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Overview of Alternative Desalination Technologies

by

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1. INTRODUCTION

Approximately 97.5% of the water on the planet earth is located in the oceans and therefore, is classified as seawater. Freshwater contributes the balance of 2.5%, of which approximately 70% is in the form of polar ice and snow, and the balance of 30% lies in groundwater, rivers and lakes, and air moisture. Even though the volume of water is vast, less than 8.4 million of the 333 million cubic miles (mi^3) of water is of low salinity suitable for use, after applying conventional water treatment only. Desalination provides a means for tapping into the world's largest water resource: the ocean.

The use of desalination for production of fresh drinking and industrial water has gained significant momentum over the past two decades. The number and size of desalination projects worldwide have been growing at a rate of 5 to 7% per year since 2010, which corresponds to an addition of between 780 and 1,100 million gallons per day (MGD) of new installed fresh water production capacity every year (from 284,700 to 401,500 million gallons per year). As of the end of July 2019, there are over 20,000 desalination plants worldwide with total installed fresh water production capacity of 110 million m^3/day (29,000 MGD).

Approximately 75% of the new globally installed desalination plant capacity for the year to July 2016 was for seawater desalination (570 MGD) while 15% was for brackish water desalination (85 MGD). The remaining 10% was associated with the construction of desalination plants applying other desalination technologies such as electrodialysis reversal (EDR), ion exchange (IX), etc. (0.32 million m^3/day).

This trend is expected to continue in the future with an overall slowdown in the construction of new brackish water desalination plants, as most of the known brackish water aquifers near large urbanized centers worldwide are already utilized, and brackish water in general is of limited availability. Approximately 1% of the worldwide water resources exist in brackish water aquifers while 97.5% of the planet's water is in the oceans and seas.

At present, 95% of all desalination plants worldwide apply membrane desalination technology (typically reverse osmosis) for production of fresh water. In 2019, over 96% of the new desalination plants employed reverse osmosis membrane technology, while less than 4% of all new desalination plants were thermal evaporation facilities. This trend is expected to continue in the future due to the clear advantages membrane desalination offers in terms of energy use and overall water production costs. This is especially true outside of the Middle East and North Africa

(MENA) region where seawater salinity concentrations and biofouling potential are lower, and low-cost thermal and electrical energy are not readily available.

The desalination market is expected to continue to grow steadily in the future. This growth can be attributed to a number of long-term global trends:

i. steadily increasing population growth and associated demand for fresh drinking water in urbanized coastal areas;
ii. prolonged drought in the arid and semi-arid areas coastal areas of the world, and
iii. limited availability of untapped traditional low-cost fresh water resources in these areas.

Arid and semi-arid coastal zones of the world are home to over 70% of the world's population and are usually the fastest growing and most urbanized areas.

Over 80% of the new desalination plants contracted during the year 2019 are located in the MENA region. Traditionally, the MENA market has been the largest market for desalination projects and services worldwide. East Asia and the Pacific provide the second largest market for desalination projects.

Over 70% of the fresh drinking water in the Middle East, the majority of the Caribbean, the Canary Islands, Cyprus and Malta, is provided by seawater desalination. However, at present seawater desalination supplies only a small percentage of water to rest of the world's arid and semi-arid coastal areas.

The key challenges associated with the wider use of desalination as compared to conventional water supply in these areas today are threefold:

i. the relatively high costs of water production;
ii. the significantly larger energy use and carbon footprint of the desalination processes, and
iii. the unique environmental impacts associated with desalination plant intake and discharge operations.

While desalination currently provides only around 5% of water supply worldwide, it is expected that in the next decade the construction of new desalination plants will more than double. This can be attributed to the impact of climate change, increased demand due to population growth, limited availability of new, inexpensive terrestrial water sources and advances in membrane technology which are projected to further reduce cost and energy use needed for desalination.

Over 50% of world's population lives in urban centers bordering the ocean. In many arid parts of the world such as the Middle East, Australia, Northern Africa and Southern California, the population concentration along the coast exceeds 75%. Coastal zones tend to have high population growth as well. Seawater desalination therefore, provides the logical solution for the sustainable long-term management of growing water demand in coastal areas. Brackish desalination is also expected to increase in capacity, especially in inland areas with still untapped brackish water aquifers.

A clear recent trend in seawater desalination is the construction of larger capacity plants, which deliver an increasingly greater portion of the fresh water supply to coastal cities around the globe. While most of the large desalination plants built between 2000 and 2005 were designed to supply only 5 to 10% of the drinking water of the coastal urban centers, today most regional or national desalination project programs in countries such as Spain, Australia, Israel, Algeria and Singapore aim to secure 20 to 25% of their long-term drinking water needs with desalinated seawater. Increased reliance on seawater desalination is often paralleled with ongoing programs for enhanced water reuse and conservation with a long-term target of achieving a near even contribution of conventional water supply sources, seawater desalination, water reuse and conservation to the total water portfolio of large coastal communities.

2. TERMINOLOGY

The mineral/salt content of water is usually measured by a water quality parameter referred to as total dissolved solids (TDS) concentration. In engineering practice, salinity, total dissolved solids, and salt content of water are terms carrying the same meaning and are often used interchangeably.

Usually, salinity is expressed in milligrams per liter (mg/L), or parts per thousand (ppt) where 1.0 ppt = 1,000 mg/L. Based on the World Health Organization (WHO) water quality guidelines, the palatability of drinking water in relation to TDS concentration is rated as follows:

- excellent, less than 300 mg/L;
- good, between 300 and 600 mg/L;
- fair, between 600 and 900 mg/L;
- poor, between 900 and 1200 mg/L; and
- unacceptable, greater than 1200 mg/L.

Water with extremely low concentrations of TDS (lower than 50 mg/L) has a flat, insipid taste.

The United Sates Environmental Protection Agency (US EPA), under the Safe Drinking Water Act has established a maximum TDS concentration of 500 mg/L as drinking water standard. This

TDS level can be used as classification limit to define fresh water. Waters with TDS over 1,000 mg/L are referred to as saline waters as for most people they will have a salty taste.

Waters with TDS concentration > 500 mg/L and ≤ 15,000 mg/L are classified as brackish. The limit of 15,000 mg/L is somewhat arbitrary and is selected based on the type of reverse osmosis (RO) membranes which have to be used to desalinate such waters. Usually, if source water salinity is > 15,000 mg/L, the standard brackish water reverse osmosis (BWRO) membranes and vessels would not be able to handle the operating pressures required to desalinate the water. In this case, seawater reverse osmosis (SWRO) membranes and vessels will have to be used. Salinity of most brackish water aquifers in the US varies between 800 and 4,000 mg/L.

Natural saline water with TDS concentration > 15,000 mg/L, such as sea, bay and ocean water, is generally referred to as seawater. Pacific and Atlantic Oceans' seawater has average TDS concentration of 35,000 mg/L. This concentration can vary in the range of 33,000 to 36,000 mg/L at various locations and depths along the coast. The Caribbean sea has a slightly higher average TDS concentration of 36,000 mg/L, which can reach up to 38,000 mg/L in some locations. The Gulf of Mexico also has an average salinity of 36,000 mg/L with variation between 33,000 and 37,000 mg/L. The highest salinity water body used to produce drinking water by desalination is the Arabian (Persian) Gulf where the average salinity is 45,000 mg/L and varies between 42,000 and 46,000 mg/L.

3. OVERVIEW OF DESALINATION TECHNOLOGIES

Sea and brackish waters are typically desalinated using two general types of water treatment technologies –thermal evaporation (distillation) and membrane separation. In thermal distillation fresh water is separated from the saline source by evaporation. In RO desalination fresh water is produced from saline source water by its pressure-driven transport through semi-permeable membranes. The main driving force in RO desalination is the pressure that is needed to overcome the naturally occurring osmotic pressure, which in turn is proportional to the source water salinity.

Besides thermal and RO, two other desalination technologies currently widely applied in the industrial and municipal sector are electrodialysis (ED) and ion exchange (IX). Electrodialysis is an electrically driven desalination process where salt ions are removed out of the source water by exposure to direct electric current. The main driving force for ED separation is electric current, which is proportional to the salinity of the source water. Ion exchange is the selective removal of salt ions from water by adsorption on ion-selective resin media. The driving force in this desalination process is the ion charge of the IX resin, which can selectively attract and retain ions of opposite charge contained in the saline source water.

Table 1 provides a general indication of the range of source water salinity for which distillation, RO separation, ED and IX can be applied cost effectively for desalination. For processes with overlapping salinity ranges, a lifecycle cost analysis for the site-specific conditions of a given desalination project is typically applied to determine the most suitable desalination technology for this project.

Table 1: Desalination Process Applicability

Separation Process	**Range of Source Water TDS Concentration for Cost-Effective Application (mg/L)**
Distillation	20,000 to 100,000
Reverse Osmosis Separation	50 to 46,000
Electrodialysis	200 to 3,000
Ion Exchange	1 to 800

At present, the majority of all desalination plants worldwide employ RO separation for production of fresh water, which percentage has been increasing steadily over the past decade due to the remarkable advances in membrane separation and energy recovery technologies. This has led to a reduction in the overall water production costs. ED and IX-based technologies currently contribute less than 7% of the total installed desalination plant capacity worldwide.

4. THERMAL DESALINATION

4.1. Overview

All thermal desalination technologies apply distillation (heating of the saline source water) to produce water vapor, which is then condensed into low-salinity water. The principle of evaporation is based on water molecules requiring less heat to be turned from liquid to vapor than dissolved solids contained in the water. Since the energy for water evaporation is practically not dependent on the source water salinity concentration, thermal evaporation is suitable for desalination of high salinity waters and brine.

This is one of the reasons why thermal desalination has been widely adopted by all Middle Eastern countries including Saudi Arabia, Oman, Qatar, United Arab Emirates, Bahrain and Kuwait. The Red Sea, Arabian (Persian)Gulf, Gulf of Oman and the Indian Ocean are of the most saline water bodies. At present, around three-quarters of the total world's thermal desalination plants are located in the Arabian Peninsula, half of which are in Saudi Arabia.

All thermal desalination plants have the streams shown in Figure 1. Input streams include source water and steam needed for evaporation of the source water. Cooling water is needed to condense the fresh water vapor generated or condensate from evaporation. The waste stream produced is called concentrate or brine, and contains all salts and other impurities separated from the source water.

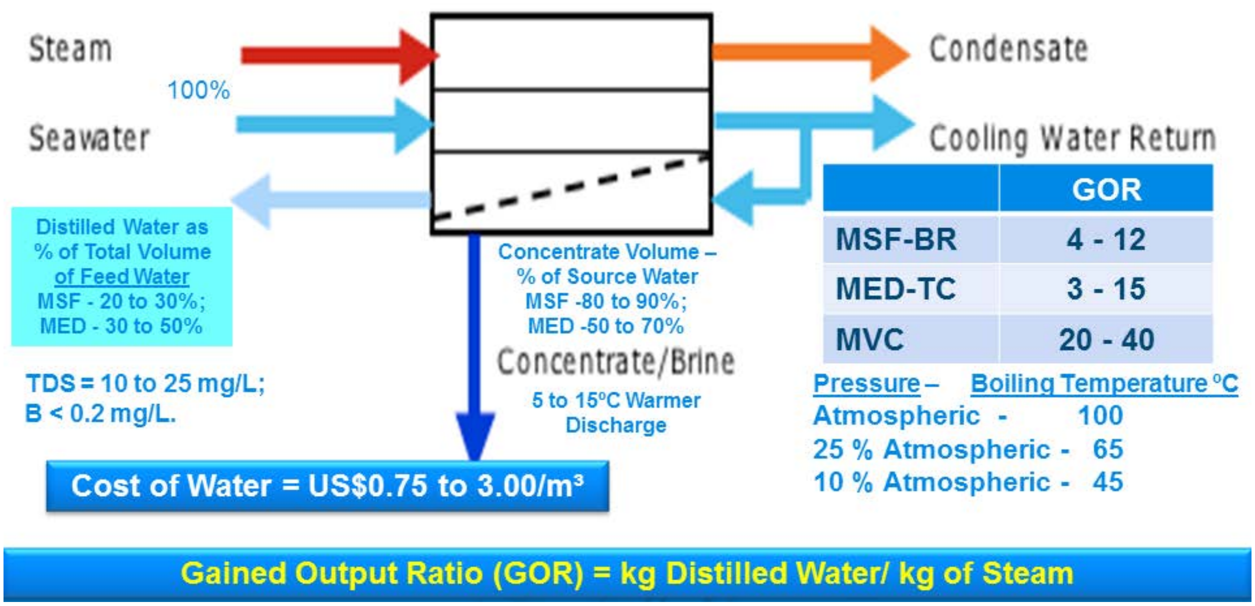


Figure 1: General Schematic of Thermal Evaporation Technologies

The three most commonly used types of thermal desalination technologies are multistage flash distillation (MSF), multi-effect distillation (MED) and vapor compression (VC). Each class of these technologies has evolved over the past 40 to 60 years towards improvements in efficiency and productivity.

In Figure 1, "MSF-BR" refers to a multistage flash distillation process with brine recycle. This reduces the source water volume and steam needed for evaporation. Similarly, "MED-TC" refers to multi-effect distillation with thermal compression, which is a state-of-the art technology.

"MVC" is an acronym for mechanical vapor compression, a technology that can run without the need of an outside source of steam.

The temperature and pressure at which the source water is boiled to generate fresh water vapor differ in these three technologies. MSF distillation is the oldest technology and boils water at near atmospheric pressure, and temperature close to 100^0C (212^0F). This requires a large quantity of high temperature steam.

The improved efficiency in the newer technologies of MED and VC stems from water boiling at lower temperature at pressure lower than the atmospheric pressure. Boiling water at lower temperature requires less, and lower quality steam to produce the same volume of distilled water.

In MED desalination vessels, the boiling process typically occurs at lower temperatures and pressures than in MSF distillation systems. VC thermal desalination systems operate at lower pressure than both MSF and MED, which allows evaporation at even lower temperatures and self-generation of steam instead of depending on external sources.

The ratio between the mass of produced low salinity water (distillate) and the mass of heating steam used to produce this water is commonly referred to as the gained output ratio (GOR) or performance ratio. The ratio varies depending on the technology used, site specific conditions and source water quality. The GOR typically varies between 4 and 40, in other words producing between 4 and 40 kilograms of fresh water using one kilogram of steam. The higher the technology GOR, the more efficient the technology is, producing more fresh water from the same amount of steam. Figure 1 shows the typical range of GORs for MSF, MED and VC technologies. In general, MVC and MED have higher GORs than MSF.

All thermal desalination technologies generate water with very low salinity (TDS in a range of 10 to 25 mg/L). This fresh water also has a very low content of pathogens and other contaminants of concern such as boron, bromides and organics.

Thermal desalination is most popular in the Middle East, where seawater desalination is typically combined with power generation that provides low-cost steam for the distillation process. Thermal desalination requires a large quantity of steam. Most power plants outside the Middle Eastern region are not designed to yield significant amounts of waste steam as a byproduct of power generation. This is one of the main reasons why thermal desalination has not found wider application outside of the region.

4.2. Multistage Flash Distillation (MSF)

In MSF evaporator vessels (also referred to as “flash stages” or “effects”), high-salinity source water is heated to a temperature of between 90 – 115 ^{0}C (194 to 239 ^{0}F) in a vessel to create water vapor. The heating section receives waste heat from an outside source – usually a power generation plant. The pressure in the heating section prevents flashing from occurring until the seawater enters the first stage, which has lower pressure. The pressure in the first stage is maintained slightly below the saturation vapor pressure of the source seawater. When the high-pressure vapor created in the heating section enters into the first stage, its pressure is reduced to a level at which the vapor “flashes” into steam. The process is shown schematically in Figure 2.

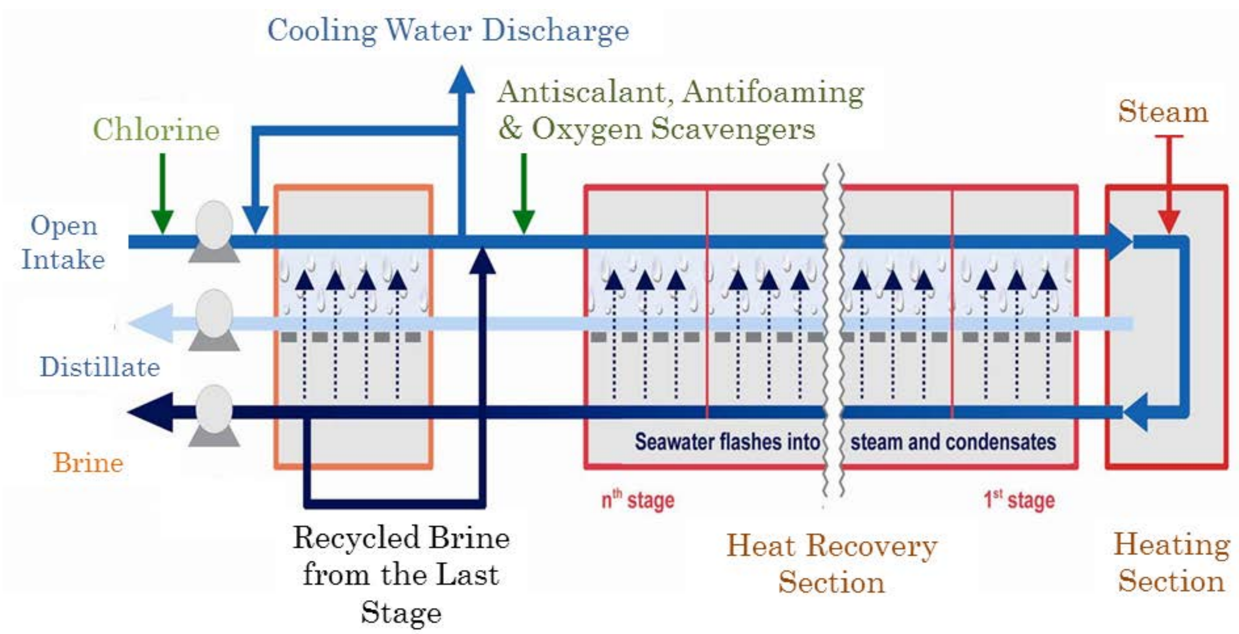


Figure 2: Schematic of MSF Distillation System

Steam for the heating section is provided from waste heat by the power plant collocated with the desalination plant. Each flash stage (effect) has a condenser to turn the steam into distillate. The condenser is equipped with heat exchanger tubes, which are cooled by the source water fed to the condensers.

Entrainment separators (mist eliminators/demister pads) remove the high-salinity mist from the low-salinity rising steam. This steam condenses into pure water (distillate) on the heat exchanger tubes and is collected in distillate trays from where it is conveyed to the next stage in the opposite direction of the movement of the source seawater and is ultimately collected in the last stage from where it is conveyed to the product water tank.

The concentrate (brine) generated in each stage and after collection at the last stage, some of it is typically recycled to the source water stream to reduce the total volume of source water that has to be collected at the plant intake. The recycled brine flowing through the interior of the condenser tubes also removes the latent heat of condensation. As a result, the recycled brine is pre-heated close to maximum operating temperature, thereby recovering the energy of the condensing vapor and reducing the overall source water heating needs. This "brine recycle" (BR) feature is adopted in practically all more recent MSF facility designs and significantly improves the overall cost-competitiveness of MSF installations.

Each flash stage produces approximately 1% of the total volume of desalination plant condensate. Since a typical MSF unit has 19 to 28 effects, the total MSF plant recovery (the volume of distillate expressed as percentage of the total volume of processed source water) is usually between 19 and 28%. For comparison, seawater reverse osmosis desalination plants have recovery of 40 to 45%. The latest MSF technology has 45-stage units and can thus operate at 45% recovery. This feature allows it to compete with RO systems in terms of recovery.

Typically, the exchanger tubes of the MSF systems are made of 70/30% or 90/10% copper nickel or aluminum brass alloys. Water boxes in the individual stages are made of carbon steel cladded with copper-nickel alloys. Carbon steel cladded with 316 L stainless steel is used up to the mist eliminators and duplex stainless steel is used above the eliminators. In the past, most MSF shells were made of copper-containing alloys. The current trend is to use duplex stainless steel. The dominating unit MSF capacity at present is between 7 and 9 MGD. The largest individual MSF units have a capacity of 20 MGD and are located in Shuweihat, United Arab Emirates (UAE).

MSF distillation is the oldest desalination technology used for production of large quantities of fresh drinking water. The first MSF plant was built in the Kingdom of Saudi Arabia (KSA) in 1907. At present, approximately 53% of all desalination plants in the region use this technology for production of fresh drinking water.

While MSF technology is cost competitive for mega-size desalination projects (projects with production capacity of 150 MGD or more), MED and SWRO desalination are gaining grounds for small, medium and large size desalination plants due to their higher energy efficiency and lower costs of fresh water production.

The GOR for MSF systems is typically between 4 and 12. The energy required for MSF operation is mainly for heating and pumping. Pumping power required for the operation of MSF systems is 2.0 to 3.5 kWh per cubic meter of product water. When source water salinity exceeds 42,000 mg/L such as the Red Sea and Arabian (Persian)Gulf, large MSF systems can produce drinking water very competitively to reverse osmosis desalination plants.

4.3. Multiple Effect Distillation (MED)

In multiple-effect distillation systems, saline source water is typically not heated. Cold source water is sprayed via nozzles or perforated plates over heat exchanger tube bundles. As the feed water sprayed on the tube bundles boils, the vapor generated in the boiling process passes through mist eliminators, which collect brine droplets from the vapor.

The feed water that was converted into vapor in the first stage (effect) is introduced into the heat exchanger tubes of the next effect. Because the next effect is maintained in a slightly lower pressure, although the vapor is a bit cooler, the lower pressure allows it to condense into fresh water at this lower temperature. This process of reducing the ambient pressure in each successive stage allows the feed water to undergo multiple successive boils without introducing new heat.

Steam flowing through the exchanger tubes is condensed into pure desalinated water (see Figure 3) and is collected from each effect. Heating steam (or vapor) introduced in the heat exchanger tubes of the first effect is provided by a steam ejector from an outside source.

Evaporation occurs throughout the vessel and vapor condenses in the upper section of the vessel. Similar to MSF systems, evaporator chambers are equipped with mist eliminators (demister pads) to remove entrained brine droplets. Mist eliminators typically consist of multiple layers of wire mesh.

The MED system shown in Figure 3 is equipped with a brine recycling system. This allows introduction of warmer than ambient water in the first effects of the MED system thereby reducing the volume of feed water collected by the plant intake system and the overall energy needs of the system. A technological enhancement of the conventional MED systems built over the past 20 years is the installation of a thermal vacuum compressor (TVC). The TVC uses steam from the boilers of the collocated power plant to recompress and recycle a portion of the vapor produced from the last effect of the MED unit to the first effect. Such technology enhancement results in significant energy cost savings and therefore, MED-TVC is the most widely applied MED technology alternative today.

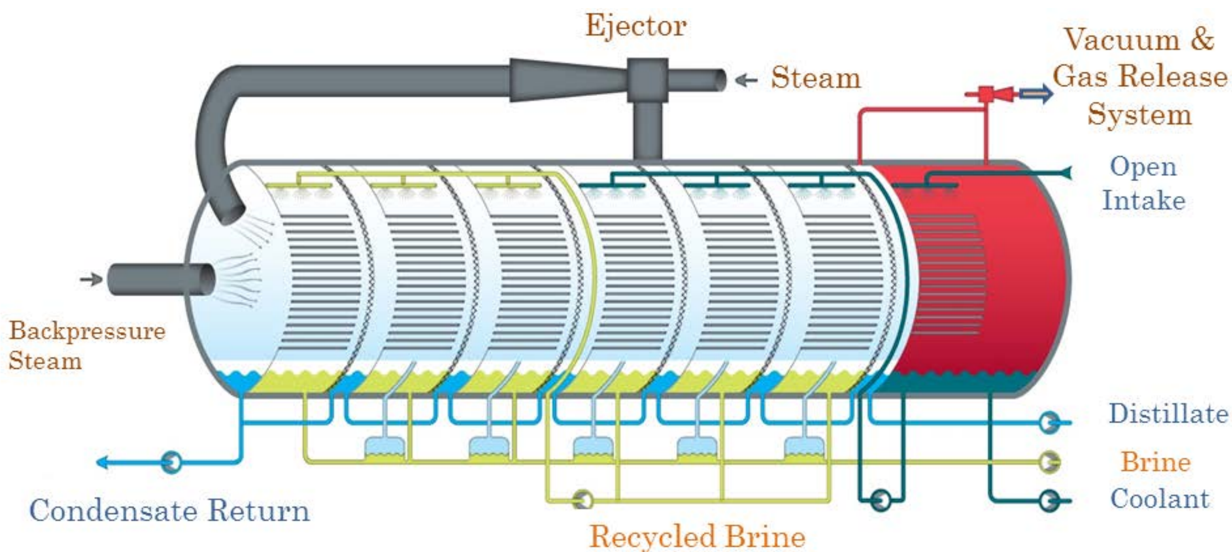


Figure 3: Schematic of MED System

The MED system shells and tube plates are usually made of 316L or duplex stainless steel. Most commonly used materials for the exchanger tubes are aluminum-brass, copper-nickel or titanium. Vane-mist eliminators are made of polypropylene, while wire mesh mist eliminators and the main ejector (vapor-compressor) are fabricated of 316L stainless steel. Cylindrical shells with diameters smaller than 20 ft are predominant.

The main difference between the MED and MSF processes is that while in MSF system vapor is created through flashing, evaporation of feed water in MED is achieved through heat transfer from the steam in the condenser tubes into the source water sprayed on these tubes. This heat transfer at the same time results in condensation of the vapor to fresh water.

MED desalination systems typically operate at lower temperatures than MSF plants (maximum brine concentrate temperature of 62 to 75^{0}C vs. 115^{0}C) and yield higher GORs. The typical GOR for MED systems varies in a range of 3 to 15. The newest MED technologies, which include vertically positioned effects (vertical tube evaporators or VTEs), may yield GOR of up to 24 kilograms of potable water per kilogram of steam.

MSF has certain advantages and disadvantages as compared to MED. For example, the MSF systems have larger heat exchanger surface and more stages, which result in an enhanced plant efficiency, but comes at higher capital costs. In general, MSF installations of the same size have lower GOR. MSF systems also have higher O&M costs due to the higher boiling temperature, which results in higher scaling rates and the need to use more scale inhibiting and corrosion protection chemicals. Based on its existing track record, MSF systems are more reliable, and easier to operate using lower-skilled staff. These reasons often make it more desirable to use thermal desalination technologies despite the slightly (10 to 15%) higher overall water production costs.

Typically, MED systems are more competitive than MSF for plants smaller than 10 MGD. The dominating size of individual units is 0.8 to 1.5 MGD. The largest MED units operating to date are 6 MGD, located in Sharajah, UAE. In the last five years, larger units of up to 10 MGD have also been introduced on the market. The dominating configuration of MED plants has 4 to 20 effects with GOR of 8 to 18.

The GOR of the MED systems depends on whether they use low- or high temperature (LT-MED or HT-MED). The low temperature MED systems usually operate at temperatures below 70^0C (158^0F), and have lower scale formation (thus use less scale inhibiting chemicals) but have lower number of effects and lower GOR – up to 10:1. The high-temperature MED systems operate at temperatures close to 110^0C (230^0F), have more effects and can yield higher GORs - up to 24:1.

At present, the two largest MED-TVC plants in operation are the 210 MGD Al Jubail plant in KSA and the 130 MGD Az Zour North 1 plant in Kuwait. MED technology is very competitive to RO in the case of source seawaters with elevated salinity and which are prone to heavy algal blooms.

The pumping power required for the operation of MED systems is also lower than that typically needed for MSF plants (0.8 to 4 kWh per cubic meter of product water). Therefore, MED is now increasingly gaining ground over MSF desalination, especially in the Middle East where thermal desalination is still the predominant method for potable water production from seawater.

4.4. Vacuum Compression (VC)

The heat source for VC systems is compressed vapor produced by a mechanical compressor or a steam jet ejector rather than a direct exchange of heat from steam (see Figure 4).

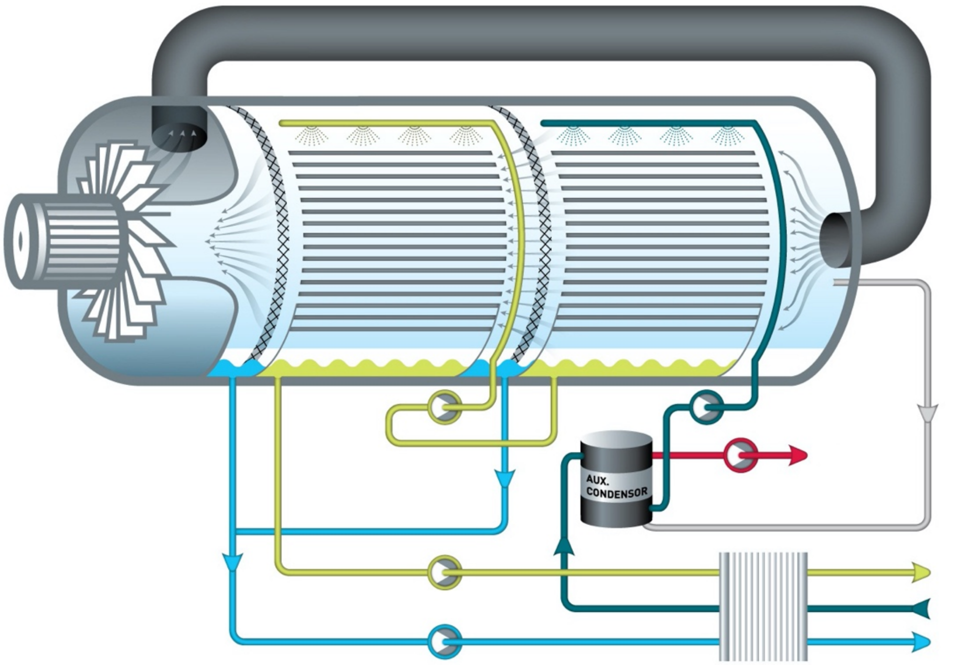


Figure 4 : Schematic of VC System

In VC systems the source water is evaporated and the vapor is conveyed to a compressor. The vapor is then compressed to increase its temperature to a point adequate to evaporate source water sprayed over tube bundles through which the vapor is conveyed. As the compressed vapor exchanges its heat with the new source water, which is being sprayed on the evaporation tubes, it is condensed into pure water. A feed water pre-heater (plate type heat exchanger) is used to start the process and reach evaporation temperature.

VC and MED work based on similar principles. However, while in MED the steam produced by source water evaporation is introduced and condensed in a separate condenser located in the downstream effect, in VC the steam generated from evaporation of new source water sprayed on the outside surface of the pressure exchanger tubes is recycled by the vapor compressor and introduced into the inner side of the of the same pressure exchanger tubes in which it condenses to form distillate. As indicated previously, there are two types of VC units – mechanical (MVC) and thermal (TVC) and they differ by energy source – MVC uses mechanical energy rather than steam. Single-effect MVC systems are the most commonly used in practice at present.

The VC process has found applications mostly for small thermal desalination plants (0.1 to 2 MGD) providing municipal and industrial water supply. VC is also suitable for industrial zero liquid discharge (ZLD) applications where water from cooling towers is fed to the VC units, which are combined with crystallizers.

The largest thermal vacuum compression desalination plant has four 2.4 MGD TVC units and is located in Trapani, Italy. In the US VC technology is not commonly applied for production of desalinated water. The total amount of power required for the operation of mechanical VC systems is typically between 8 to 12 kWh/m^3 (30 to 45 kWh/1,000 gallons) of product water.

5. MEMBRANE DESALINATION

Membrane desalination is a process of separation of minerals from the source water using semi-permeable membranes. Two general types of technologies currently used for membrane desalination are: reverse osmosis and electrodialysis (ED). Reverse osmosis is a process where the product water (permeate) is separated from the salts contained in the source water by pressure-driven transport through a semi-permeable membrane. In ED systems salts are separated from the source water by applying direct current.

5.1. Electrodialysis

In ED-based desalination systems minerals/product water separation is achieved by applying direct electric current (DC) to the source water. This current drives the mineral ions and other ions with strong electric charge contained in the source water through ion-selective membranes to a pair of electrodes of opposite charge (see Figure 5).

As ions accumulate on the surface of the electrodes, they cause fouling over time and have to be cleaned frequently to maintain steady-state ED process. A practical solution to this challenge is to reverse the polarity of the oppositely charged electrodes periodically (typically 2 to 4 times per hour) to avoid frequent electrode cleaning. An ED process, which includes periodic change of the polarity of the system electrodes is referred to as electrodialysis reversal (EDR) process. At present, practically all commercially available ED systems are EDR type.

EDR systems consists of large number (300 to 600 pairs) of cation and anion exchange membranes separated by dilute flow dividers (spacers) to keep them from sticking together and to convey the desalinated flow through and out of the membranes. Each pair of membranes is separated by the two adjacent pairs above and below it, by concentrate spacers which collect, convey and evacuate the salt ions retained between the adjacent membranes (see Figure 6).

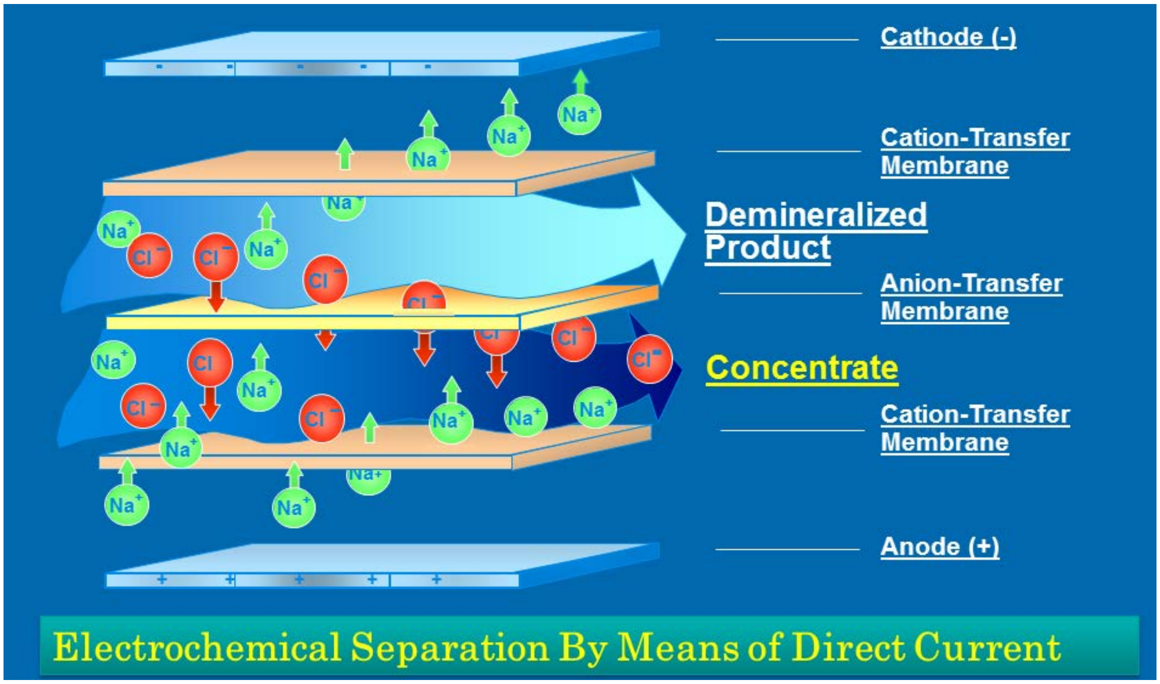


Figure 5: Schematic of Electrodialysis Process

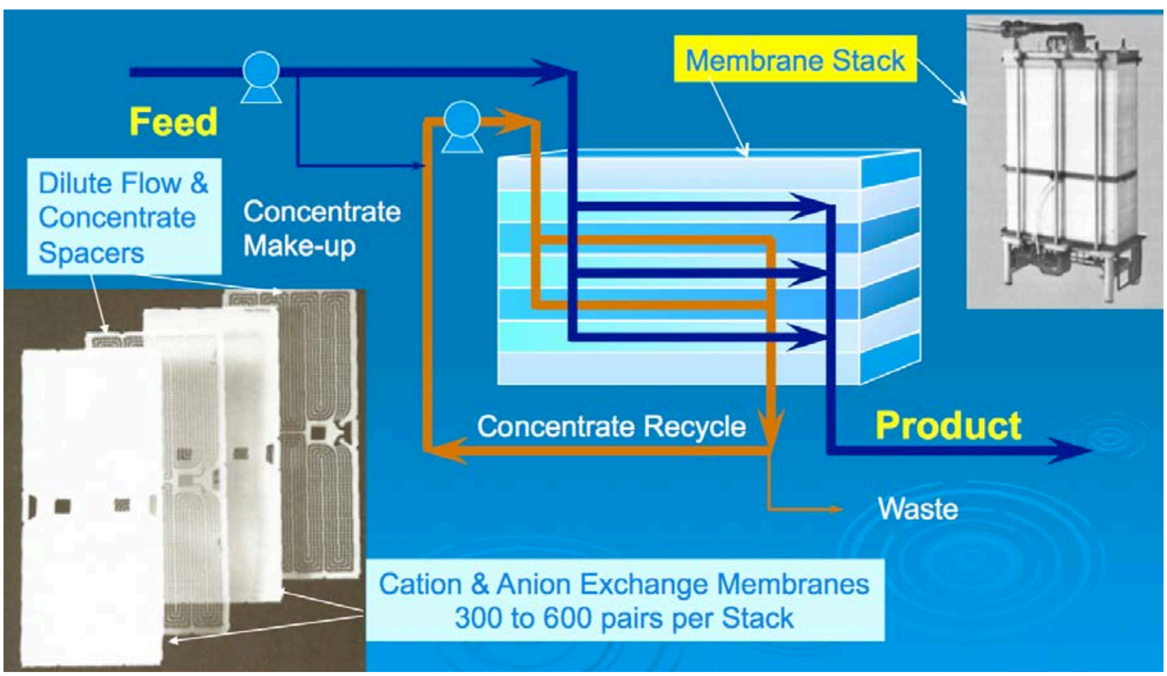


Figure 6: Key Components of EDR Desalination System

The membranes used for ED are different from those applied for RO desalination, having a porous structure similar to that of microfiltration (MF) and ultrafiltration (UF) membranes. RO membranes do not have physical pores. ED membranes are more chlorine and fouling resistant and significantly thicker then RO membranes.

A single set of EDR stacks can only yield approximately 50% of salt removal. As a result, multiple EDR stacks connected in series are often used to meet more stringent product water TDS targets (see Figure 7).

Compared to BRWO membranes which typically have only up to 85 – 90% recovery, EDR systems can reach fresh water recovery of more than 95%. The energy needed for ED desalination is proportional to the amount of salt removed from the source water. TDS concentration and source water quality determine to a great extent which of the two membrane separation technologies will be more suitable and cost-effective for a given application.

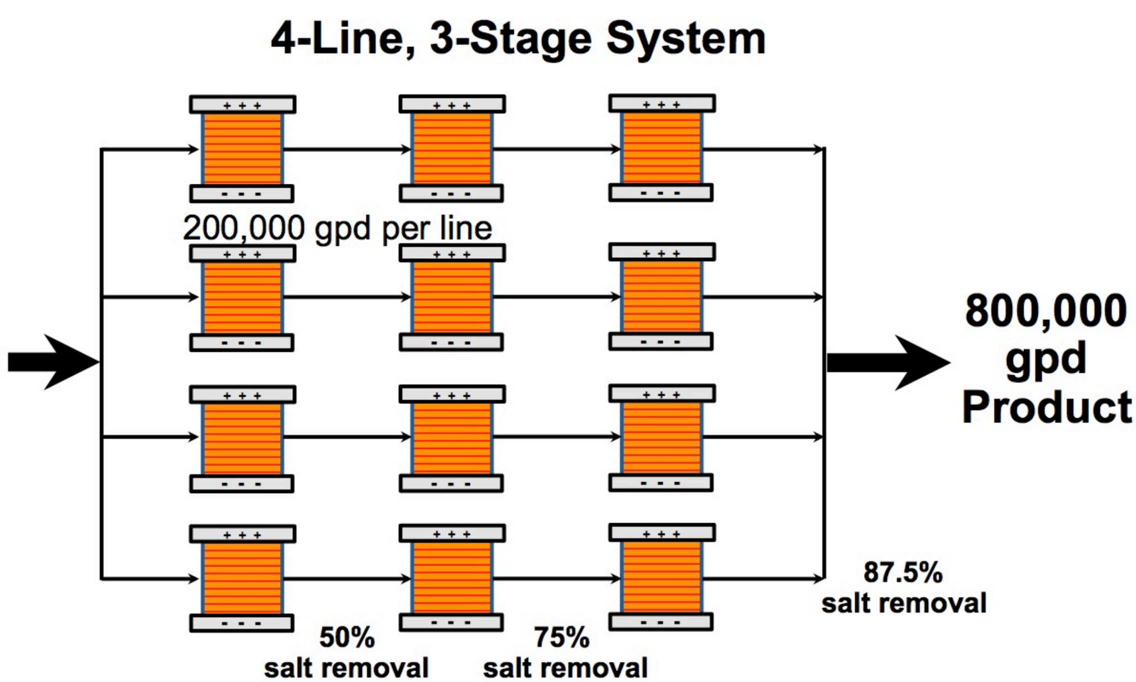


Figure 7: Typical Three-stage EDR System of 0.8 MGD Capacity

ED membrane separation has generally been found to be cost-competitive for source waters of TDS concentration lower than 3,000 mg/L. The threshold is however also a function of the unit cost of electricity and thus varies from project to project.

The TDS removal efficiency of ED desalination systems is not affected by non-ionized compounds or by objects of weak ion charge (including solid particles, organics, and microorganisms). ED membrane desalination processes can thus treat source waters of higher turbidity, biofouling and scaling potential than RO systems. However, the TDS removal efficiency of ED systems is typically lower than that of RO systems (15.0 to 90.0% vs. 99.0 to 99.8%), which is one of the main reasons why they have found practical application mainly for brackish water desalination.

In general, EDR systems can only effectively remove particles that have strong electric charge such as mono- and bivalent salt ions, silica, nitrates, and radium. However, ERD systems have very low removal efficiency in terms of low-charged compounds and particles, such as organics and pathogens. Table 2 provides comparison of the removal efficiency of distillation, EDR and RO systems for source water quality compounds.

Table 2: Contaminant Removal by Alternative Desalination Technologies

Contaminant	Distillation (%)	ED/EDR (%)	RO (%)
TDS	> 99.9	15 - 90	99.0 - 99.8
Pesticides, Organics/VOCs	50 - 90	< 5	5 - 50
Pathogens	> 99	< 5	> 99.99
TOC	> 95	< 20	95 - 98
Radiological	> 99	50 - 90	90 - 99
Nitrate	> 99	60 - 69	90 - 94
Calcium	> 99	45 - 50	95 - 97
Magnesium	> 99	55 - 62	95 - 97
Bicarbonate	> 99	45 - 47	95 - 97
Potassium	> 99	55 - 58	90 - 92

An important observation from Table 2 is that, as compared to distillation and RO separation, EDR desalination only partially removes nutrients from the source water. This explains why EDR is often considered more attractive than RO or thermal desalination, which remove practically all minerals from the source water, if the desalinated water is planned to be used for agricultural purposes, generating fresh and/or reclaimed water for irrigation of agricultural crops.

Construction and equipment costs for brackish water RO (BWRO) and EDR systems of the same fresh water production capacity are usually comparable or EDR is less costly, depending on the RO membrane fouling capacity of the source water. However, since the amount of electricity consumed by EDR systems is directly proportional to source water salinity, at salinities of 2,000 to 3,000 mg/L the energy use of EDR systems usually exceeds that of BWRO or NF systems for source waters. Therefore, EDR systems are not as commonly used RO systems for BWRO desalination and are never applied for SWRO desalination.

Salinity is not the only criterion for evaluation of the cost-competitiveness of EDR and BWRO systems. Often other compounds such as silica play a significant role in the decision making process. Table 3 illustrates some of the reasons why is specific projects EDR was selected instead of RO.

Table 3: Key Reasons for Selection of EDR versus RO for Specific Water Quality Conditions

Project/Application	Capacity	Reasons for Selection of EDR over RO
San Diego North City Water Reclamation Plant, US Irrigation Water	5.5 MGD	• Higher recovery (85% vs 80%) • No pretreatment (10µ cartridge filters only) • 25% lower construction cost
Mason City, Iowa Drinking water – Radium removal	9.5 MGD	• Higher recovery (88% vs 80%) • 12% lower construction costs (86% Radium removal)
Gran Canaria, Spain Drinking water	5.3 MGD	• High level of silica in the feed (70 mg/L vs RO threshold of 20 mg/L)
Barcelona, Spain Drinking water	50 MGD	• High level of silica in the feed (85 mg/L vs RO threshold of 20 mg/L)
Albuquerque, NM, US Drinking water - removal of TDS, As, Fe and Mg	2 MGD	• Higher recovery (92% vs 80%) • High level of silica in the feed
Safaria, Israel Nitrate removal (from 100 mg/L to 46 mg/L NO3	0.6 MGD	• Higher recovery (94% vs 80%) • Adequate Nitrate removal – 54% (<50mg/L)

As seen from Table 3, the main circumstances when EDR was preferred over RO were when:

i. 5 to 15% higher recovery needed to be achieved from the same volume of highly fouling water;
ii. when silica content was quite high – typically saline source waters with silica content over 20 mg/L favor EDR;
iii. when the water contained high levels of radium;

iv. the source water is of relatively low salinity but contains high level of nitrates, and
v. the desalinated water was used for agricultural application (San Diego North City Water Reclamation Plant) and retaining the maximum amount of nutrients was very important for the beneficial use of the treated water.

At the 50 MGD Barcelona desalination facility in Spain (see Figure 8), the use of EDR technology was preferred as compared to BWRO desalination. This is the largest operational EDR plant at present. The brackish surface water source for this plant (the Llobreagat River) contains a very high level of silica which would limit a BWRO plant recovery to only 65%, while an EDR system can achieve 90% recovery. In addition, Llobreagat River was found to have very high organic content, which was projected to cause heavy fouling and operational constraints on a BWRO plant of similar size. The EDR plant has 9 modules with 32 lines per module and reduces salinity by between 75 and 85%.

Figure 8: 50 MGD Barcelona EDR Desalination Plant in Spain

5.2. Reverse Osmosis

Reverse osmosis is a process where water containing inorganic salts (minerals), suspended solids, soluble and insoluble organics, aquatic microorganisms, and dissolved gases (collectively called source water constituents or contaminants) is forced under pressure through a semi-permeable membrane as shown in Figure 9. Semi-permeable refers to a membrane that selectively allows water to pass through at a much higher rate than the transfer rate of any other constituents contained in it.

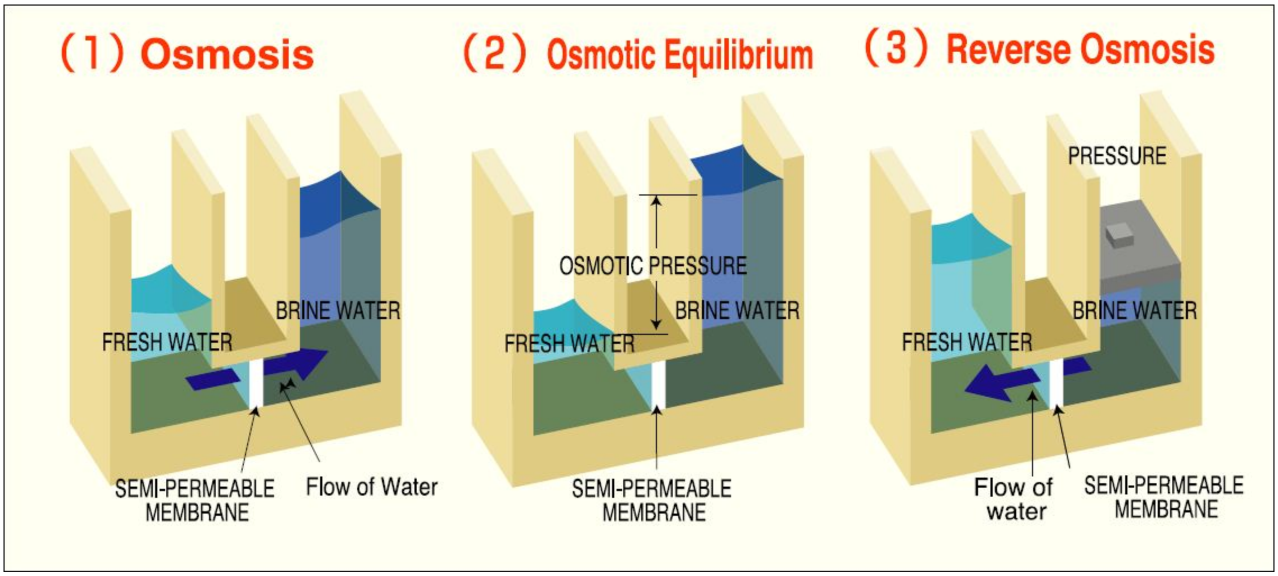


Figure 9: Reverse Osmosis Process

Depending on their size and electric charge, most water constituents are retained (rejected) on the feed side of the RO membrane and the purified water (permeate) passes through the membrane. Figure 10 illustrates the size and type of solids removed by RO membranes as compared to microfiltration (MF) membranes that is used for production of drinking water by treatment of fresh surface water sources such as rivers, lakes and dams.

Reverse osmosis membranes can reject particulate and dissolved solids of practically any size. However, they do not reject gases well due to small molecular size. Usually RO membranes remove over 90% of compounds of weight of 200 Daltons or more. One Dalton (Da) is equal to 666054 x 10^{-24} grams. In terms of physical size, RO membranes can reject solids larger than 1 Angstrom. This means that they can remove practically all suspended solids, protozoa (Giardia and Cryptosporidium), bacteria, viruses, and other human pathogens contained in the source water.

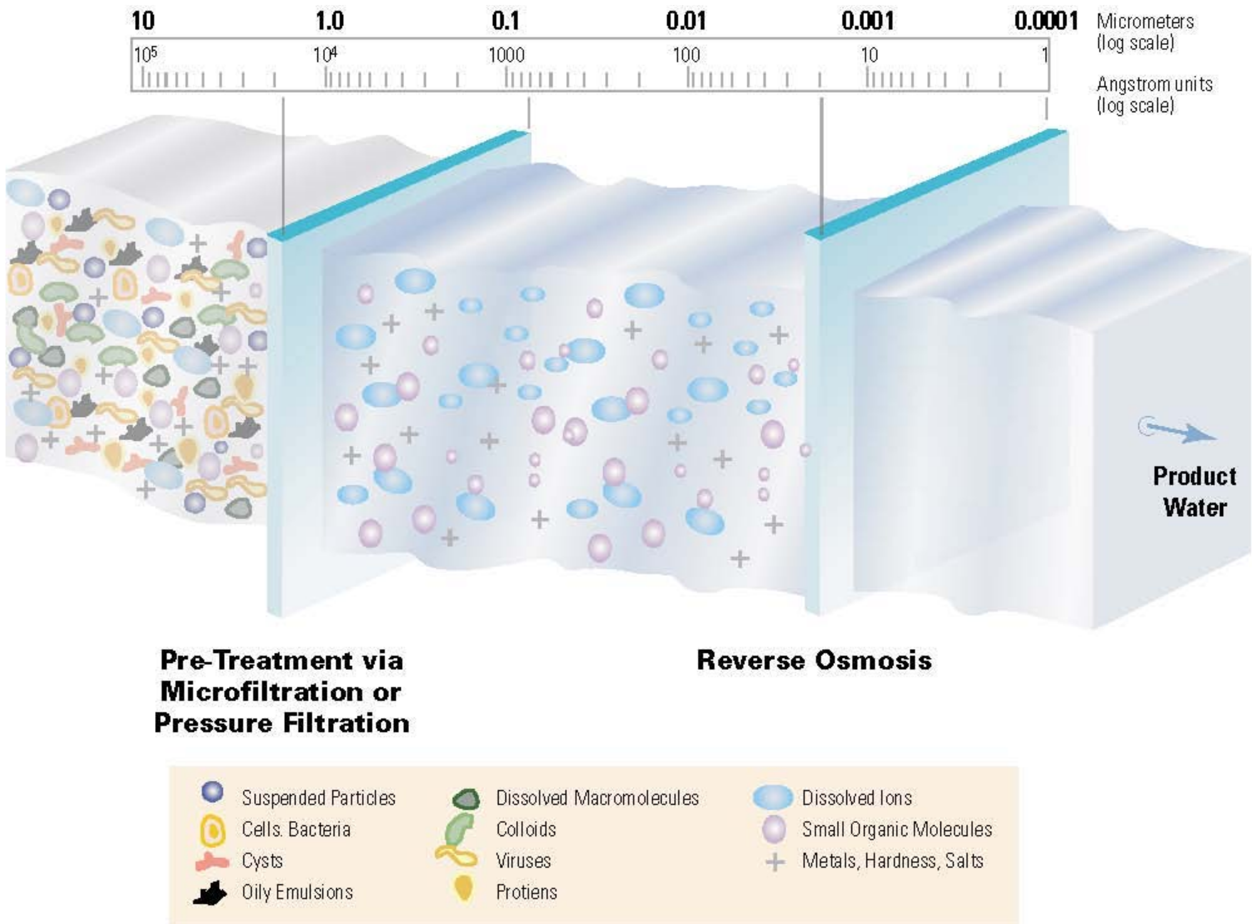


Figure 10: Comparison of Size of Contaminants Removed by MF and RO Membranes

While RO membranes can retain both particular and dissolved solids, they are designed to primarily reject soluble compounds (mineral ions). The RO membrane structure and configuration is such that these membranes cannot store or remove large amounts of suspended solids from their surface. If left in the source water, the solid particulates would accumulate and quickly plug (foul) the surface of the RO membranes, not allowing the membranes to maintain a continuous steady state desalination process. Therefore, the suspended solids (particulates) contained in source water used for desalination have to be removed before they reach the RO membranes.

At present, practically all reverse osmosis (RO) desalination plants, such as that shown on Figure 11, incorporate two main treatment steps designed to sequentially remove suspended and dissolved solids from the source water. The purpose of the first step – source seawater pretreatment - is to remove the suspended solids and to prevent some of the naturally occurring soluble solids from turning into solid form, and precipitating on the RO membranes during the salt separation process. Typically, pretreatment of saline surface source water is accomplished by clarification, using lamella settlers and dissolved air flotation clarifiers (DAFs), and/or granular media or membrane filtration.

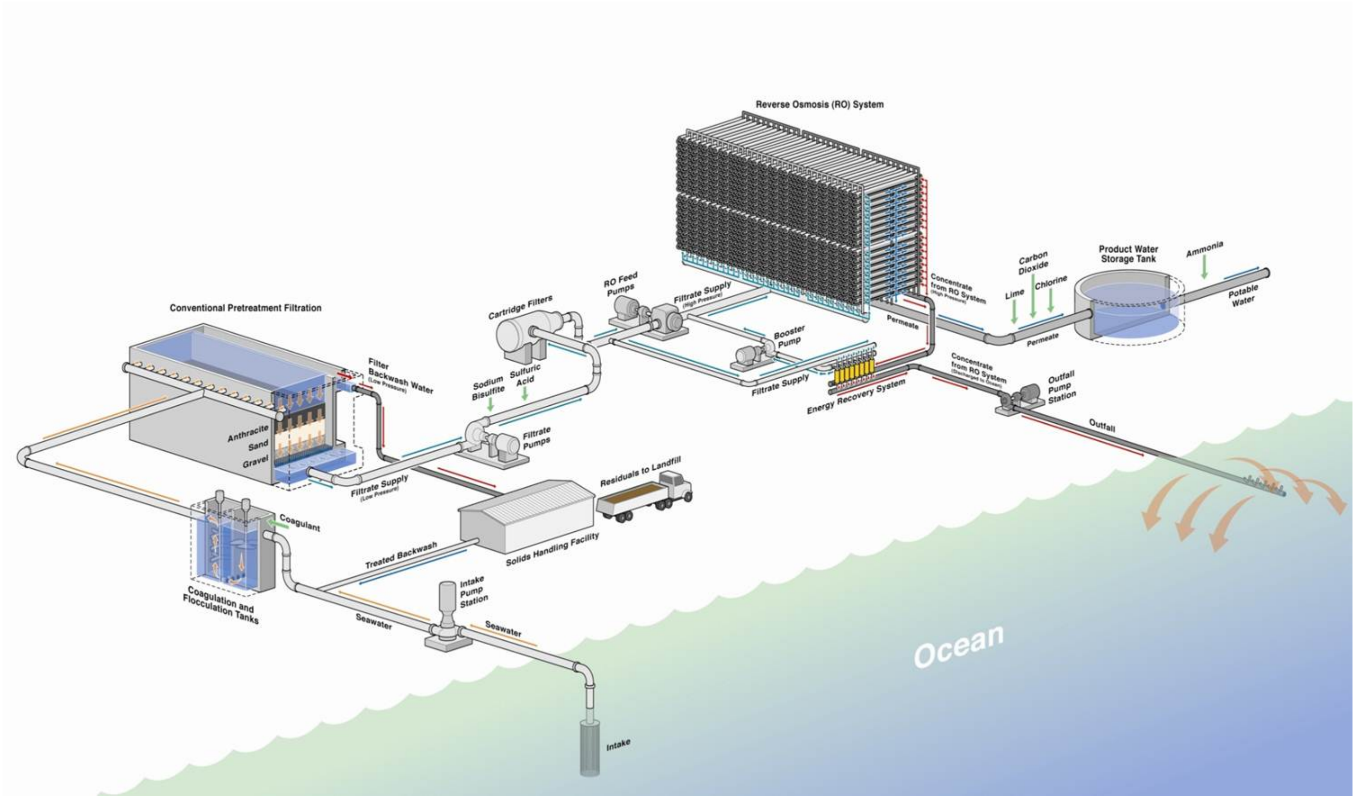


Figure 11: Schematic of Typical Seawater Desalination Plant

The second step, the reverse osmosis (RO) system, separates dissolved solids from the pretreated source water, producing fresh low-salinity water suitable for human consumption, agricultural uses, industrial and other applications. Once the desalination process is complete, the fresh water produced by the RO system is further treated for corrosion and health protection, and disinfected prior to distribution for final use. This third step of the desalination plant treatment process is referred to as post-treatment. Figure 11 presents a general schematic of a seawater desalination plant. The plant shown collects water using open ocean intake, which is conditioned by coagulation and flocculation and filtered by granular media pretreatment filters to remove most particulate and colloidal solids, and some organic and microbiological foulants.

The two man types of pretreatment filtration technologies used for desalination plants are conventional (granular media) filtration and membrane (micro- or ultra) filtration. At present, over 90% of the SWRO desalination plants employ granular media (anthracite & sand) filtration. Membrane pretreatment is however gaining wider acceptance.

Practical experience to date shows, counterintuitively, that membrane pretreatment typically increases the cleaning frequency of the downstream RO membranes and does not extend the useful life of the RO membranes when compared to granular media filtration. Quite the opposite, during algal blooms membrane pretreatment may cause a higher rate of SWRO membrane biofouling compared to gravity granular media filters. This is due to pressurization of the filtered water in the membrane pretreatment process accelerating the breakage of the algal cells contained in the source seawater, which release easily biodegradable substances that accelerate bacterial growth on the RO membrane surface.

The filtered water produced by the pretreatment system is conveyed via transfer pumps through 5 to 20 micron-size filters (referenced on Figure 8 as cartridge filters) into the suction headers of high-pressure pumps. These pumps deliver the filtered water into the RO membrane vessels at net driving pressure adequate to produce the target desalinated water flow and quality.

The reverse osmosis vessels are assembled in individual sets of independently operating units referred to as RO trains or racks. All RO trains collectively are termed a reverse osmosis system. The RO system usually has energy recovery equipment, which allows reusing the energy contained in the concentrate for pumping of new source water into the membrane system.

The permeate generated by the RO trains is stabilized by addition of lime and carbon dioxide to provide an adequate level of alkalinity and hardness for protection of the product water delivery and distribution system against corrosion. The conditioned water is stored and disinfected prior to delivery to the final users.

The particulate solids removed from the source water by the pretreatment filters are collected in the filter backwash and further concentrated by thickening and dewatering for ultimate offsite disposal to sanitary landfill. While this solids handling approach is adopted by many of the more recently built desalination plants, in some older facilities the concentrate and backwash water are mixed and disposed of to the water body used for source water collection. Most existing seawater desalination plants at present have a general configuration similar to that shown on Figure 12.

Figure 12 depicts typical configuration of RO desalination system.

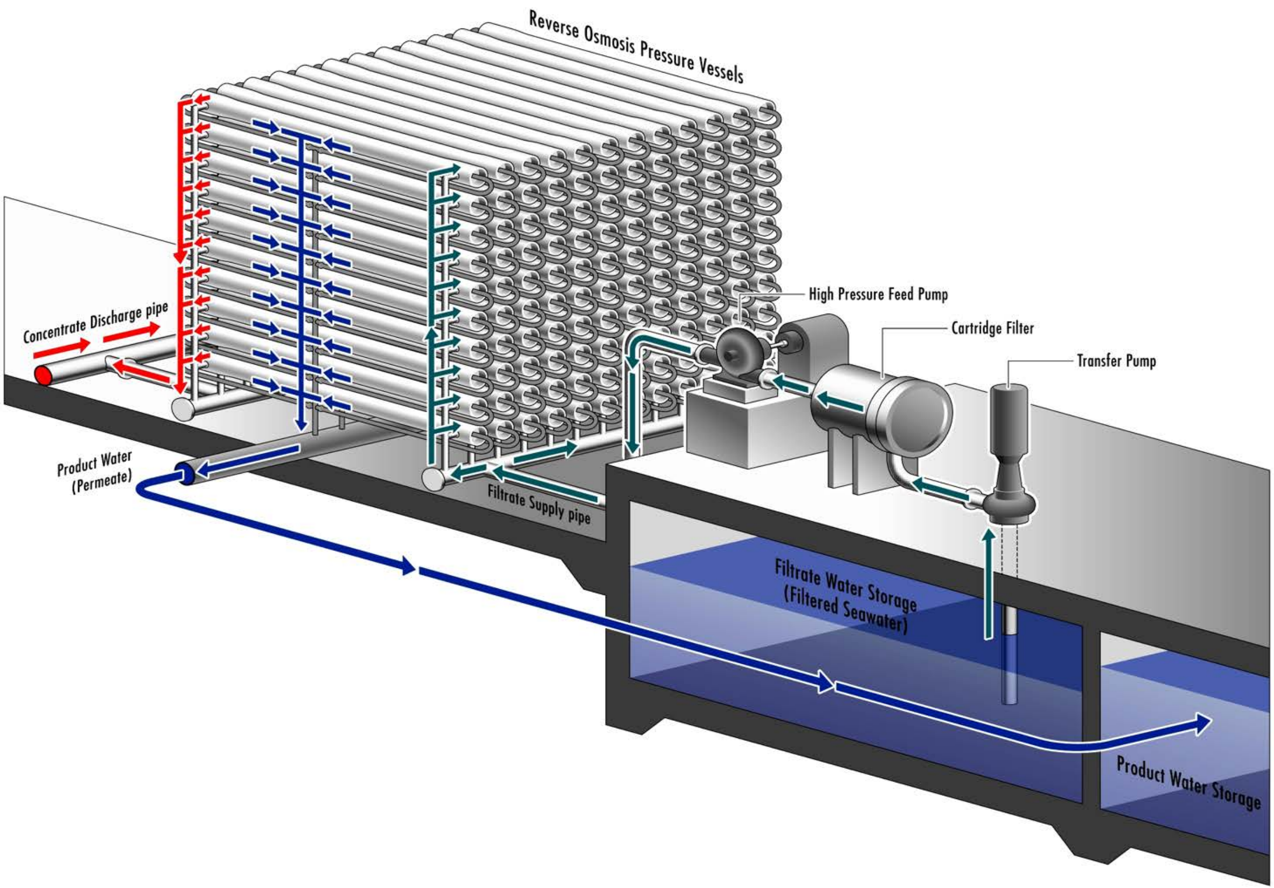


Figure 12: Typical Configuration of SWRO Desalination System

Filtered water, which is produced by the desalination plant's pretreatment system is conveyed by transfer pumps from a filtrate water storage tank through cartridge filters and into the suction pipe of the high pressure RO feed pumps.

The main purpose of the cartridge filters is to protect the RO membranes from damage. Cartridge filters are usually used for desalination plants with granular media filtration systems only. Pretreatment systems employing microfiltration (MF) or ultrafiltration (UF) membranes typically do not have cartridge filters.

The high pressure feed pumps are designed to deliver the pretreated water to the RO membranes at pressure required for membrane separation of the fresh water from the salts, typically between 55 to 80 bars. The actual required feed pressure is site-specific and mainly determined by the source water salinity, temperature, permeability of the RO membranes and the configuration of the RO system. The RO membrane elements are installed in pressure vessels, which usually house six to eight elements per vessel (see Figure 13).

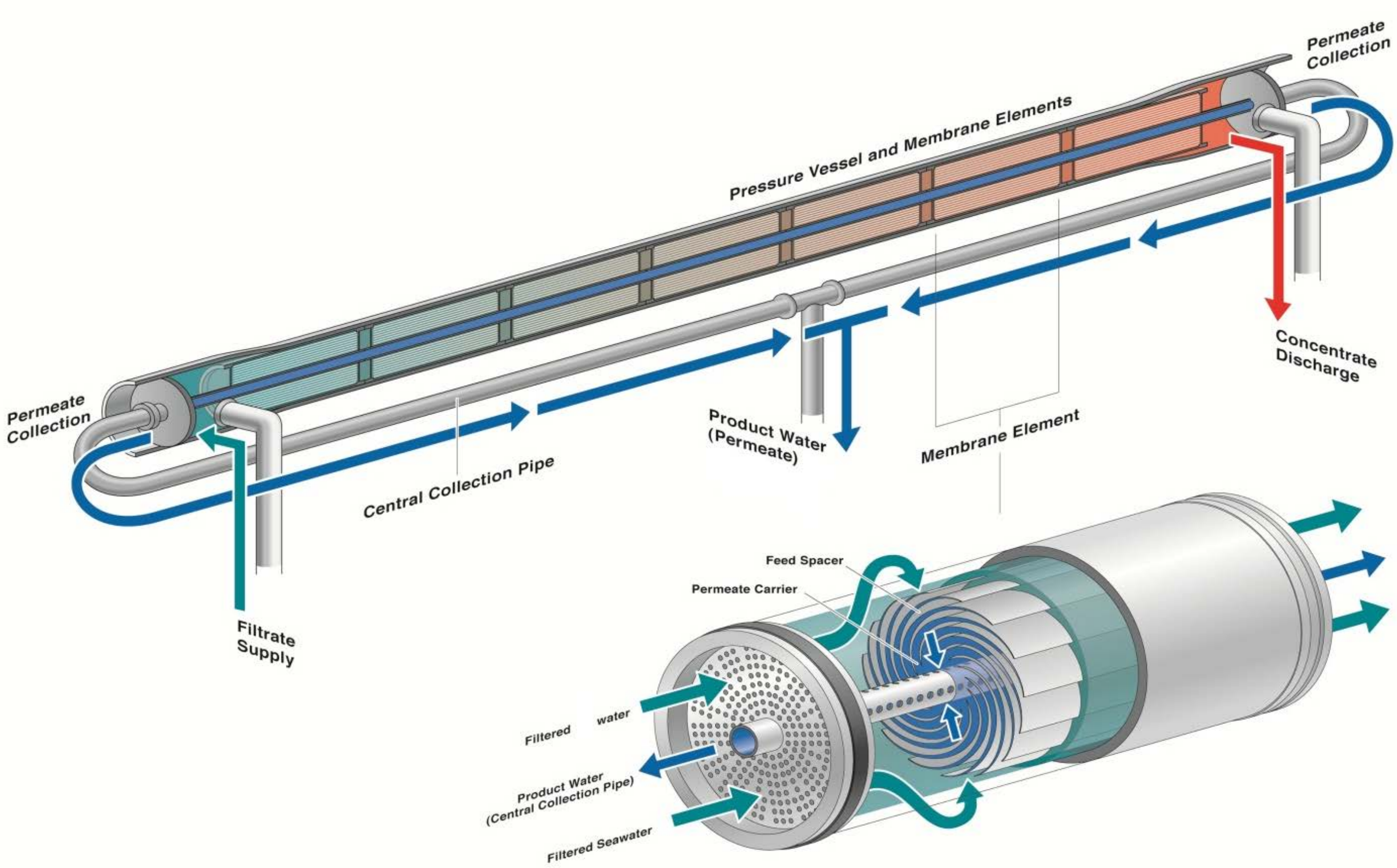


Figure 13: Typical Configuration of Spiral-wound RO Membrane and Pressure Vessel

Multiple pressure vessels are arranged on support structures (racks), which form RO trains. Each RO train is typically designed to produce between 10 and 20% of the total amount of the membrane desalination product water flow.

Commercially available membrane RO elements are of standardized diameters and length, and salt rejection efficiency. Standard RO membrane elements have limitations with respect to a number of performance parameters such as: feed water temperature (45^0 C); pH (minimum of 2 and maximum of 12); silt density index (less than 4); chlorine content (not tolerant to chlorine in measurable amounts); and feed water pressure (maximum of 83 bars). Some producers offer 16- and 18-inch spiral-wound SWRO and BWRO membrane elements but they have found very limited application in large-scale installations due to their relatively higher costs.

The ratio between the volume of the product water produced by the membrane desalination system and the volume of the source water used for its production is commonly defined as recovery in percentage of the plant RO system feed water volume. The maximum recovery that can be achieved by a given pressure-driven membrane desalination system mainly depends on the source water salinity. It is limited by the magnitude of the osmotic pressure to be overcome by the RO system high-pressure feed pumps, and by the fouling and scaling potential of the source seawater.

The higher the salinity and fouling potential of the saline source water, the lower the target design RO system recovery should be. For example, lower salinity of the Pacific Ocean (33 to 35 ppt) allows the SWRO systems to be designed for recovery of 50%, as long as the seawater has relatively low fouling potential. In contrast, the Red Sea and Arabian (Persian) Gulf have salinities of 42 to 46 ppt, with sustainable design SWRO system recovery of 40 to 45%. For desalination plants in the Middle East exposed to severe algal blooms, the sustainable design recovery is even lower at 36 to 38%. Higher recoveries of 40 to 45% could be achieved here if the desalination plant is equipped with more robust pretreatment.

RO membrane scaling occurs when the minerals left behind on the rejection side of the membrane are concentrated to a level at which they begin to precipitate. The precipitates or crystalline compounds in turn plug the membrane surface and interfere with fresh water transport through the membrane. Typically, seawater desalination plants can only turn between 40 and 60% of the source water into low-salinity permeate.

Membrane performance tends to naturally deteriorate over time due to the combination of material wear-and-tear and irreversible fouling of the membrane elements. Typically membrane elements have to be replaced every five to seven years to maintain their performance in terms of water quality and power demand for salt separation.

Improvements of membrane element polymer chemistry and production process have made membranes more durable and have extended their useful life. Use of conservatively designed dual or tri-media granular filtration systems and MF or UF-filtration pretreatment prior to RO desalination allows extension the membrane useful life beyond seven years. On the other hand, practical experience shows that MF and UF membrane pretreatment systems designed for very high fluxes (80 lmh or more) usually result in accelerated aging of the downstream SWRO membrane elements and reduction in useful life below three years.

The three largest SWRO desalination plants in the world are the 140 MGD plant in Sorek, Israel, the 130 MGD Magtaa plant in Algeria and the 110 MGD Victoria plant in Australia. The two largest SWRO desalination plants in operation in the US are the 50 MGD Carlsbad SWRO plant in California and the 25 MGD Tampa Bay plant in Florida. The largest BWRO desalination plants in the US are the 72 MGD Yuma Desalting Plant in Arizona, the 70 MGD Boca Raton water treatment plant in Florida and the 27.5 MGD Kay Bailey Hutchinson Plant in El Paso, Texas.

6. HYBRID DESALINATION

Hybrid desalination plants incorporate a combination of a thermal (MSF or MED) and a SWRO desalination system, co-located with a power generation station sharing common intake and outfall. Such plants have been in use for over 20 years in the Middle East. Depending on the site-specific local power and water demand and project size, can be more cost competitive than stand-alone thermal or SWRO plants. This is due to a more energy efficient configuration, economy of scale from use of joint intake and outfall facilities, and lower energy consumption of the RO system. Warm cooling water from the thermal desalination plant results in a lower RO energy requirement.

While the construction of combined power generation, thermal and SWRO desalination plants (hybrid plants) have yielded some of the lowest desalinated water production costs, these plants have not found widespread use. In many locations the demand for power and water differ significantly due to existing capacity from large electrical power generation and/or desalination plants.

Combining power and water generation in one hybrid plant in such locations may not always be suitable to address local demands due to the generated surplus of water or power. On the other hand, building conveyance infrastructure to transport surplus power and/or water over long distances to meet demand elsewhere often nullifies the savings from hybrid production of power and water.

Hybrid plants have thus found application mainly in locations with limited existing generation capacity for both water and power, and large, new future demand for both. This is typical in new industrial development zones. The two largest hybrid plants in the world are the 274 MGD Ras

Al-Khair plant in KSA (192 MGD of MSF/82 MGD of SWRO) and the 160 MGD Fujairah II desalination plant in UAE (120 MGD of MED/40 MGD of SWRO). Both of these plants are located in large industrial development zones.

7. COMPARISON OF ALTERNATIVE DESALINATION TECHNOLOGIES

Over the past 20 years, RO membrane separation has evolved more rapidly than any other desalination technology, mainly due to competitive energy consumption and lower water production costs. The energy and cost analysis presented in Table 4 indicates that the all-inclusive energy consumption for fresh water production of thermal desalination plants is typically over double that of brackish and seawater desalination.

Table 4: Energy and Water Production Costs for Alternative Desalination Technologies

PROCESS/ ENERGY TYPE	MED	MSF	VC	BWRO	SWRO
Steam Pressure (atm)	0.2 - 0.4	2.5 - 3.5	Not Needed	Not Needed	Not Needed
Electric Energy Equivalent:					
kWh/m³	4.5 - 6.0	9.5 - 10	NA	NA	NA
kWh/1,000 gal	17.0 - 22.7	35.9 - 46			
Electricity Consumption:					
kWh/m³	2 - 8	3.2 - 4	8 -12	0.3 - 2.8	2.5 - 4
kWh/1,000 gal	4.5 - 6.8	12.1 - 15.1	30.3 - 45.4	1 - 10.6	9.5 - 15.1
Total Energy Use:					
kWh/m³	5.7 - 7.8	12.7 - 15	8 - 12	0.3 - 2.8	2.5 - 4
kWh/1,000 gal	25 - 29.5	48 - 56.7	30.3 - 45.4	1 - 10.6	9.5 - 15.1
Water Production Costs:					
US$/$m^3$	0.7 - 3.5	0.9 – 4.0	1.0 - 3.5	0.2 – 1.2	0.5 – 3.0
US$/1,000 gal	2.6 - 13.2	3.4 - 15.1	3.8 - 13.2	0.8 – 4.5	1.9 – 11.4

Note: NA – Not applicable.

BWRO desalination yields the lowest overall production costs as compared to all other desalination technologies. Note that MED projects built recently have been completed at costs comparable to similarly sized SWRO plants. However, for the majority of medium and large projects, SWRO desalination is more cost competitive than thermal desalination technologies.

Generation of a waste steam of large-enough quantity to run large and mega-size thermal evaporation systems which are cost competitive to SWRO is found feasible mainly in the Middle East. The demand for electricity per capita (and therefore the amount of waste heat generated from production of electricity per capita) in this region is typically an order of magnitude higher than that in the rest of the world. Most of the world do not generate as much waste heat to satisfy their demand for electricity, and thermal evaporation technologies have never gained nor are likely to gain worldwide application for large desalination projects in future. In the past, such type of technologies have found limited use for small and medium size municipal plants on remote islands of the Caribbean, Canary Islands and other parts of the world where power generation is dependent on fossil fuels, such as diesel oil.

Table 5 presents costs for the most common types of desalination technologies for different seawater sources for relatively new desalination plants.

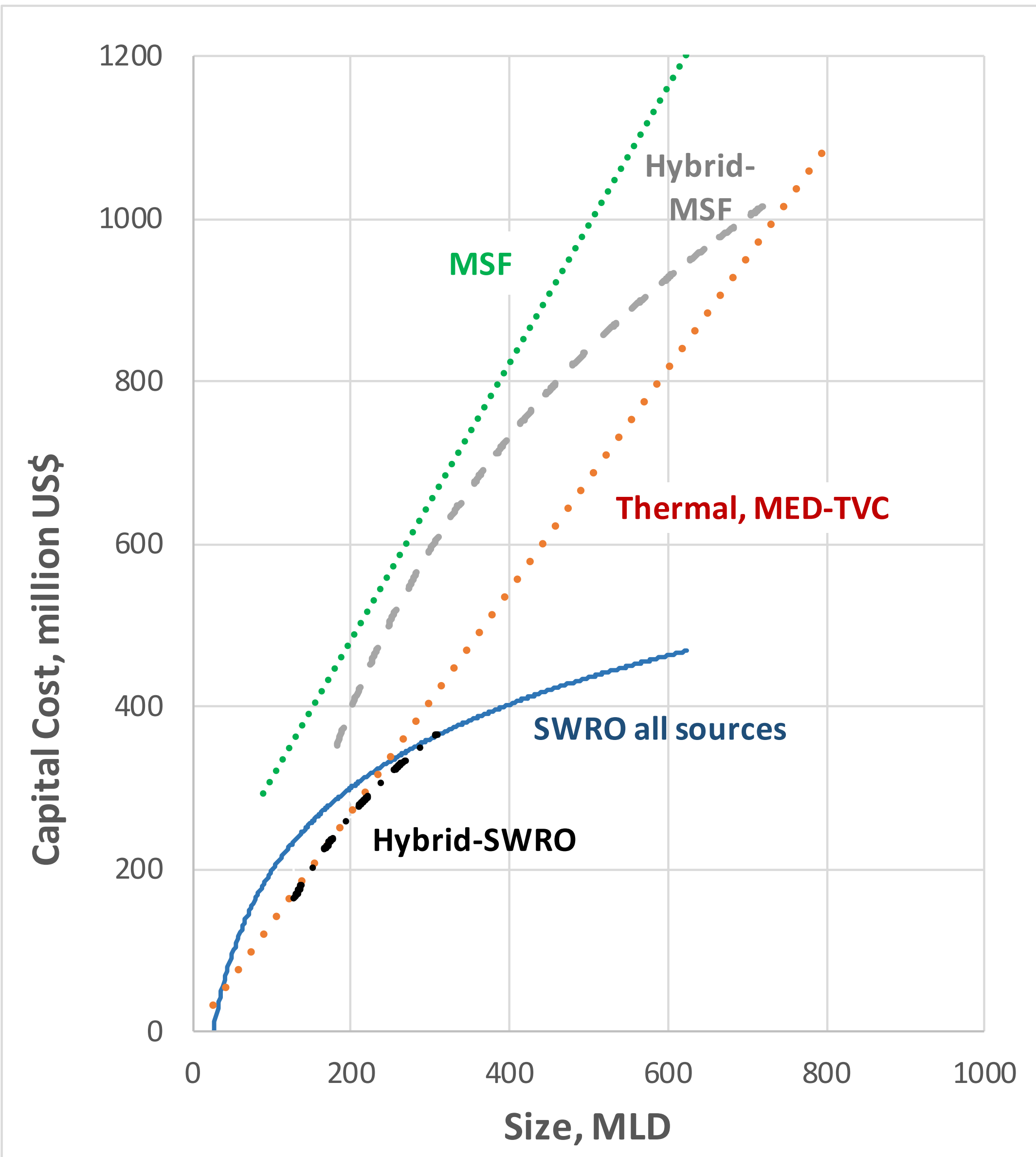
Table 5: Desalination Costs for Different Technologies and Seawater Sources

Desalination Plant Type	**Capital Costs (Million US$/MLD)**		**O&M Costs (US$/m^3)**		**Cost of Water Production (US/$m^3)**	
	Range	Average	Range	Average	Range	Average
MSF	1.7 – 3.1	2.1	0.22 – 0.30	0.26	1.02 – 1.74	1.44
MED-TVC	1.2 – 2.3	1.4	0.11 – 0.25	0.14	1.12 – 1.50	1.39
SWRO Pacific and Atlantic Oceans	1.1 – 6.3	1.4	0.20 – 0.85	0.38	0.50 – 3.0	1.25
SWRO Mediterranean Sea	0.8 – 2.2	1.2	0.25 – 0.74	0.35	0.64 – 1.62	0.98
SWRO Arabian (Persian) Gulf	1.2 – 1.8	1.5	0.36 – 1.01	0.64	0.96 – 1.92	1.35
SWRO Red Sea	1.2 – 2.3	1.5	0.41 – 0.96	0.51	1.14 – 1.70	1.38
Hybrid – MSF/MED	1.5 – 2.2	1.8	0.14 – 0.25	0.23	0.95 – 1.37	1.15
Hybrid – SWRO	1.2 – 2.4	1.3	0.29 – 0.44	0.35	0.85 – 1.12	1.03

Note: 1 MLD = 0.264 MGD; 1 US$/m^3 = 3.785 US$/1,000 gallons

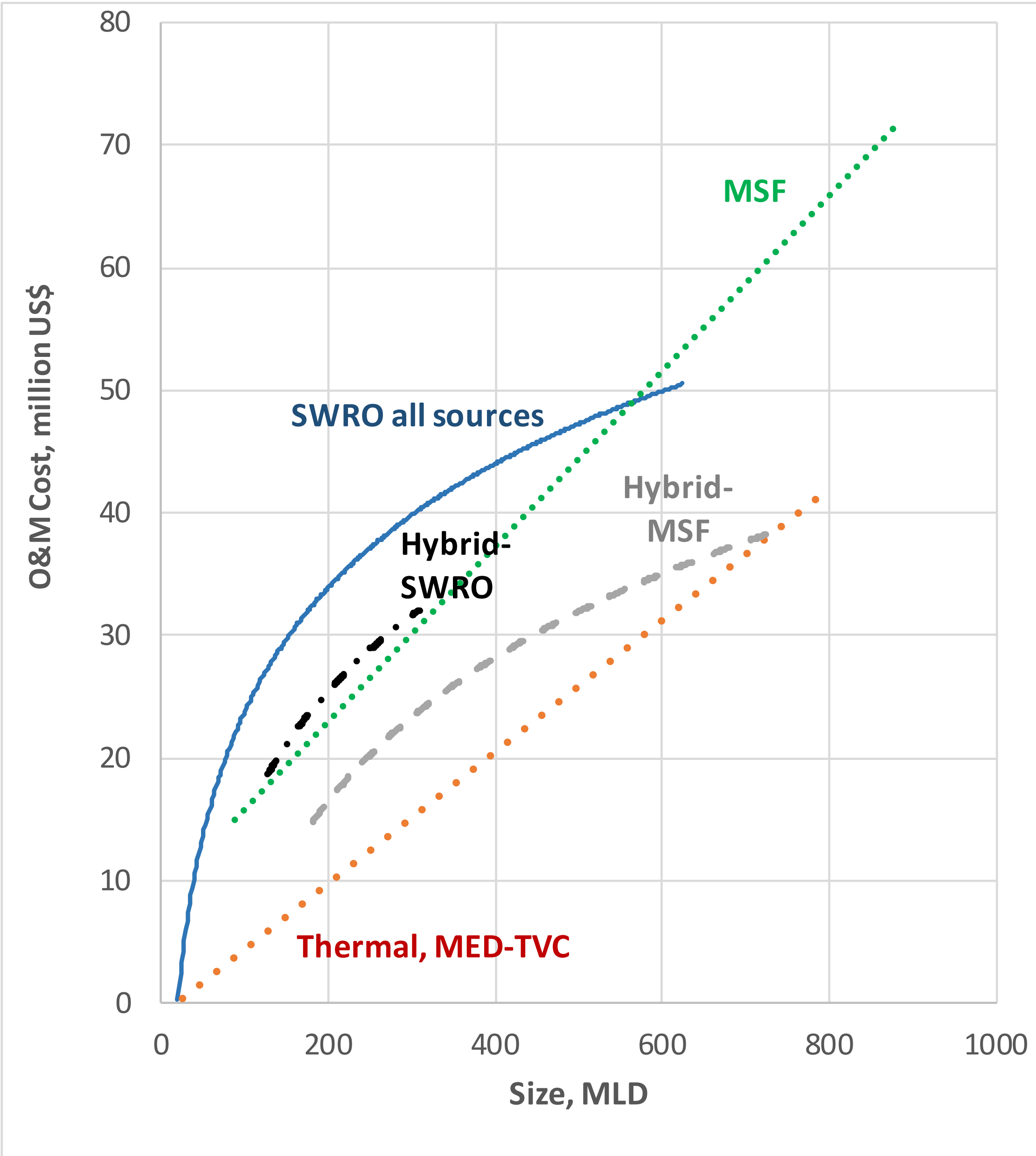
The cost of water production by thermal desalination (MSF, MED) is not sensitive to source water quality, which makes these technologies competitive in the Arabian (Persian) Gulf and the Red Sea.

Figures 14 through 16 present the capital, O&M and water production costs for various technologies as a function of desalination plant capacity. The desalination technologies plotted are thermal evaporation, reverse osmosis separation and hybrid desalination. The figures include summary graphs depicting project capital costs, O&M costs and the costs of fresh water production as a function of plant size and source water quality.



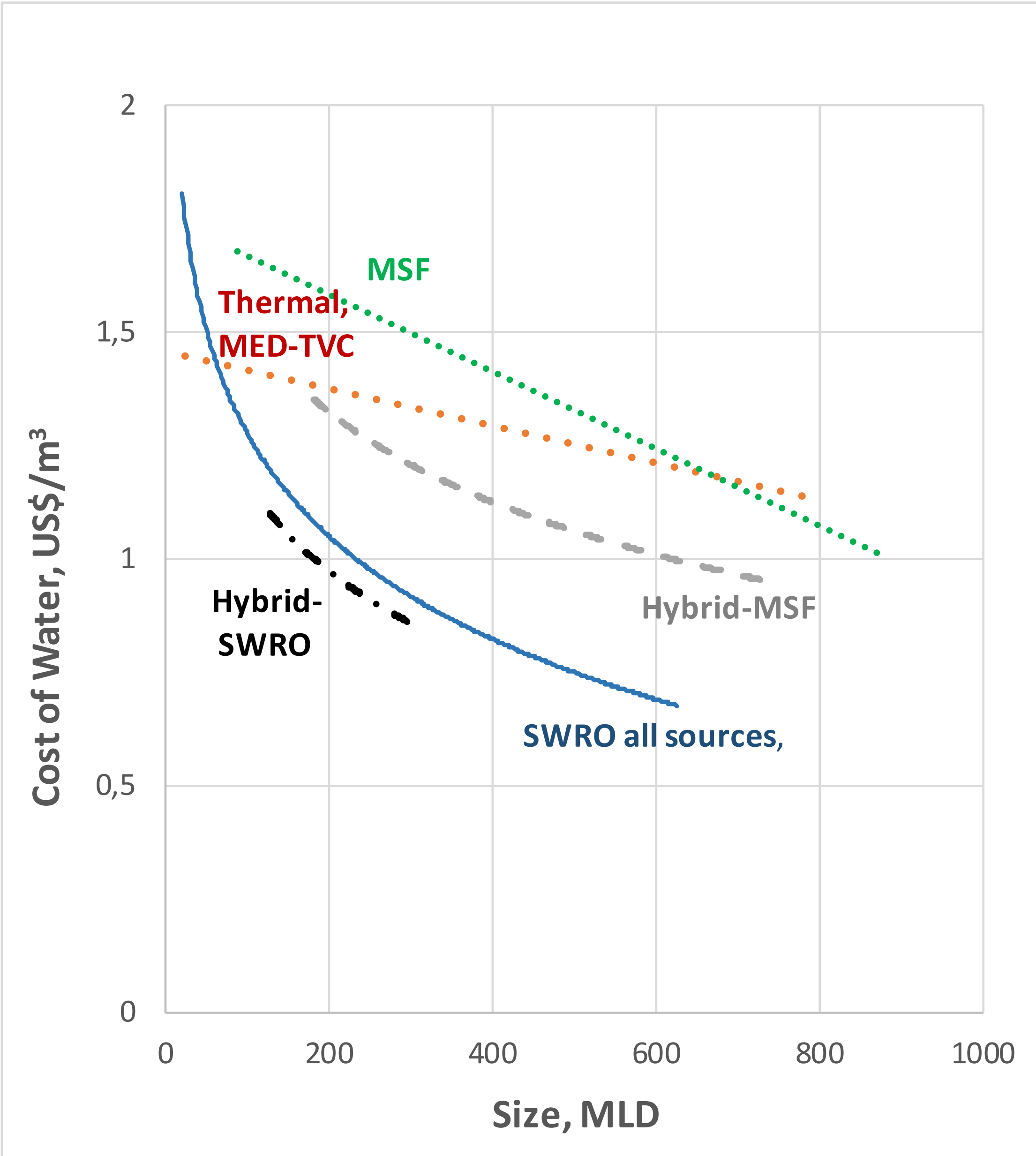
Note: 1 MLD = 0.264 MGD

Figure 14: Capital Costs of Seawater Desalination Plants



Note: 1 MLD = 0.264 MGD

Figure 15: Annual O&M Costs of Seawater Desalination Plants



Note: 1 MLD = 0.264 MGD; 1 US$/$m^3$ = 3.785 US$/1,000 gallons

Figure 16: Seawater Desalination Plants – Costs of Water Production

The capital costs are expressed in US$ per million liters per day (1 MLD = 0.264 MGD). The annual operation and maintenance costs are expressed in US$/$m^3$ (1 US$/$m^3$ = 3.785 US$/1,000 gallons of desalinated water). The cost of water production is the all-inclusive cost for producing fresh water from seawater, and is calculated by dividing the sum of the total annual O&M cost and the annualized capital cost by the annual volume of fresh water produced.

The SWRO cost curves presented in Figures 14 through 16 are derived based on the analysis of actual data from more than 50 SWRO desalination plants worldwide built since 2000. Figure 14 shows that thermal and SWRO desalination plants follow different patterns in terms of economy of scale. Two important features of the cost curves are evident: the steeper the curve, the higher the economy of scale, and a straight line means that the economy of scale is steady over the entire plant capacity range shown on the graph, while a curved line means that the economy of scale changes with capacity. The capital cost–capacity relationship for thermal desalination plants is a straight-line for all sizes of desalination plants, while the SWRO plants have curvilinear relationship between capacity and costs.

For up to approximately 25 MGD, the SWRO desalination curve is the steepest, which indicates that for small and medium size desalination plants, SWRO technology yields the highest economy of scale as compared to all other thermal desalination technologies. However, beyond 26 MGD, the economy of scale for SWRO desalination plants decreases significantly and tends to be the lowest. Extrapolated, the cost curve tends to flatten beyond 100 MGD.

The difference in the economies of scale of thermal and SWRO desalination plants is the result of SWRO plants consisting of smaller individual modular units. All plants use 8-inch SWRO elements and the largest SWRO plant production unit used at present has a capacity of 8 MGD.

The practical inability to distribute flow evenly to all of the SWRO trains reduces the theoretical maximum number of individual trains to 16, and therefore the maximum production size of an individual SWRO facility is 8 MGD x 16 trains = 128 MGD (484,480 m^3/day). Bigger SWRO plants are usually designed as multiples of 26 MGD (100 MLD), 53 MGD (200 MLD) or 78 MGD (300 MLD) facilities.

Another practical constraint in the individual unit size of the SWRO systems is that the time needed for cleaning of larger trains and associated production capacity downtime doubles for larger trains. Fresh water production capacity of SWRO trains is often limited to 2.5 MGD for this reason.

With existing technology, plants are practically designed and constructed as multiples of 25 MGD (100 MLD) or 106 MGD (400 MLD). The capital cost curve for SWRO plants shown in Figure 14 is reflective of these practical limitations of existing SWRO desalination technology – up to 26

MGD (100 MLD), this economy-of-scale curve is steeper than that of thermal desalination plants; between 26 and 106 MGD (100 and 400 MLD) however, the rate of economy of scale diminishes significantly, and above 106 MG (400 MLD), the SWRO capital cost curve nearly flattens.

For comparison, MSF and MED technologies, which are much more mature than SWRO have a great variety of sizes of units available on the market which have evolved and have been optimized over the last 50 years. This allows the same economy of scale to be maintained in practically all unit sizes, hence the straight-line nature of the cost-size relationship for these technologies.

Thermal desalination units have advantages over SWRO in that they do not require frequent cleaning which involves taking individual thermal units out for cleaning, and do no rely on only one standard unit of limited production as a building block for all sizes of plants.

Individual standard size thermal desalination units are available in practically all sizes – from 0.025 to 5.3 MGD (0.1 MLD to over 20 MLD), which allows preserving the benefit of high economy of scale for practically all sizes of thermal desalination units.

Similar trends are observed for SWRO plant O&M costs and the overall costs of water production. For both annual O&M costs and costs of water production, the economy of scale rate is the highest for plant capacities of up to 26-40 MGD (100 – 150 MLD) after which it is reduced and is lower than that associated with thermal desalination technologies.

MSF offers slightly better but fairly comparable economy of scale benefits to MED for all sizes of thermal desalination plants, which is reflective of MSF being the older and more mature technology than MED, which offers a wider range of individual unit sizes. The difference is not that significant as MED technology has experienced a higher rate of advancement in recent years. MED systems of comparable size to MSF units have recently become commercially available.

Figures 17 through 20 show the magnitude of the main capital and O&M cost components of thermal and SWRO desalination plants under average project conditions. As seen on Figure 19, thermal energy is a significant portion of the O&M cost of thermal desalination plants and this energy is typically included in the plant O&M Costs.

For most thermal desalination plants, the thermal energy (steam) and electricity are purchased by the operator of the desalination plant or the plant owner from the owner of the power generation plant with which the desalination plant is collocated or from the local or state-wide utility responsible for power and/or steam supply.

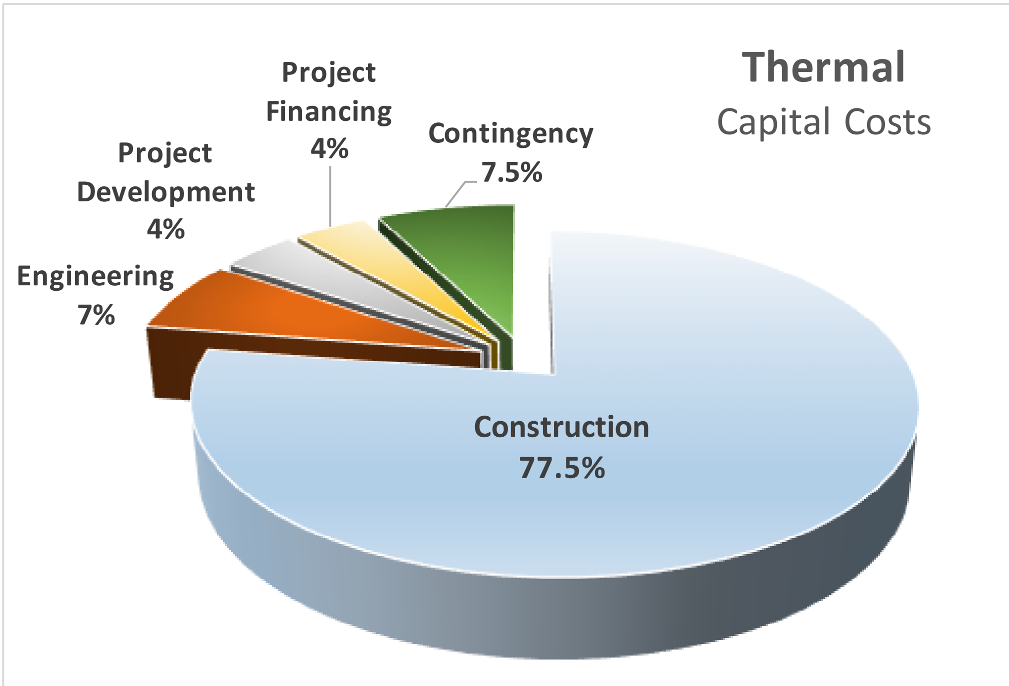


Figure 17: Capital Cost Breakdown for Thermal Desalination Plants

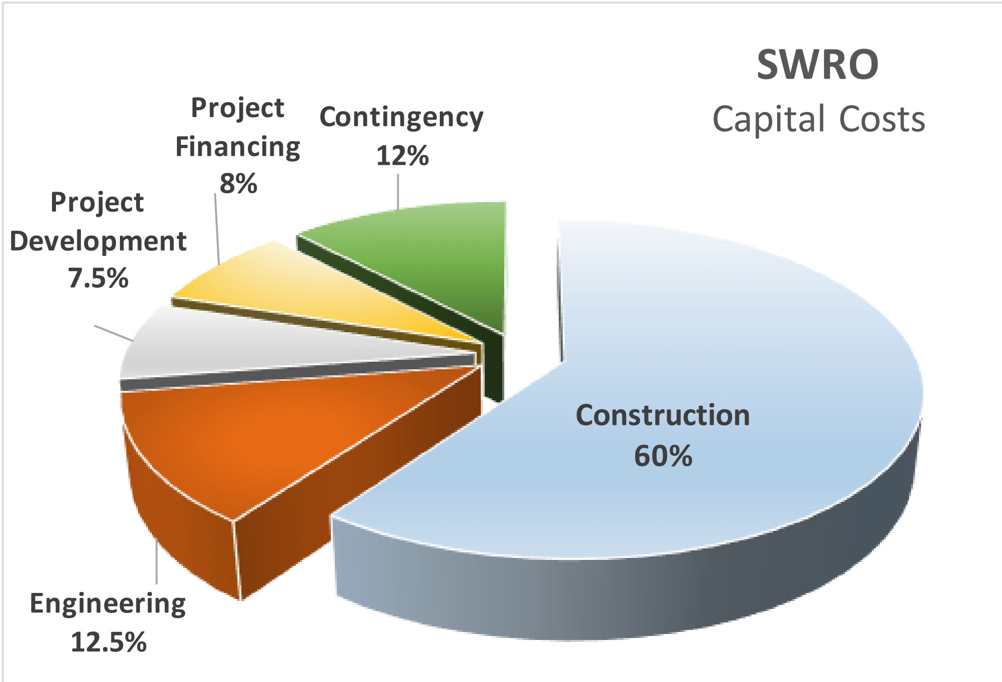


Figure 18: Capital Cost Breakdown for SWRO Desalination Plants

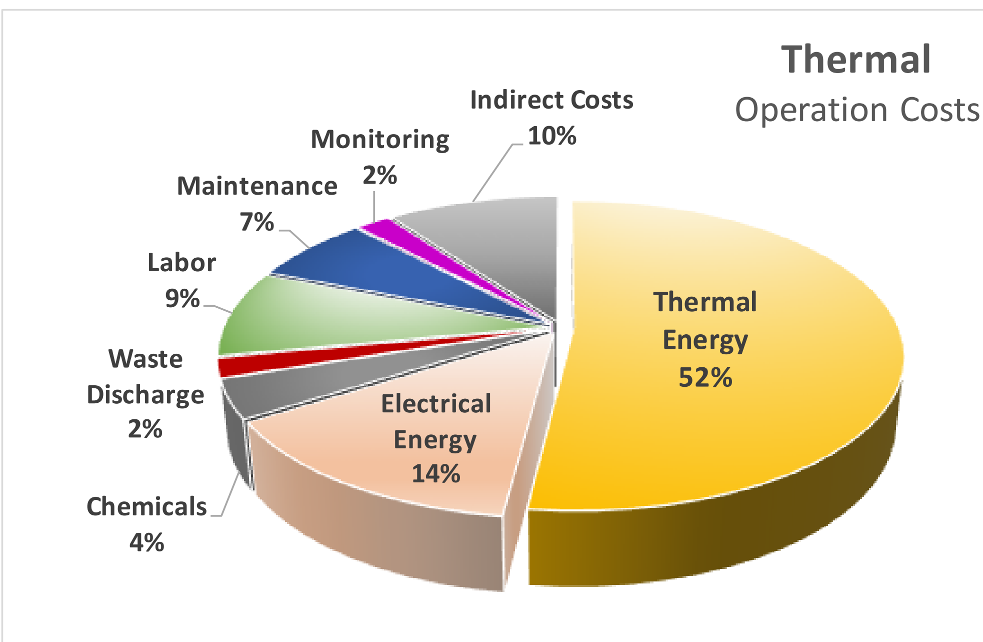


Figure 19: O&M Cost Breakdown for Thermal Desalination Plants

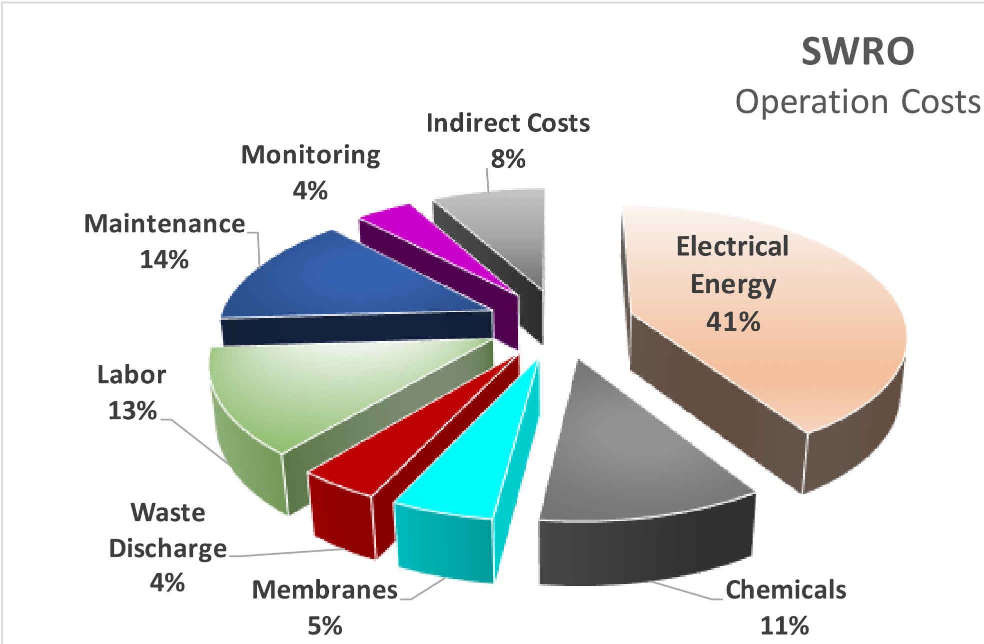


Figure 20: O&M Cost Breakdown for SWRO Desalination Plants