The Cost of Desalination

1. Introduction

In the 1960s, desalination emerged as one of the most important means of treating saline water to bring it to acceptable water quality standards for use in various parts of the world and industrial sectors (Ghaffour, et al., 2012). The effects of climate change, population growth, and the rise of industrialization have played a significant role in water scarcity and have had a substantial impact on water demand. A large number of countries in Africa, the Middle East, and Asia are under serious freshwater stress and are facing a projected increase in water scarcity well into 2025. It is also important to note that almost 40 percent of the world's population lives within 100 km of an ocean or sea (Ghaffour, et al., 2012), thereby justifying seawater desalination as an integral part of the globe's response to water scarcity.

This paper presents an overview of the cost of desalination and the main components of associated capital cost (CAPEX) and operation and maintenance cost (OPEX). Examples of desalination facility costs have been presented to illustrate the range of costs that can be expected and to aid in conceptual planning and development of desalination projects.

2. Desalination Market Share and Trends

The most prevalent forms of desalination can be divided into two technology types:

Thermal desalination (using heat energy to separate distillate from high salinity water), represented primarily by Multiple Effect Distillation (MED) and Multi-Stage Flash distillation (MSF). Mechanical

Vapor Compression (MVC) is primarily used to desalinate high TDS (> 45,000 mg/l) and/or industrial wastewater for the purpose of reuse and not necessarily potable uses.

1.Reverse Osmosis (RO) membrane separation, which uses a membrane barrier and pumping energy to separate salts from high salinity water (typically < 45,000 mg/l).

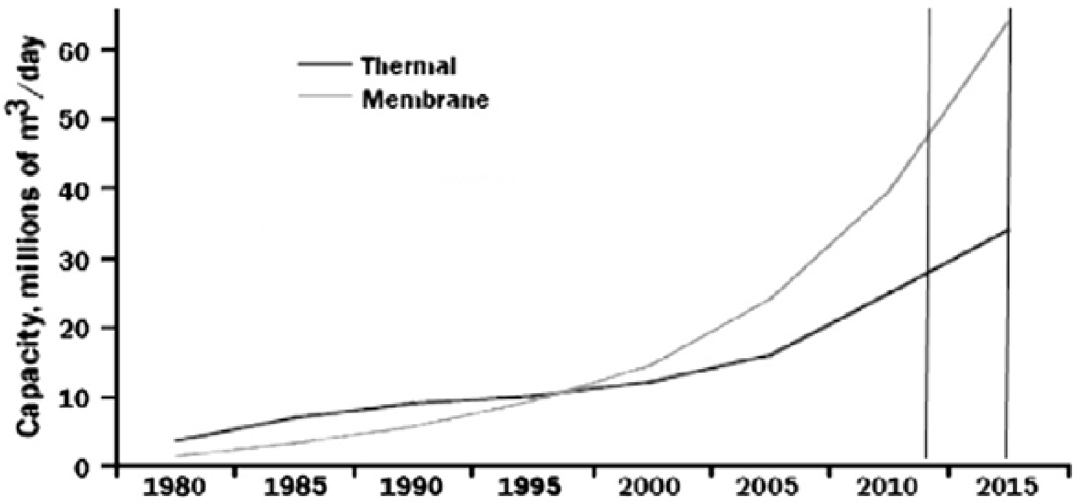
Desalination technologies are capable of treating water from a wide variety of sources, including, but not limited to, brackish groundwater, surface water, seawater, and domestic and industrial wastewater. As desalination technologies have developed and improved, the cost to build desalination plants has declined. This decrease in cost has been one of the primary factors for the acceptance, growth and success of desalination. Since the 1960s, the cost for Multi-Stage Flash Distillation (MSF) to desalinate water has decreased approximately by a factor of 10, with approximate unit costs of US$ 10.00/m3 in the 1960s to less than US$1.00/m3 ($3.79 per 1000 gallons) in 2010. Currently in 2017, in some locations, the cost of MSF has decreased by up to 20 percent from 2010 due to technological development and lower energy prices. Similarly, technological improvements in membrane design and system integration have decreased the cost to desalinate brackish water by over half in the last two decades (Ghaffour, et al., 2012). As an example, in 2012 the Texas Water Development Board estimated that the total production cost of desalinating brackish groundwater ranged from $0.29 to $0.66 per m3 of capacity ($1.09 to $2.49 per thousand gallons) (Arroyo, et al., 2012). However, a Water Reuse Association study in 2012 showed that cost trends for large Seawater Reverse Osmosis (SWRO) projects appear to have flattened since 2005, but have varied widely in the range of $0.79 to $2.38 per m3 ($3.00 to $9.00 per thousand gallons) of capacity since then (WRA, 2012). This wide variation is due to many cost factors and variables, which will be discussed in Section 3.

The charts (Fig. 1 to 5) below show total desalination capacity and growth by type, location and end-user applications.

2.1 Total capacity

Total desalination capacity exceeded 64 million m3/day in 2010 and was close to 98 million m3/day in 2015. Figure 1 shows how capacity has grown rapidly in the 21st century (Source: GWI Desal Data & IDA).

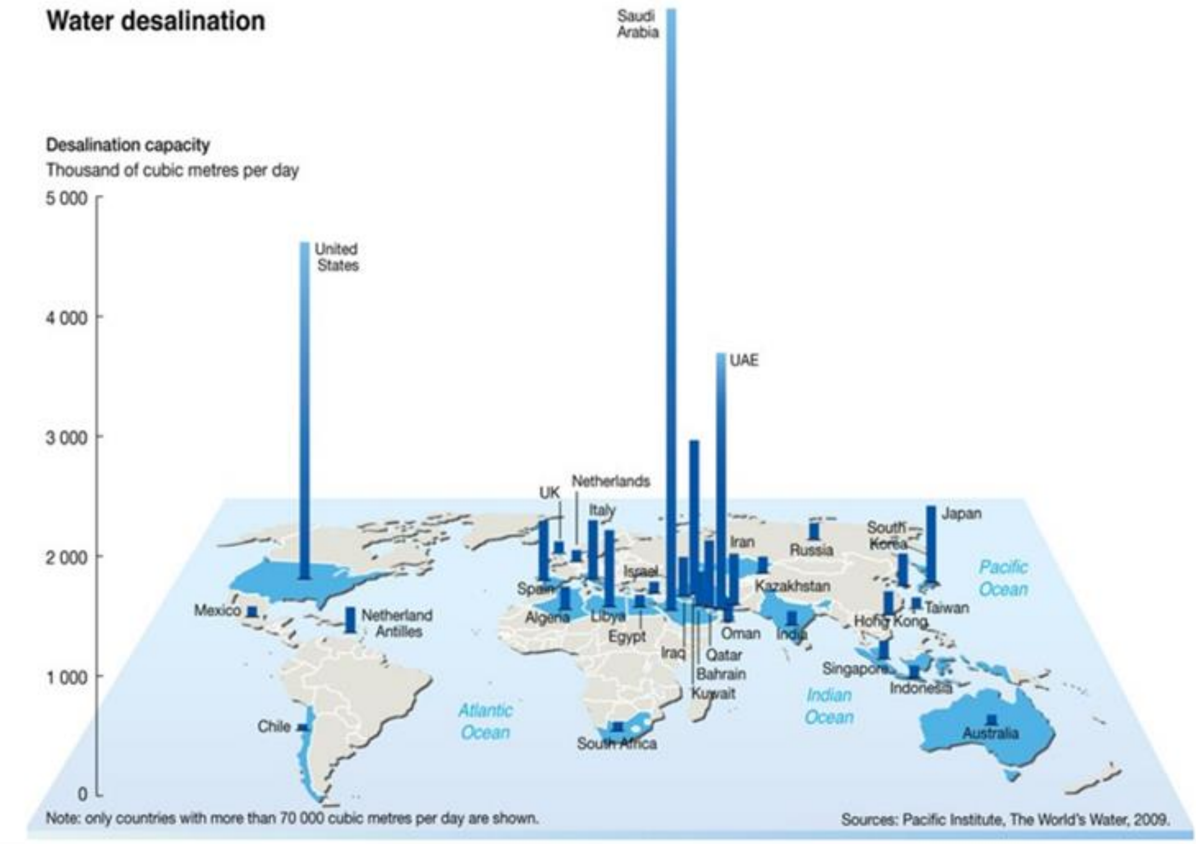
Figure 1 - Total worldwide desalination capacity (m3/d) [Source: Ref. 7]



2.2 Growth and installed capacity by region

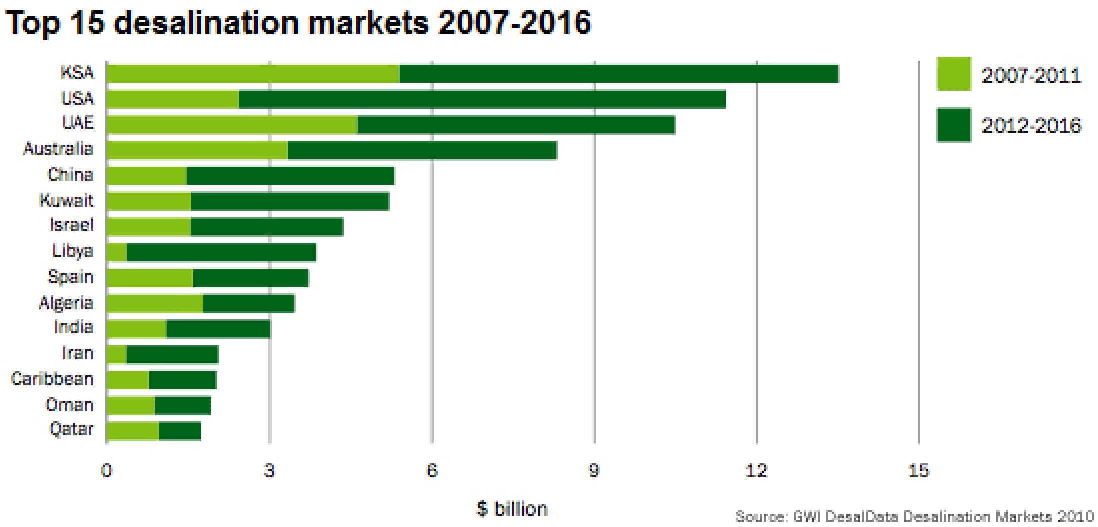
The largest production capacity by location is in the Middle East, due to their lack of freshwater sources and abundant energy resources, as can be observed from Figures 2 and 3. The largest desalination user by capacity is the Kingdom of Saudi Arabia, followed by the United States, UAE, Australia, China, Kuwait, and Israel.

Figure 2 - Desalination capacity by country [Source: Ref. 10]



The top 15 desalination markets for a nine-year period from 2007 – 2016 is shown in Figure 3. The United States has shown the largest increase in installed capacity since 2012.

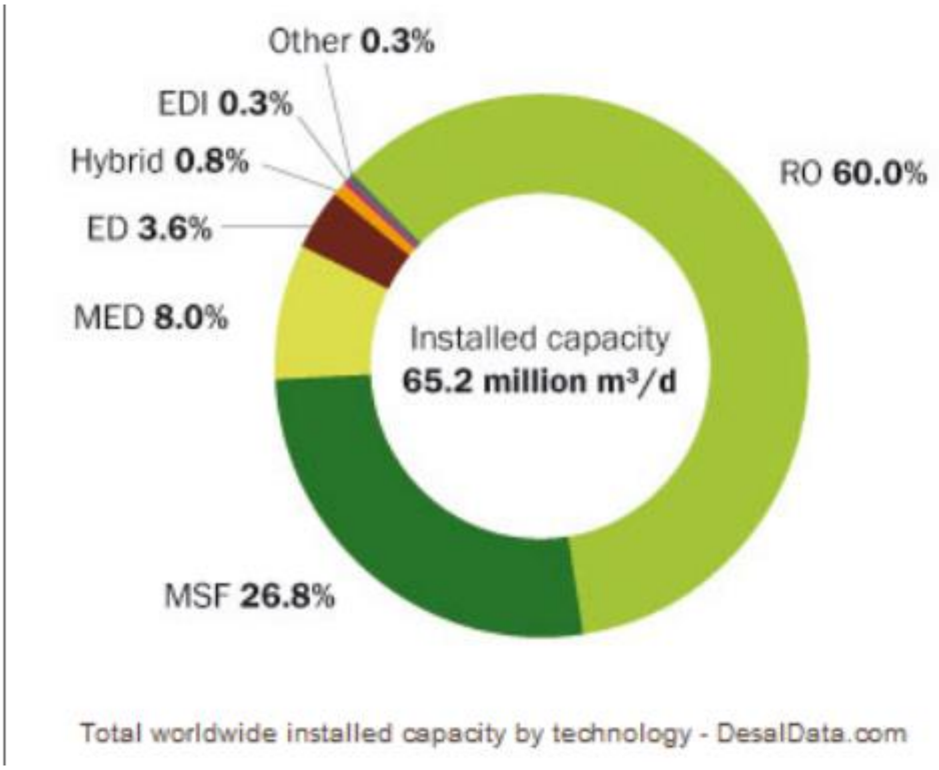
Figure 3 - Desalination market share 2007 – 2016 [Source: Ref. 7]



2.3 Installed capacity by technology

Figure 4 shows installed capacity vs. technology. The predominant type of desalination technology used today is Reverse Osmosis (RO). The use of RO has been a tradeoff between low OPEX (using electromechanical energy vs. typically more expensive thermal energy) vs. high CAPEX (due to the cost and relatively short life of membranes, so high replacement cost). Over the years, membrane prices have reduced dramatically and membrane life has increased due to better feedwater pretreatment and a better understanding of how to operate RO systems.

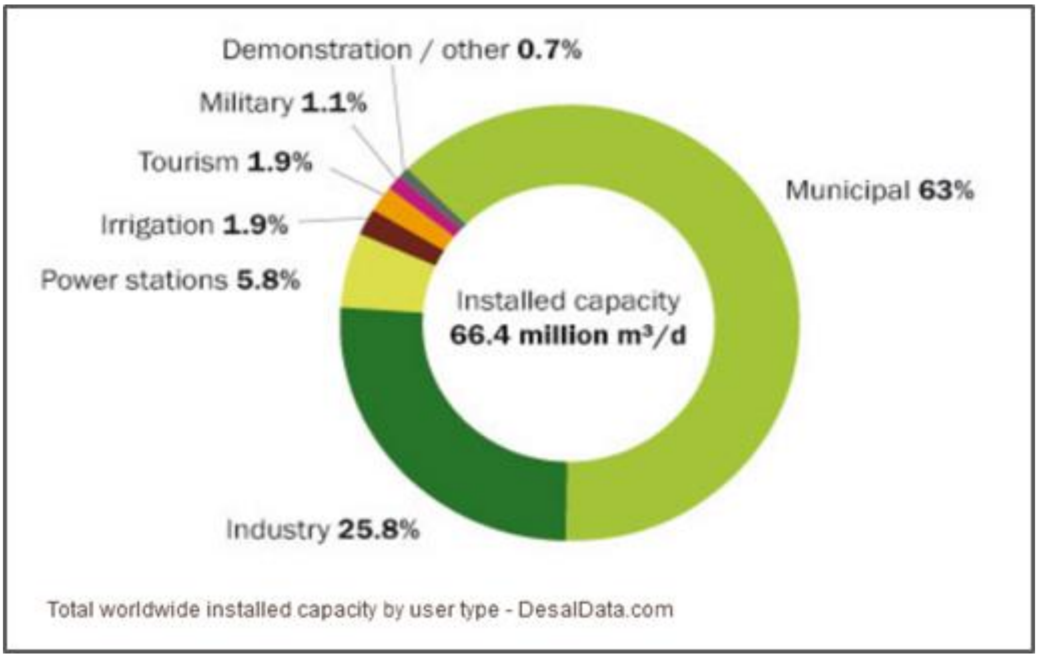
Figure 4 - Total worldwide capacity by desalination type [Source: Ref. 1]



2.4 Installed capacity by application and use

Figure 5 illustrates desalination market share by end-user application. Municipal use for desalination compromises the largest portion of the total installed capacity followed by industrial, power, irrigation and tourism uses.

Figure 5 - Global capacity of desalination by market application [Source: Ref. 7]



The factors noted above (Section 2), such as capacity, location, type, and application, have a significant impact on cost. There are other important site-specific factors that directly impact desalination cost, which are discussed in the following section.

3. Major Impacts on Desalination Cost

Factors that have a direct and major impact on desalination cost include, but are not limited to, desalination technology, raw and product water quality, type of intake and outfall, the location of the plant or project, the type of energy recovery used, the price of electricity, post-treatment needs, storage, distribution, local infrastructure costs, and environmental regulations.

3.1 Desalination technology

Almost 95 percent of the installed desalination capacity today is either thermal (35 percent) or membrane based (60 percent) technology (Ghaffour, et al., 2012). Each type of system varies considerably in footprint, materials of construction, equipment, pre-treatment requirements, power and steam requirements, amongst other differences. The technology selection will also determine the type of chemicals that will be used for pretreatment and post-treatment which impact operational costs.

3.2 Location

The site where a desalination facility is constructed can have a major impact on the overall costs of the project. For example, for an SWRO (Sea Water Reverse Osmosis) desalination plant, the plant should be located as close as possible to the seawater intake source to avoid higher costs for intake pipelines and complex intake structures. Optimal project siting will also reduce the concentrated brine discharge line back to the sea. However, real estate acquisition cost is a significant factor that may require greater water transmission in locations where land cost may exhibit orders of magnitude differences in relatively short distances. From a construction point of view, careful considerations are recommended for items such as local soil conditions (may require new soil fill or structural concrete piles) and close proximity to a reliable power source to reduce the power transmission costs.

3.3 Raw water quality

The site-specific raw water quality can have a major impact on the number and type of pretreatment steps required ahead of the desalination step itself, and the overall sizing of the desalination plant. The total dissolved solids (TDS) level of the source water directly impacts the operational costs, as higher operating pressures (RO) and temperatures (thermal) must typically increase as raw water salinity increases. Higher raw water salinity may also reduce the feasible product water recovery per gallon of raw water for both RO and thermal systems. In the case of SWRO, in areas such as small bays, gulfs or channels, seawater currents, and the resultant natural mixing from the larger body of seawater (i.e., the ocean) may be minimal. These areas can have higher local salinity levels, higher total suspended solids, higher temperature variations, and higher organic loadings and biological activity compared to water in the open ocean. All of these factors add design and construction complexity and, therefore, can significantly increase both CAPEX and OPEX costs.

Furthermore, feedwater temperature has a large impact on RO operating pressure costs, with feed pressure increasing by 10 percent to 15 percent for a 10 ^{0}F drop in feedwater temperature below 70 ^{0}F (WRA, 2012).

For an RO system, the required product water quality will dictate the number of membrane passes required, thereby impacting costs.

3.4 Intake and outfall

The type of intake and outfall selected for a desalination plant is one of the most important technical considerations for a plant's cost-efficient design and optimum operation. Important factors need to be evaluated such as the most suitable intake type (submerged vs. open intake), the distance of the intake relative to the plant, the type of intake screens, the type of intake structure, the type of intake pipeline (buried vs. above ground), and environmental considerations with regards to impingement and entrainment of marine life. Each of these items has a significant cost impact. The cost of the intake system can vary from a low of $0.13MM per thousand m3/day ($0.5MM per MGD) of capacity for an open intake to $0.79MM per thousand m3/day ($3.00MM per MGD) for complex tunnel and offshore intakes (WRA, 2012).

To illustrate the potential significance of intake and discharge structure costs, SWRO plant discharges located close to marine habitats that are highly sensitive to elevated salinity require elaborate concentrate discharge diffuser systems, with costs that can exceed 30 percent of the total desalination project expenditures. In contrast, the desalination plants with the lowest water production costs have concentrate discharges either located in coastal areas with very high natural mixing or are combined with power plant outfall structures, allowing good initial mixing and better discharge plume dissipation. The intake and discharge facility costs for these plants are usually less than 10 percent of the total desalination plant costs (WRA, 2012).

3.5 Pretreatment

Pretreatment costs are impacted by the type and complexity of the pretreatment system. The type of pretreatment required depends on the raw water quality at the project site. Some raw seawater or brackish surface water sources have a high level of organics and biological activity and require more robust pretreatment technologies, such as DAF (Dissolved Air Flotation) and UF (Ultrafiltration). Other raw water sources that use submerged intakes or well-based intakes may require less pretreatment, such as a single-step media filtration or MF (Microfiltration).

According to an article by the Water Reuse Association entitled "Seawater Desalination Costs," pretreatment costs will typically range from $0.13MM to $0.40MM per thousand m3/day ($0.5MM to $1.5MM per MGD). At the lower end of this range, conventional single-stage media filtration systems are adequate. Pretreatment costs increase as additional pretreatment steps are added, such as two-stages of media filters or media filtration followed by MF or UF systems.

Pretreatment costs are typically greater if the water source is wastewater. This may be due to many factors, such as the necessity to remove high calcium and magnesium (hardness) levels, the addition of chlorination and dechlorination steps to destroy microbes, or the necessity of using UF to remove high molecular weight organic compounds.

3.6 Energy recovery

RO systems use high-pressure pumps to overcome the osmotic pressure of the raw feedwater. For example, some SWRO plants can require up to 70 bar (1000 psig) feed pressures. The RO concentrate brine stream from this process contains pressure energy that can be recovered in order to reduce the overall RO system energy requirements. Energy recovery technologies reduce the overall energy input, thereby reducing operating expenditures.

3.7 Electric power

Local energy prices, transmission distance, connection fees, and possibly tariffs at the proposed location of the desalination facility play an important role in determining the supply price for connected power. For very large thermal desalination plants, consideration of co-locating the facility with a power plant may be promising due to the inherent advantages of such a combination.

3.8 Post-treatment

Final product water quality will determine the specific type of post-treatment that is required. Post-treatment steps add additional costs. The need for a second RO pass to achieve very low TDS levels or reduce the concentrations of specific ions, such as boron or chloride, to acceptable levels can be an expensive option. A two-pass RO system will typically be 15 percent to 30 percent more costly than a single pass RO system (WRA, 2012).

Also, stabilization of the product water typically requires a pH adjustment and the addition of bicarbonate alkalinity, which can be done using a combination of carbon dioxide, lime and/or sodium hydroxide and, again, this adds additional cost.

For desalination plants located on a coast in close proximity to the communities using the water, land is usually priced at a premium. The cost of locating a facility closer to the point of use and a suitable power source should be weighed against the costs associated with additional intake and discharge pipeline right of ways, pipeline costs, materials transport, permits, labor and maintenance associated with moving a plant farther away from the coast or distribution service area (WRA, 2012).

Post-treatment costs are typically greater if the water source is wastewater. This may be due to many factors, such as post-treatment oxidation to inactivate viruses and higher costs for waste brine or solids disposal.

3.9 Local infrastructure costs

Infrastructure costs include items such as earthworks, concrete, steel, structures, drainage, and building materials. Depending on the location of the plant, the costs for each of these items can vary significantly. Remote plant locations that are located far from industrial cities will typically have to incur higher construction costs vs. plants that are constructed near concrete-producing facilities and industrial zones that have an ample supply of building materials.

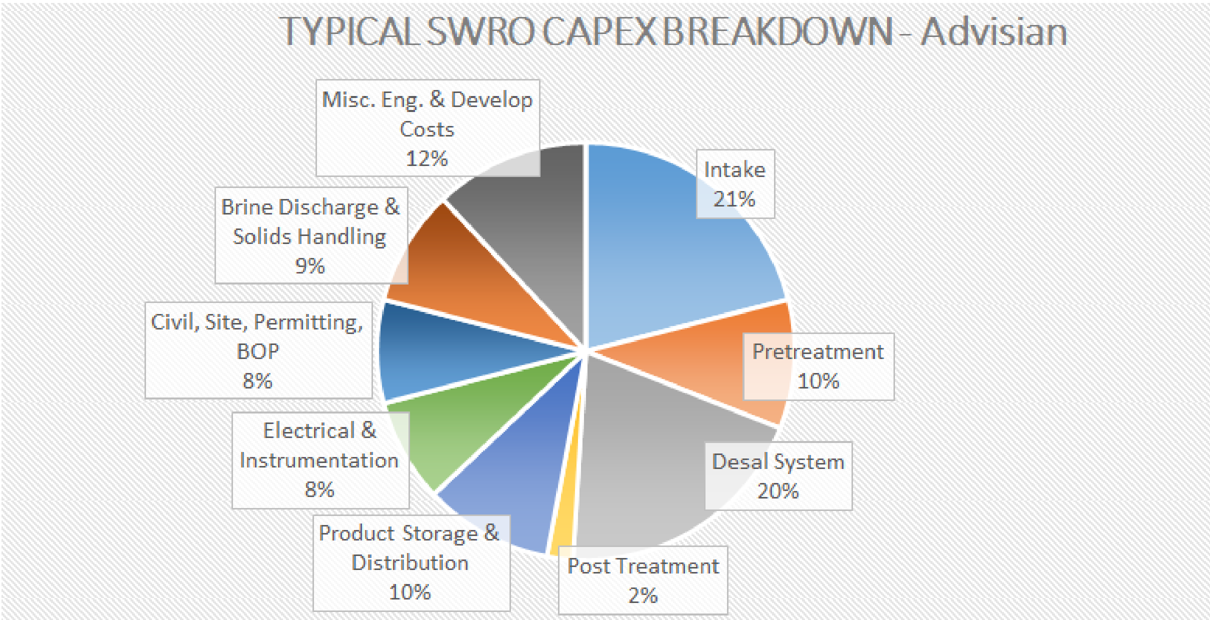
3.10 Environmental regulations

Each geographic region will have its own set of environmental rules and regulations, and these can also vary from state to state within a single country. For example, permitting costs for projects in California are almost four times the typical permitting costs in Florida (WRA, 2012). California has more stringent regulations and/or guidelines for potable water production compared to those in Texas or Florida, which adds regulatory cost to a desalination project. Longer environmental review periods can also lengthen the project schedule, which typically results in higher project costs as well. In fact, the number of years required to develop and permit a project in a state like California, with very stringent regulations, may be significantly longer than the time necessary to construct the plant and initiate start-up. (WRA, 2012)

4.0 Cost Components – CAPEX

CAPEX is subdivided into the two major categories of direct and indirect costs. Direct costs include equipment, buildings and other structures, pipelines, and site development, and are typically in the range of 50 percent to 85 percent of the total CAPEX. The remaining indirect costs include financing interest and fees, engineering, legal and administrative costs, and contingencies (Ghaffour, et al., 2012). The typical CAPEX cost and components for most desalination plants can be further divided into nine parts, as follows: intake and raw water conveyance; pretreatment; desal treatment; post-treatment; product water pumping and storage; electrical and instrumentation system; plant buildings, site and civil works and balance of plant; brine discharge and solids handling; and miscellaneous engineering and development costs. Other costs, such as financing fees and other commercial related fees, also have to be considered. Figure 6 shows one example of a CAPEX cost breakdown for an SWRO plant.

Figure 6 – Typical SWRO desalination plant CAPEX breakdown (Source: Advisian)



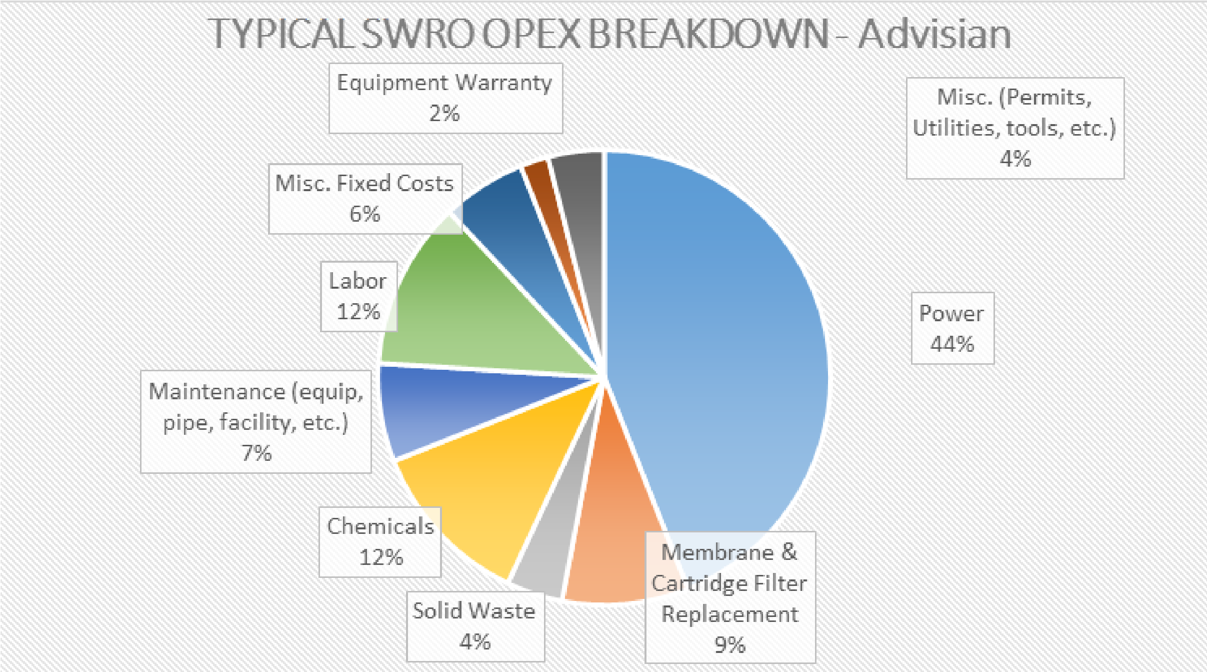
CAPEX, to a significant extent, depends on scale with larger desalination plants costing less per million gallons of installed capacity. Based on Figure 7 below, a medium size 10 MGD SWRO plant would cost about $80 million to build and a large plant, such as the 35 MGD Carlsbad SWRO plant near San Diego, would be expected to cost $250 million. *Note: Due to environmental, permitting and construction issues, that plant ended up costing much more.*

Figure 7 – Unit construction cost vs. capacity for SWRO plants [Source: Ref. 3]

5.0 Cost Components – OPEX

Operating costs (OPEX) generally fall into two broad categories: fixed costs (such as labor, administrative, equipment and membrane replacement costs, and property fees/taxes [as applicable to the locality], etc.) and variable costs (such as power, chemicals, and other consumables. (Arroyo, et al., 2012). The typical OPEX cost and components for most desalination plants can be further subdivided into nine parts comprising the following: power consumption, consumables, solid waste, chemicals, labor, maintenance, equipment warranty, balance of plant & utilities, and other fixed costs (administration, spares, contingency, etc.), as shown in Figure 8.

Figure 8 – Typical SWRO desalination plant OPEX breakdown (Source: Advisian)



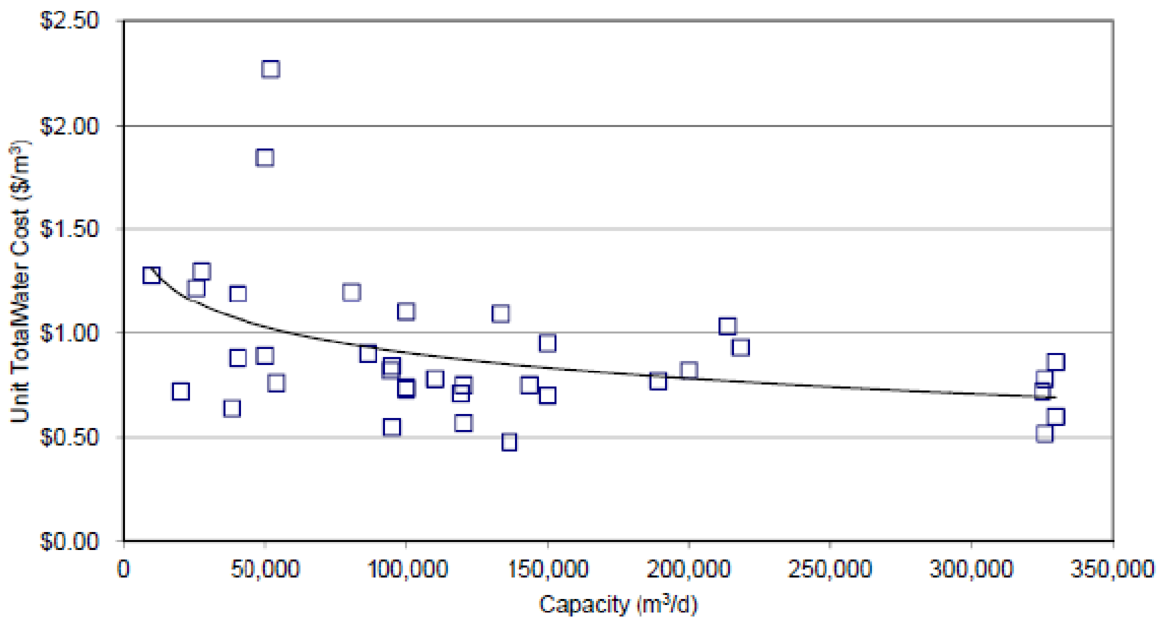
6.0 Total cost to desalinate water

Life cycle cost, also called unit production cost or annualized cost, is the cost of producing a thousand gallons or cubic meter of water by desalination and considers all CAPEX (including debt servicing) and OPEX, and may be adjusted by a predicted or actual plant operating factor. Because of all the variables involved, these annualized costs can be very complex, and unit production cost differences among projects may not be directly comparable. At best, predicting future costs using past plant cost information will typically only result in ballpark estimates.

Figure 9 shows that annualized costs for various types of completed RO projects have varied widely. The average costs, represented by the best fit line in the data shown, are about $0.70/m3 ($2.65 per thousand gallons) for very large plants (325,000 m3/day) and rise to $1.25/m3 ($4.75 per thousand gallons) for small plants (10,000 m3/day).

However, costs can range as high as $3.20/m3 for very small capacity plants (less than 4,000 m3/day or 1 MGD) that have costly site-specific intake, discharge, and conveyance peculiarities. Removing the effects of intake, discharge, and conveyance reduces and narrows the annualized cost range to $0.53/m3 to $1.58/m3 ($2.00 o $6.00 per thousand gallons) for SWRO plants and $0.11 to $1.10/m3 ($0.40 to $4.00 per thousand gallons) for brackish water RO plants (WRA, 2012).

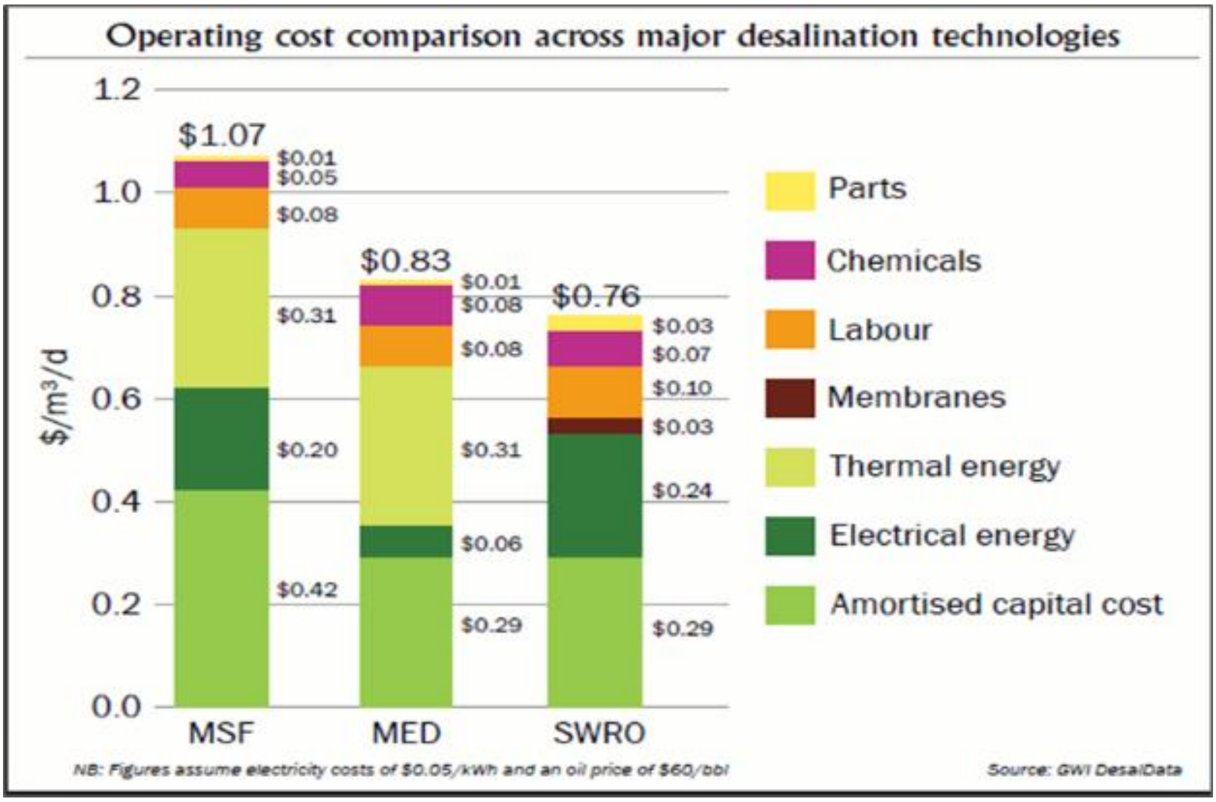
Figure 9 – RO plant unit production cost vs. project capacity [Source: Ref. 9]



The cost to desalinate industrial wastewater for reuse can be much greater than this. For example, WorleyParsons/Advisian conducted a study to develop the CAPEX and OPEX for a 35,000 m3/day desalination plant located in the Arabian Gulf region and being fed with oil field produced water and producing boiler feed water. Based on budgetary CAPEX and OPEX costs generated in that study, the unit production cost was roughly four times higher than would be predicted using Figure 9.

Figure 10 below shows a typical life cycle cost comparison of MSF, MED, and SWRO to produce one cubic meter (264 gallons) of water per day. As shown, MSF and MED, which are thermal desalination technologies, require steam (thermal energy) in addition to electrical energy, which is the main reason why they have higher total water life cycle costs compared to SWRO.

Figure 10 – Unit production cost of water for desalination technologies [Source: Ref. 7]



7.0 Examples of desalination facility costs

As noted in this paper, the cost of developing, constructing, and operating a desalination facility depends on the location of the plant, the raw water type and quality, type of intake and outfall, the desalination technology and energy recovery systems used, the cost of electrical power, any required post-treatment and storage, distribution costs, and environmental regulations. These differences can make a large plant built in one region of the world more expensive than a smaller plant built in another region of the world and result in significant differences in OPEX. This is illustrated by the projects shown in

Table 1 for three SWRO plants located in various locations of the globe, such as the US, the Middle East, and Australia.

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Region	USA [6]	Arabian Gulf [11]	Australia [5]
Project name	Carlsbad Desalination Project	Fujairah F1 Extension SWRO	Gold Coast Desalination Plant
Plant location	Carlsbad, CA, USA	Fujairah, UAE	Tugin, Australia
Plant construction date	2014	2013	2009
Plant capacity m3/d (MGD)	189,000 (50)	136,000 (30)	133,000 (35.1)
Plant recovery	45-50%	45-50%	45%
Raw water salinity (ppm)	36,000	45,000	38,000
Product water quality (ppm)	200	500 (WHO standard)	200
Intake type	Open intake, co-location	Open intake	Open intake, drum screens, intake/outfall tunnel
Pretreatment type	Dual media filtration	Dissolved gas flotation + filtration	Dual media filtration
Desalination technology	2 Pass SWRO	2 Pass SWRO	2 Pass SWRO
Energy recovery type	ERI	ERI	DWEER ERD
Post-treatment	CO2 and lime addition, chlorination, fluoridation	CO2 and lime addition, chlorination	CO2 and lime addition, chlorination, fluoridation
Storage and distribution	3.4 MG + 10 miles conveyance pipeline and pumping	NA	8 MG + 16 miles pipeline + pumping

Brine discharge	Direct to sea with power plant	Direct to sea	300 meters into sea, diffusers
Environmental regulations	Very stringent	Moderate	Stringent
Specific energy (kwh/ m^3)	N/A	3.7 – 4.0	3.40
TIC cost (US$)	$692,000,000 (529 MM + 163 MM conv. pipeline) + $213 MM finance costs ($904 MM total)	$200,000,000	$943,000,000 (745 MM plant + 198 MM tunnels)
Projected lifetime, years	20	20	20
Simple annualized CAPEX, US$/year	N/A	N/A	$47,150,000
OPEX (US$/year)	$53,100,000	$26,900,000*2	$32,000,000
Unit production cost, US$/$m^3$-day	$1.86 *1	< $0.60	$1.63

**1 Total unit cost to owner that included payments, finance fees on pipeline, misc. construction improvements, misc. O/M costs, admin costs.*

**2 Estimated*

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