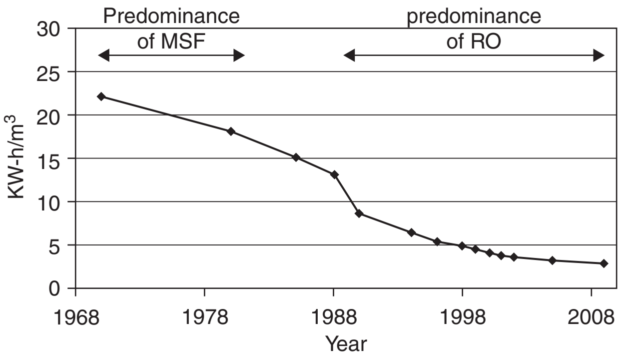

Figure 7. Evolution of the energy consumption necessary per m^3 of desalted seawater in Spain over the last decades (adapted from AEDyR, 2009).

i.e. the energy required per m^3 of desalted water has been reduced by almost 90%. It can also be seen in the figure that the emergence of the RO technology in the market notably helped in reducing the energy needs for desalination. These lower costs associated with RO promoted the expansion of RO facilities around the world (Reddy & Ghaffour, 2007; Karagiannis & Soldatos, 2008).

It must be pointed out that water costs of existing desalination plants vary widely and are not completely comparable because of differences in the cost-determining factors. This explains why values in Figure 7 are scattered, providing a general trend instead of giving definitive cost values. Site-specific cost-determining factors depend on a number of issues, such as feed water characteristics, product water quality, plant capacity, plant reliability, concentrate disposal, space requirements, operation and maintenance aspects, geographic location, energy availability, etc. (Blank *et al.*, 2007; Reddy & Ghaffour, 2007). Among them, the most critical factor is clearly energy consumption and availability, and this dictates not only the final cost but often also the desalination method. Hence, most MSF plants operate in oil-producing countries (basically in the Persian Gulf), whereas RO plants are more common worldwide in those places where there is a lack of adequate freshwater supplies and a good source of available seawater (e.g. the Mediterranean basin or Asia-Pacific region) (Lattemann & Höpner, 2008). Despite the variability of factors affecting the final cost of desalination, some general remarks on costs can be made according to the type of feed water, plant capacity, energy source and desalination technology.

6.2 *Water desalination cost with regards to feed water nature and plant capacity*

The amount of salt to be removed greatly affects desalination cost. In general, the more salts to be removed, the more expensive the desalination process. The cost of desalting seawater is about 3 to 5 times the comparable cost of desalting brackish water. Besides the salinity influence, the plant capacity also impacts desalination cost, with larger plants generally being more economical.

Table 6 summarizes the costs of desalination according to the nature of feed water and plant capacity. As can be seen, brackish water can be desalted more economically (at cost of about 0.21–0.43 €/m^3 at large scale) than seawater (at cost of about 0.40–0.80 €/m^3 also at large scale). At smaller capacity plants (<1,000 m^3/day), desalination costs increase to about 0.63–1.06 €/m^3 and 1.78–9.00 €/m^3 for brackish and seawater, respectively, or even more if equipment is not operated under optimal conditions.

6.3 *Water desalination cost with regards to energy source*

Desalination processes require significant quantities of energy to achieve separation of salts from seawater. Existing MSF and RO plants are powered mainly by conventional energy sources (gas,

Table 6. Cost of water produced according to the type of water desalted (Karagiannis & Soldatos, 2008).

Type of feed water	Plant capacity (m^3/day)	Cost (€/m^3)
Brackish	<1,000	0.63–1.06
	5,000–60,000	0.21–0.43
Seawater	<1,000	1.78 – 9.00
	1,000–5,000	0.56–3.15
	12,000–60,000	0.35–1.30
	> 60,000	0.40–0.80

Table 7. Cost of water produced according to the type of energy supply system (Karagiannis & Soldatos, 2008).

Type of feed water	Type of energy used	Cost (€/m^3)
Brackish	Conventional	0.21–1.06
	Photovoltaic	4.50–10.32
	Geothermal	2.00
Seawater	Conventional	0.35–2.70
	Wind	1.00–5.00
	Photovoltaic	3.14–9.00
	Solar collectors	3.50–8.00

oil electricity) because they still represent the most economic way to satisfy the energetic needs of desalination facilities. However, the coupling of renewable energy sources (RES) and desalination systems holds great promise as a feasible solution to water scarcity in remote areas where drinking water and conventional energy infrastructure is currently lacking. Several renewable energy powered desalination plants that operate only on solar, wind or geothermal energy to produce freshwater have been installed throughout the world and the majority have been successfully in operation for a number of years.

Table 7 compares desalination costs according to the source of energy used. It is clear that RES are still much more expensive than the conventional sources, although the higher cost of RES is counterbalanced by its environmental benefits. Hence, while the cost of desalination using a conventional source of energy ranges between 0.21 and 2.70 €/m^3 depending on whether the feed water is brackish or seawater, the cost of desalination when RES are used rises up to between 1.00 and 10.32 €/m^3, depending on the type of feed water and also on the type of renewable energy used.

Renewable energy powered desalination systems may not compete nowadays with conventional systems in terms of the direct cost of water produced. Nevertheless, their application is steadily expanding in certain areas and it seems clear that they will become a competitive alternative to conventional energy powered plants in the future as fuel prices keep rising and fuel supplies decreasing (Reddy & Ghaffour, 2007).

6.4 *Water desalination cost with regards to type of desalination technology*

Generally, MSF systems are more cost intensive but usually have larger production capacities than RO (Fritzmann *et al*., 2007; Karagiannis & Soldatos, 2008; Lattemann & Höpner, 2008). As stated, they are mostly used in oil-producing countries where fuel availability is not a limiting factor, such as the Persian Gulf countries, where thermal desalination processes account for 90% of overall desalted water production (Lattemann & Höpner, 2008). RO emerged as a cheaper and more

Table 8. Cost of water produced according to the desalination method (Karagiannis & Soldatos, 2008).

Desalination method	Type of feed water	Plant capacity (m^3/day)	Cost (€/m^3)
MSF	Seawater	23,000–528,000	0.42–1.40
RO	Brackish	<20	4.50–10.32
		20–1,200	0.62–1.06
		40,000–46,000	0.21–0.43
	Seawater	<100	1.20–15.00
		250–1,000	1.00–3.14
		1,000–4,800	0.56–1.38
		15,000–60.000	0.38–1.30
		100,000–320,000	0.36–0.53

flexible desalination technology and has been gaining ground worldwide in the last years as the cost of membranes and their operation decreases. During the last few years, and thanks to these reduced costs, RO has become increasingly installed at larger plants and applied for the desalination of both brackish and seawater, as opposed to MSF, which is rarely used for the desalination of brackish water due to its much higher energy consumption at low salinity in comparison with RO (Fritzmann *et al*., 2007; Reddy & Ghaffour, 2007).

Table 8 shows desalted water cost in relation to the desalination method used and the size of the plant. The desalination cost of seawater ranges between 0.42 and 1.40 €/m^3 for MSF. For comparative purposes, it must be taken into account that MSF plants have usually larger production capacities than RO and that this low cost is favored by economies of scale. The desalination cost through RO is between 0.38 and 1.38 €/m^3 for a mid-sized RO plant producing 1,000–60,000 m^3/day, while it is between 0.36 and 0.53 €/m^3 for larger plants producing between 100,000 and 320,000 m^3/day. For brackish water desalination using RO, the cost is even lower (0.21–0.43 €/m^3).

By inspecting data in Table 8, one can conclude that there are no significant differences in the cost per m^3 of product water when using RO or MSF for seawater desalination. However, as summarized in Table 2, the energy demand per m^3 of product water is significantly higher when operating with MSF technology than with RO. This is primarily due to the absence of thermal energy demand in RO plants. Thus, desalination costs should be evaluated in terms of energy demand per m^3 of product water. The cost similarities between RO and MSF shown in Table 8 are caused by the variability of energy costs depending on the country where the desalination plant is installed.

6.5 *Desalination cost breakdown*

The economic analysis of a desalination plant is based on a number of technical and economic determining factors such as capital, energy, labor, chemicals, materials, and consumables that are specific to the location, the process type, the plant capacity, the feed water components, the energy availability, the pre-treatment required, the product salinity desired and other site-related costs for land, plant, and brine disposal. Figure 8 shows the cost composition for standard MSF and RO desalination plants.

While amortization clearly represents a significant portion of the total cost (approximately one third of the total for both MSF and RO), the greatest cost driver actually arises from the energy consumption, which amounts up to 55.2% for MSF (including both fuel and electricity consumption) and to 42.6% for RO. Other components that contribute to the overall cost are labor and the use of chemicals (which amount to 9.3% and 6.5% for RO, much higher than 3.5% for MSF). For RO, the contribution to the total cost of the membrane replacement is 4.7%, a percentage which has decreased over the years owing to the improvements in membranes. Figure 8 compares well with those published by Reddy & Ghaffou (2007) and Fritzmann *et al*. (2007).

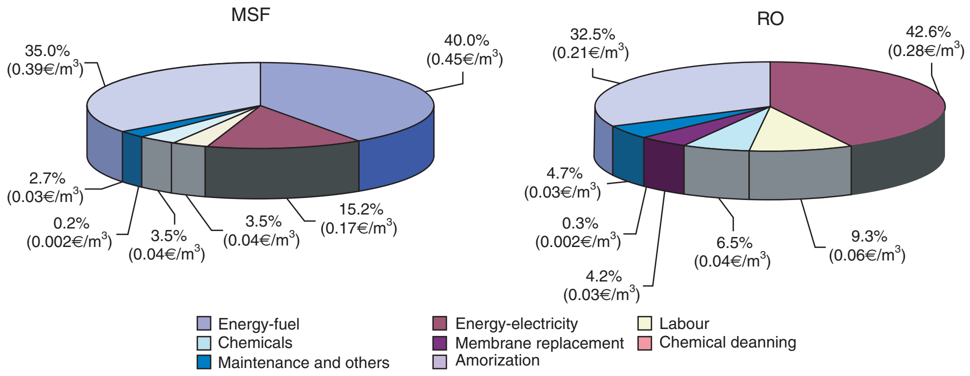

Figure 8. Comparison of freshwater production costs from seawater for MSF and RO (AEDyR, 2009).

7 RESOURCE COSTS

Supplying enough water to fulfill current demand in a certain region is the essential element of water policy. Water deficit in domestic, industrial, agricultural, recreational or environmental uses should be measured or accounted as a resource cost, not just as a probability (Gaya, 2008).

Policy-makers must properly manage water demand and supply. For this reason, water demand policies are acquiring more and more relevance (Dinar & Albiac, 2009). As water supply guarantee is not free of cost, a compromise between benefits gained and investment associated is required.

In this field, desalination can play an important role in most water scarce regions worldwide. In spite of its relatively high costs, desalination seems to appear as one of the most suitable alternative resources to satisfy water demand.

Several benefits derived from integrated water resources management have been identified (Mujeriego, 2007):

- Increase of own resources availability, which can decrease the dependence on water transfers from distant locations or from other uses, such as irrigation.
- Higher direct control on the available volume of water resources by the regulator or operators.
- Increased protection against delivery service failure due to circumstances beyond control, such as natural disasters or other threats on current water resources.
- Diversification of water sources.

Boxes 1 and 2 examine water management actions in Israel and Singapore, showing how resource costs play an essential role when policy-makers readdress water policy and choose whether to foster desalination or not.

8 ENVIRONMENTAL IMPACT AND COSTS

Adverse impacts on ecosystems caused by water related issues have usually been associated only with water uses. However, it is well known that water treatment technologies themselves also origin environmental costs, which are entailed in the final water use.

The environmental costs of desalination are not negligible and there is much debate about its extent. Basically, there are two main impacts on ecosystems that need to be addressed:

- Brine discharges and their impact on the receiving water bodies.
- Greenhouse gas emissions arising from high energy requirements.

Box 1. Israel: Cost-effective supply through desalination

Total water demand in Israel is expected to reach 2,500 Mm^3/yr in 2010, while the available natural resources (surface and ground water) are only around 1,500–1,800 Mm^3/yr. As there is a big gap for water supply, the Israeli government recently prioritized desalination as the most appropriate non-conventional water source as opposed to wastewater reuse and reductions in the water allocations for irrigation.

Production of water from surface and ground water resources represents about 0.15–0.45 US\$/m^3 and 0.37–0.45 US\$/m^3 for desalted water produced from the Sea of Galilee. Environmental and resource costs, which are not included in the costs given above, are estimated to be high because water withdrawal and distribution (carrier of 130 km along one of the tensest regions in the world) consume considerable amounts of energy. On the other hand, supplying reclaimed wastewater and brackish water is still a more expensive system (0.50–0.60 US\$/m^3).

Ashkelon desalination plant is the first step of a wider plan in order to supply enough water in Israel and, therefore, reduce the resource costs that eventually could challenge the country. Desalination presents additional benefits such as the improvement of water quality (softer and less mineralized, with a reduction on costs for customers' domestic facilities and subsequent wastewater treatment for reuse) and savings in pumping energy from the North provision. For these reasons, desalination is expected to provide 580 Mm^3/yr of freshwater in 2015, which will mean 22% of total supply.

Source: Dreizin (2006)

Box 2. Singapore: Self-sufficiency from water reuse and desalination

Water supply in Singapore has traditionally relied on different small reservoirs and on water imports from Malaysia, which represented the main source. The government has developed two new action plans to become self-sufficient in water by 2060: water reuse and desalination. However, these alternatives may imply higher costs than current water transfers (the price of transferred water from Malaysia is only 0.20 US\$/m^3). Therefore, the determining factor in this scenario is the resource cost, which depends on a third country, along with constraints from other alternatives to meet the increasing water demand.

The seawater RO plant, with a capacity to produce 136,000 m^3/day, in operation since 2005, under a public-private scheme is producing desalted water at 0.78 US\$/m^3. Reclaimed water, which is produced in three plants with similar technology, is reused for indirect potable use (discharge in urban reservoirs) and direct non-potable use (urban landscape irrigation) at 1.00 US\$/m^3, including both production and distribution costs.

Source: GWI (2009); Tortajada (2006)

8.1 *Brine discharges*

Brine discharges can damage the environment due to: 1) their high salinity and density, which can impact on benthic sea life, being the case of the *Posidonia Oceanica* (this sea grass plays a key role in marine sustainability); and 2) the possible oxygen depletion when sodium bisulphite is used as chlorine control. Pre-treatment residual turbidity/TSS can also have an impact on photosynthesis activity by lowering the transmissivity of the water body at the spilling point. In order to reduce the environmental impact of desalination, in the USA and Australia, there are regulations limiting the content of TDS and chlorides in brine discharges. The United States Environmental Protection Agency (USEPA) sets a limit of 10% for TDS while Australian desalination projects are requested to guarantee less than 1–2% increase of TDS at the discharge zone limit. Temperature variations can also have an adverse impact on marine ecosystems. Thus, when dealing with thermal desalination processes (RO brine temperature increase is expected to be only between 1 and 2°C), brine temperature impact on the receptor environment has to be considered and efficiently reduced.

Table 9. Estimated quantities of GHG emissions on a world basis by diverse fossil fuelled plants and desalination processes (Nisan & Benzarti, 2008).

	MSF (Mt/yr)				RO (Mt/yr)			
Power plant	CO_2	SO_x	NO_x	Particles	CO_2	SO_x	NO_x	Particles
Coal fired	264.45	0.33	0.54	0.04	32.25	0.04	0.07	0.005
Oil fired	216.22	1.31	0.3	0.03	25.74	0.16	0.04	0.003
Gas turbine, CC	141.58	0.01	0.23	0.01	12.87	0.001	0.02	0.001

Mt: million tonnes [1 tonne = 1,000 kg]

With the aim of minimizing the impact of brines disposal on receiving water bodies, transport direction and the potential impact range of a discharge plume is controlled by site-specific oceanographic conditions such as currents, tides, water depth and the bottom and shoreline topography. As for the characterization of environmental and operational conditions, they can be investigated by hydrodynamic computer models.

Quantifying this environmental impact and the associated cost has caught the interest of many researchers (Lattemann & Höpner, 2008). In order to properly manage this environmental cost and consider it in the full-cost approach, further estimations on the effects of brines discharge need to be carried out via monetization of the impact.

8.2 *Greenhouse gas emissions*

The significant quantities of energy required by conventional desalination plants and the consequent high greenhouse gas (GHG) emissions are major issues with desalination that need to be addressed. Table 9 gives the estimated quantities of GHG by diverse fossil fuelled plants and desalination processes for a representative plant with a total desalting capacity of 20.1 Mm^3/day (Nisan & Benzarti, 2008). In view of the values in Table 9, it seems clear that energy consumption in desalination contributes to environmental pollution, including global warming.

It is possible to roughly approximate the value of the environmental costs through the international carbon market. In this market, a value for an emitted tonne of CO_2 is agreed and considered as a cost for polluting industries, which need to buy extra credit in order to continue with their economic activity. However, the carbon market is not applicable for calculating the environmental costs generated by SO_x, NO_x and particles. The data obtained by the carbon market can be used as a proxy of the cost of pollution. For rapid calculations, the average value for 2008 of a tonne of CO_2 is 16.78 US$ (World Bank, 2009). By using the data for oil-powered plants, it can be found that, as Table 9 shows, the environmental cost from GHG emissions is 0.49 US$/$m^3$ for MSF and 0.06 US$/$m^3$ for RO. Therefore, the consideration of these costs in the production stage of the water cycle implies an important impact on overall costs, especially for MSF.

8.3 *Actions to mitigate the environmental impact*

Once the external costs of desalination over ecosystems have been identified, a number of actions need to be taken in the near future to reduce its impact. These actions are listed below:

- Brine discharges: waste streams generated in desalination processes can be efficiently treated and its impact reduced if they are diluted with the effluent from near wastewater treatment plants prior being discharged into the sea. This mitigation method is used in the desalination plant of Barcelona (Spain).
- GHG emissions: increasing the energy efficiency of desalted water production and integrating non-pollution renewable energy sources is crucial for decreasing environmental impact of desalination. Nisan & Benzarti (2008) compare RO processes using nuclear power and other fuel fossils and conclude that the desalination costs of nuclear options, which include environmental costs, are 10–80% lower than the cheapest fuel fossil options. However, it has to be pointed out

that nuclear wastes, which have an adverse impact onto the environment, are generated during nuclear energy production.

9 ECONOMIC INSTRUMENTS IN AN INTEGRATED WATER CYCLE

The above sections identify the costs imposed by the final use of water in the whole cycle and assess how desalination can be incorporated in this framework. At this point, it is time to raise the most controversial question: who should be charged for this, and how? The background behind this economic analysis is the need to fulfill the principle of cost recovery: all the agents involved in the water public service would have to participate in their appropriate part of full cost.

Legislation worldwide is incorporating these relatively new concepts into water policy. Policy-makers are gradually modifying the economic instruments intended to recover all the costs, the most noteworthy being the so-called 3Ts: tariffs, taxes and transfers (OECD, 2009). The right combination of these instruments contributes to a sustainable cost recovery, which is a more realistic and practical policy principle than the traditional financial basis.

a) *Tariffs* are a basic element of pricing policy and are paid directly by consumers. Tariffs can take on various forms but they are usually focused on and designed according to the final users characteristics (industry, agricultural, etc.). Mathys (2008) gives an exhaustive and complete assessment of the different tariff structures currently applied, their main policy objectives and their consequences on the water service and users. Due to the increased need of using alternative water resources, conventional tariff structures need to be adapted considering the integrated water resources pricing approach (Rogers *et al.*, 2002). Moreover, as alternative water sources full production costs impact differently on the average supply cost, a redefinition of the tariffs is needed.

   The price of each m^3 delivered to the user should reflect the water source in that particular moment (surface water, groundwater, seawater…) which in turn depends on the resource availability. The sense of this tariff variability is shown by the following equation, where the tariff (P) is a function of both variables (volume and specific cost) of each source available.

$$P = f[(r_{surface}, a_{surface}); (r_{groundwater}, a_{groundwater}); (r_{desalination}, a_{desalination}); (r_{reuse}, a_{reuse}); (r_{others}, a_{others})]$$

   where r refers to the volume supplied by a particular source and a refers to its specific costs.

b) *Taxes* and other instruments related to water taxation can have several objectives: environmental, economic, social and/or territorial sustainability (Sangrà, 2008). Nevertheless, sustainability, which is mostly provided and regulated by the public sector, needs to be financed as well.

   These instruments can take different forms and be applied along the cycle usually following the user-pays and polluter-pays principle. For instance, the water agency of the State of São Paulo (Brazil) collects flat charges from all users that extract and discharge water (farmers, industries and water utilities), whose financial resources are used to restore the quality and availability within the basin (GWP, 2009). On the other hand, in France there are different taxes applied by the basin agencies and the State. For instance, charges applied to consumers polluting and withdrawing water are used for network renovations. The State also collects a levy for financing the navigable river routes.

   Finally, another diversified example is Catalonia (Spain) (Sangrà, 2008), where a water canon is levied by the regulator and to be paid by domestic and industrial users. The levy has an ecological aim: pollution prevention and maintenance of environmental flows. At the same time, it finances the water management and wastewater treatment (investment and operation) and permits a sense of equity due to increasing block-rates. The agency also applies a canon for water abstractions and a charge for financing water related infrastructures, which is paid by the direct users of these investments. It has to be noted that the construction and amortization of a desalination plant in this region is partly financed by this charge.

c) *Transfers* consist in the grants given by other public sector levels, supranational levels or institutions outside the basin or State. In particular, official development assistance from multilateral sources, financing programs provided by international finance institutions or regional development banks and the funds given by the European Union to its member States, are some examples of this kind of economic instrument.

The role played by transfers is not trivial since it represents sometimes the major or unique source for the States or regulators to finance the required infrastructures for guaranteeing water supply and the essential sanitation facilities. Recently, most of the desalination plants and urgent waterworks in the European Union have been implemented thanks to the cohesion and structural funds allocated by the European Commission. Indirectly, those investments are being paid by a wider range of taxpayers. This makes economic sense because all the steps taken for stronger water supply security will benefit all citizens and potential consumers and not only the direct users of the new waterworks.

10 CONCLUSIONS

Desalination represents a potential alternative technology for the efficient production of freshwater from many sources. MSF and RO are the most common desalination technologies and their geographical distribution strongly depends, among other factors, on energy availability. MSF is preferred in arid regions with fuel availability at low cost whilst RO is most installed in regions with lack of good-quality freshwater and with good-quality seawater.

The costs associated with desalination depend on many factors such as capital, energy, labor, chemicals, materials, and consumables that are specific to the location, process configuration, plant capacity, feed water components, energy availability, pre-treatment necessities, product salinity and other site-related costs for land, plant and brine disposal. A detailed analysis of each situation is thus required to estimate desalination costs. It could be stated that RO cost is lower than MSF one in energy and environmental terms but the available knowledge on the latter is higher than on the former. Both technologies are by far predominant in the desalination market, accounting for more than 85% of the total installed desalination capacity. Nevertheless, these technologies need to be further improved to satisfy future water demands at sustainable cost. As MSF seems to be at its technological limit, current R&D efforts are being invested mostly in RO. New-generation membranes having higher permeabilities, rejection factors, fouling resistance, etc. have to be developed and installed to decrease desalination costs. In general, knowledge on RO has to be gained and transferred from labs-to-plants so that operators can efficiently operate membrane plants and understand mechanisms involved in the desalination process.

From an economic point of view, when integrating desalination technology in water cycle economics, policy-makers should consider capital, operating and maintenance, resource and environmental costs in the decision process. Although desalination emerges as a moderate resource cost technology, environmental impact of desalination is still high and thus needs to be further minimized.

The integration of alternative water resources implies rethinking and restructuring the traditional financing framework, focusing on tariff structures. An integrated water resource pricing, where the final price varies in function of the source and where the different production costs are considered, would better adapt to the current water policies and legislation. Public transfers and environmental taxes can also be defined to foster the development of desalination technologies.

In general, it can be concluded that R&D efforts need to be invested in minimizing capital, operating and maintenance, resource and environmental costs of desalination. Furthermore, integrated water resource pricing needs to be implemented in order to properly quantify desalted water cost.

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