Analysis of Domestic and International Desalination to Outline the Decision Making Landscape for Implementation and Operation of Desalination Plants in the United States

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Executive Summary

The global shortage of freshwater was named the most impactful global risk to health and safety by the World Economic Forum in their 2015 report (World Economic Forum, 2015). The Intergovernmental Panel on Climate Change projected in 2007 that up to two billion people would be facing an increase in water-scarcity around the world by 2050 (Craig, 2010). The issue of water scarcity increases as drought, climate change, and increases in population increase the stress placed on water infrastructure. As of 2015, countries in the Middle East and Northern Africa as well as Australia were heavily affected by limited water supply. In the United States, water supply shortages were affected by droughts on the West Coast, and by saltwater intrusion on the East Coast.

In order to mitigate the effects of freshwater shortages, regions determined how to increase their water supply, or reduce their demand for freshwater. Options such as utilizing new ground or surface water supplies, importing water, and desalinating saline water were options to mitigate freshwater shortages through an increase in the water supply. Conservation and infrastructure improvements were options to decrease waste and manage the use of water to reduce demand on the water supply. This project focused on the use of desalination for mitigation of water supply issues.

Project Goal

The goal of the project was to provide the Department of Energy with a decision making landscape for the deployment and operation of desalination in the United States (Figure i). Research for the report was based on case studies of existing desalination plants and desalination technologies, as well as through interviews with experts in the area of desalination. Twenty desalination plants were studied in depth; nine were international and eleven were domestic. Relevant data for each plant such as technology used, amounts of freshwater produced, energy input, and costs was collected and catalogued into a data matrix (Appendix B). Descriptions of each plant were developed in order to capture unique information that could not be depicted in the matrix (Appendix E). The interviews conducted provided insight into new technology being developed in the field of desalination, establishing considerations that are made prior to the implementation of desalination and opportunities for innovative desalination plant design, especially as it relates to energy.

Decision Making Landscape

As shown in Figure i, the decision making landscape can be deconstructed into four steps: identification of freshwater need, comparison of mitigation methods, selection of desalination, and development of specifications for the desalination plant. There are multiple reasons a region may be in need of freshwater including drought, saltwater intrusion, arid climates, and population increases. Once a region identifies its need for freshwater, there are various methods to mitigate this water need that a municipality might explore: conservation, importing water, recycling water, desalination, and finding new sources of ground or surface water. When considering desalination, determinations must be made on the importance of long term or short term solutions, cost differentials, and potential "water portfolio" security. If desalination is chosen as a solution to supplement a region's water supply, there are various decisions that must be made by the municipality. The municipality must decide on a contract with a private company or contractor to determine the distribution of risk associated with the supply and demand of freshwater produced. The contract determines who finances the project, obtains the permits, and selects the technology and energy source. Once all of these aspects are established, construction of a desalination plant may begin.

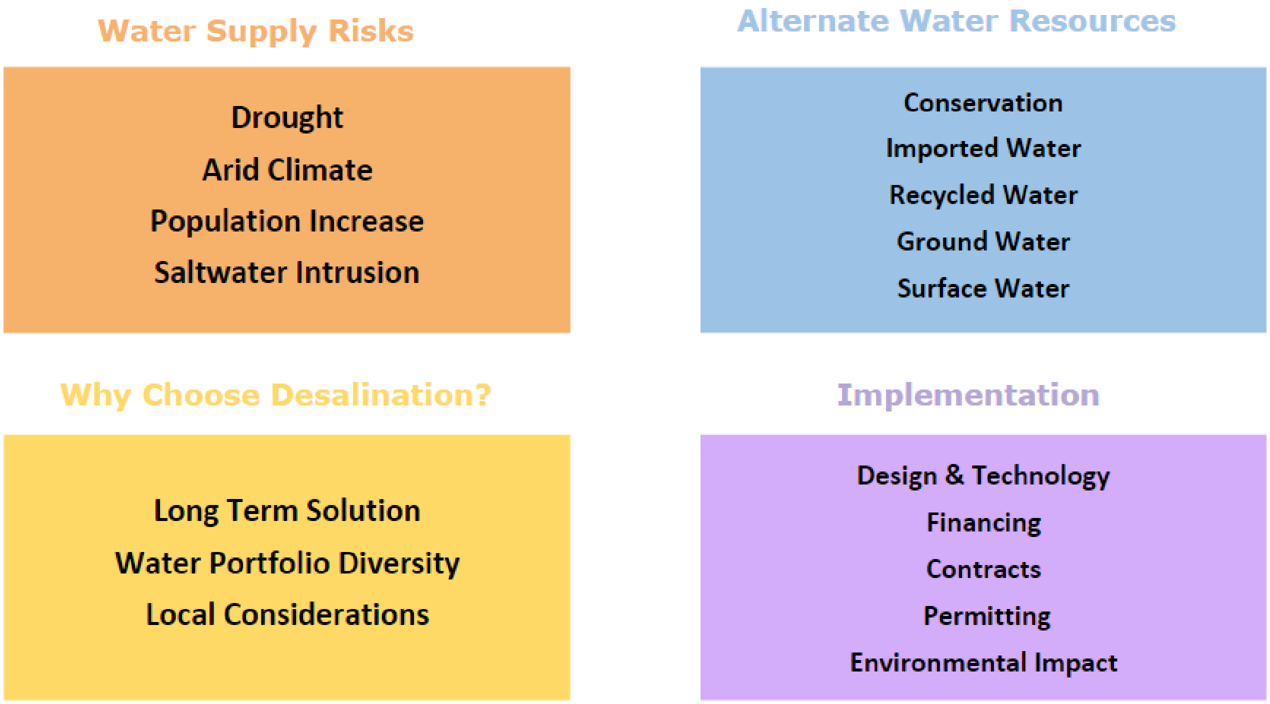


Figure i: The decision making landscape of desalination

Recommendations

The team made six recommendations to the Department of Energy regarding desalination and its development in the U.S.

1. Conservation should serve as the primary response to a lack of freshwater.
2. A database of desalination plants should be created, since desalination is a large consumer of energy.
3. The United States should work with countries from all over the world that also have experience with desalination.
4. Design desalination plants with flexible production capacity.
5. Develop mutually beneficial schemes between power plants and desalination plants.
6. Further the research into opportunities for alternative operations.

Chapter 1: Introduction

Drought, saltwater intrusion, and increases in population all affect the availability of freshwater throughout the world. Droughts in the Middle East/Northern Africa (MENA) region as well as the western coast of the United States have severely limited freshwater supplies (Hazell, 2007). Other regions such as the eastern coast of the U.S. and the Laizhou Gulf in China are experiencing saltwater intrusion, increasing the salinity of previous freshwater sources thus compromising the usability of the water. In addition to drought and saltwater intrusion, the increase in the world population has expanded the demand for freshwater.

There are two viable options to meet the need for freshwater: water conservation, which decreases the amount of freshwater used per capita, or water purification, which increases the amount of available freshwater. An example of water conservation is restricting the use of freshwater in industrial facilities, such as power plants, which accounts for around 50% of freshwater withdrawals in the United States (Feeley, 2008) and by teaching and requiring water conservation practices by all members of a community. In addition to water conservation methods decreasing water use per capita, the freshwater supply can be increased by accessing and purifying water from alternative sources. For example, wastewater, brackish water, and saltwater can be used as a way to augment the supply of freshwater in different locales. The processes required to purify those water sources can be very expensive and risky however, requiring large amounts of energy in addition to building costs, and increased rainfall or successful water conservation could jeopardize the need for those processes.

One process for producing freshwater is desalination, a method for the production of potable water. Through desalination, salt and other dissolved impurities are removed from the feed water, thus purifying the water for public consumption. Unfortunately, the establishment of desalination plants around the world has not always been at an opportune time. The Victorian desalination plant in Australia, for example, was constructed when the water supply was insufficient due to drought, but is not currently operational because local freshwater supplies have since increased. All plants still require maintenance even when they are not in operation, which is a significant economic burden for the company, municipality, and freshwater consumers (Aquasure, 2015).

Desalination plant construction has increased due to the impact both drought and the depletion of freshwater sources has had on communities, specifically in Texas and on the West

Coast, which can be seen by comparing freshwater availability prior to drought to current freshwater availability in those areas. For example, “Los Angeles has had a water conservation ordinance since 2009. Residents are permitted to water their lawns no more than three days a week and prohibited from watering when it rains” (Bloch, Ericson, Park, Watkins, 2015). In addition to water conservation efforts, desalination plants can be constructed to supplement the reduced availability of freshwater. However, if the drought ends before or shortly after the plant comes online, then a potentially billion-dollar project might no longer be needed, producing a negative reaction from the community (Roth, 2015). Plants that are no longer required to supplement the freshwater supply are either shut down or only run temporarily (City of Santa Barbara, 2015; Sydney Desalination Plant, 2015; Yuma, 2014). To ensure a plant’s successful implementation, it is necessary to identify the conditions under which the plant will be operating after its completion.

In order to determine if a desalination plant will be cost and energy effective; it is important to consider a wide range of qualities such as location, population, seasonal variations in rainfall, and the cost of energy, before construction begins. What is difficult to determine is the degree to which each of these qualities impact a plant’s success. By analyzing these qualities, it may be possible to determine whether a desalination plant should be constructed at a specific location or not.

Project Statement

The aim of this project was to provide the Department of Energy with the decision making landscape associated with the implementation and operation of desalination. In order to construct the decision making landscape, we identified a group of 11 domestic desalination plants and 9 international desalination plants that reflected the range of desalination efforts both domestically and globally. These plants are located on four different continents, spread across ten different climates, and vary in terms of production amount, feed water salinity, and operational status. Important characteristics of the plants were sorted into categories of a data matrix for comparison. In addition to the information presented in the matrix, relevant data and explanations were included in separate paragraphs to fully capture the uniqueness of each plant. After comparing the plants using the data matrix, patterns in site selection, operational process, and common barriers were identified; example patterns include rationale behind site selection, technology used, and commissioning; operational status of plants post-completion, and optimization of energy consumption.

Chapter 2: Background Information

The U.S. Department of Energy

The Department of Energy (DOE) is a government agency with a mission "to ensure America's security and prosperity by addressing its energy, environmental and nuclear challenges through transformative science and technology solutions" (DOE, 2015a). A primary goal of the agency is to find long term energy sources that meet the needs of the country while maintaining cost effective, environmentally friendly practices.

One area the DOE applies this philosophy to is the energy efficiency of the future water system. Both energy and water systems are dependent on each other; energy is needed to produce freshwater and energy production methods require water. Major interruption to either system can be detrimental to the other, a fact that has motivated the DOE to investigate the water-energy relationship and motivated our project.

Desalination may become an increasingly attractive option as population growth increases the demands for freshwater and climate-related phenomena decrease the available supply. However, existing desalination technologies are energy intensive. Through this project, the Department is trying to better understand the factors that impact implementation and operation of desalination, both domestically and abroad, to help inform potential future research and development.

Freshwater Shortages

The shortage of freshwater has been named the most impactful global risk to health and safety by the World Economic Forum in their 2015 report (World Economic Forum, 2015). The Intergovernmental Panel on Climate Change projected in 2007 that up to two billion people would be facing an increase in water-scarcity around the world by 2050 (Craig, 2010).

Countries such as Saudi Arabia, Qatar, and the United Arab Emirates have struggled to have a reliable supply of freshwater due to their harsh terrains (Perlman, 2015a). In the year 2012, Saudi Arabia had access to 21,000 gallons of freshwater per capita per year while Qatar had 7,000 and the United Arab Emirates only had 4,500. By comparison, Iceland had the most freshwater access, with 140 million gallons per capita per year in 2012 (The World Bank, 2013). As displayed by the data, the disparity in freshwater availability per capita has caused countries in arid climates to supplement their freshwater supplies using desalination. The water availability for other major countries utilizing desalination is shown in Table 1. Israel has significantly lower water availability than other countries, with only 25,000 gallons per capita per year. This explains why Israel has made large advances in desalination and water conservation. The accessible freshwater not only goes towards household consumption, but also for agricultural and industrial use, with the availability expressed per capita so the values are comparable. The availability of freshwater per capita can be connected to the annual precipitation a region receives. Low annual rainfall relative to a region's freshwater needs can prevent overall economic, population, and industrial growth, as well as limit the public's access to potable water. This lack of growth influences the need for mitigation methods to supplement freshwater supplies.

Country	USA	China	Spain	Australia	Israel	Italy	India
Gallons per capita per year	2.4 million	550,000	630,000	1.72 million	25,000	810,000	300,000

Table 1: Countries and available freshwater resources (The World Bank, 2013)

As shown in Figure 1 below, annual rainfall is currently less than average in California and Texas, and has become an issue in large regions of the United States. For example, California's precipitation is at an all-time low where cities across the state received less than fifty percent of their typical rainfall in 2014 (Oskin, 2014).

One of the effects of reduced precipitation is the decrease in natural water storage, which includes glaciers and snowcaps. Snowcaps are sources of water for many river basins such as the Colorado River that supply much of the arid southwest with water, and are expected to provide less water in the future due to the continuing impacts of climate change (Craig, 2010). Climate change is also causing the time frames of snowmelt and precipitation to become shorter, resulting in larger quantities of water release over shorter periods of time. The changes in water release make it more difficult to capture the water for storage and use (Craig, 2010). Experts indicate that the lack of water storage capacity will likely remain unchanged, or at least require years of good rainfall to replenish freshwater supplies (Diffenbaugh, 2015).

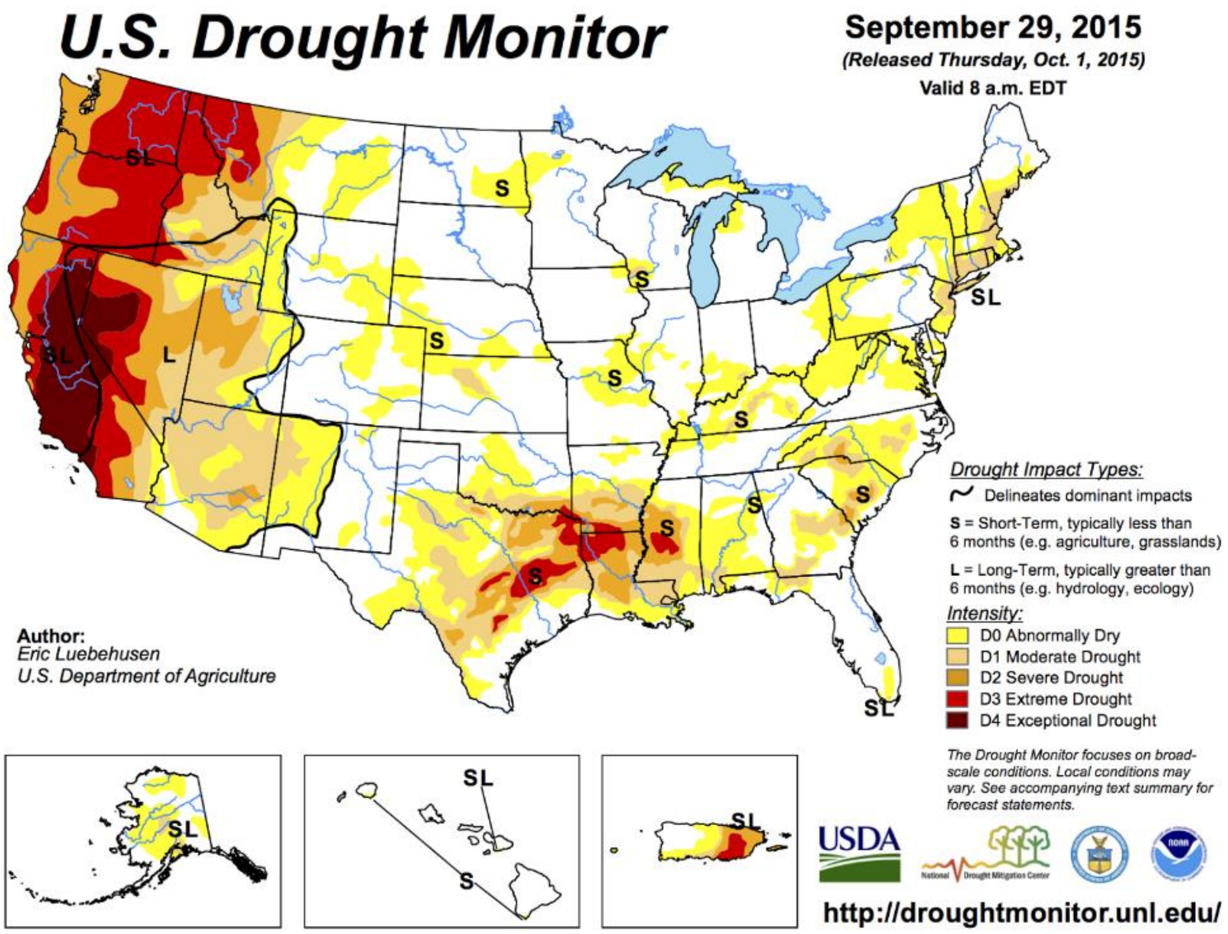


Figure 1: U.S. Drought Monitor (Eric Luebehusen, 2015)

It is common for some geographic areas, such as California, to experience multiple years without rain, followed by a period of heavy rain (California Department of Water Resources, 2015). According to the California Department of Water Resources, California experienced a drought in the early 1990's, followed by rain in the late '90s, and has since returned to drought conditions. This changing pattern has existed and been tracked since the 1920's.Unfortunately, it is difficult to know when sufficient precipitation to replenish aquifers, snowpack, and reservoirs might return. As a result, a desalination plant that is thought to be needed, and built during an extended drought, may become uneconomical to run or even maintain during years of sufficient rainfall.

In addition to reduced precipitation, population increases around the world place significant stress on freshwater sources to provide sufficient water per capita. In 2000, the world population was 6.09 billion people; in 15 years the population has grown to 7.26 billion people (United States Census Bureau, 2015). Countries that were already struggling to have enough freshwater now have more citizens, but the natural freshwater supply has not increased. It is apparent that either the amount of freshwater available must be supplemented or the consumption of freshwater must be limited.

One freshwater source the United States uses for consumption is aquifers, natural underground stone formations that filter water to form pockets of freshwater. Wells can be drilled down into aquifers and freshwater can be pumped out and later refilled by rainwater (U.S. Geological Survey, 2015). If an aquifer is large enough, it can provide water for thousands, if not millions, of people. These sources exist all over the country in varying sizes, but the largest and most actively used are those in Texas and along the east coast.

In the past decade, salinity levels of the aquifers have begun to rise, due to saltwater intrusion and excessive water removal from the aquifers. Saltwater intrusion occurs when too much freshwater is pumped out of the aquifer resulting in the natural ground filtering action becoming unsustainable since it cannot filter water at a high enough rate to prevent saltwater mixing in (Barlow, 2013). The effects of saltwater intrusion are increased as rising sea levels caused by climate change push saltwater into underground sources (Craig, 2010). Regardless of the specific saltwater intrusion mechanism, the aquifer water must now be filtered in order to be used for household purposes, agricultural needs, and industrial use.

Conservation

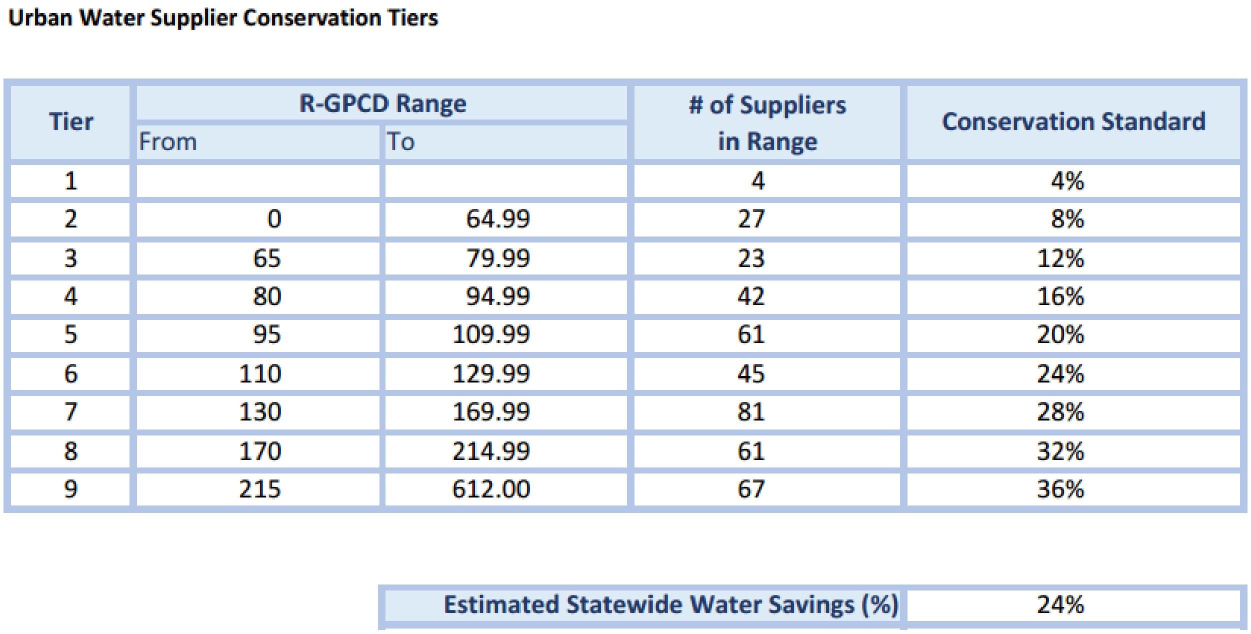
Conservation of freshwater can be accomplished through water infrastructure improvements, installation of water efficient fixtures, and restrictions on outdoor water use (Cooley, 2012; Vedachalam, 2012). To mitigate California’s drought, the suburban town of Poway has been practicing intense water conservation. Homes, apartment complexes, and businesses are allowed ten minutes on two specific days for irrigation (Poway, 2015). In addition, washing paved surfaces is prohibited, unless there is a safety hazard (Poway, 2015). These restrictions conserved water so efficiently that 550,000 gallons of freshwater were available, but not consumed in May of 2015. Unfortunately, the water was not properly cared for and became too heated, causing a chemical imbalance of Chloramine and rendering the water unsafe for residential use. It is also not cost effective to send the contaminated water to a location where it was needed and could be used (Mendes, 2015). Poway Mayor, Steve Vaus, said the city is looking into systems that can be put into place to utilize excess water from the city's conservation efforts (Mendes, 2015).

Recently in California, the State Water Resources Control Board released a plan which requires the reduction of water use in the state by 25 percent (Peterson, 2015). As shown in Table 2, this plan separated California's water agencies into nine tiers, with a total conservation goal of 4 percent per tier level. The tiers were determined by the R-GPCD formula, which stands for the rate of residential gallons used per capita per day (Figure 2).

$$\text{R-GPCD} = \frac{(\text{Monthly Water Production}) * (\text{Percentage Residential Use})}{(\text{Population}) * (\text{Days in Month})}$$

Figure 2: Rate of residential gallons used per capita per day (State Water Resources Control Board, 2015b)

The city of Poway, CA has an R-GPCD of 201.7, placing the district in tier 8 with a target reduction rate of 32 percent; additional tier rankings are provided in Appendix D. In October 2015 the Poway district narrowly missed their goal, achieving reduction rate of 29.68 percent instead of the desired 32 percent (Peterson, 2015).



Urban Water Supplier Conservation Tiers

Tier	R-GPCD Range		# of Suppliers in Range	Conservation Standard
	From	To		
1			4	4%
2	0	64.99	27	8%
3	65	79.99	23	12%
4	80	94.99	42	16%
5	95	109.99	61	20%
6	110	129.99	45	24%
7	130	169.99	81	28%
8	170	214.99	61	32%
9	215	612.00	67	36%

Estimated Statewide Water Savings (%)	24%

Table 2: Urban water supplier conservation tiers (State Water Resources Control Board, 2015a)

One renewable energy and desalination expert suggested conservation should be considered prior to implementing desalination. In cases such as Poway, California, conservation was effective enough to not require further freshwater supply augmentation efforts; however, further efforts in augmenting the freshwater supply are often required due to rapid production growth (Gleick, 1996).

The Desalination Process

Desalination is the removal of minerals, primarily salt, from water. The process is used to convert saltwater to accepted levels of salinity to be classified and used as freshwater. Some examples of water sources used for desalination include seawater, brackish water, and salty wastewater, which can be converted to freshwater via one of three purification technologies: membrane, chemical, and thermal.

Membrane technologies are the most common desalination processes in the United States (Younos & Tulou, 2005) and can be thought of as the physical filtration of water to remove contaminants such as particles, bacteria, hardness, and salt depending on the type of filter used. Membrane technologies are also further classified by how they remove contaminants from the water, and whether they are pressure-driven filters or electrical-driven technologies.

As shown in Figure 3, membrane technologies use pressure to drive feed water through a membrane to remove the salinity from the water (Younos & Tulou, 2005; Cooley, 2006). As feed water salinity increases, higher pressures are required to drive the feed water through the membranes. More energy must be consumed to achieve these higher pressures; therefore, the amount of energy required for the process increases as feed water salinity increases.

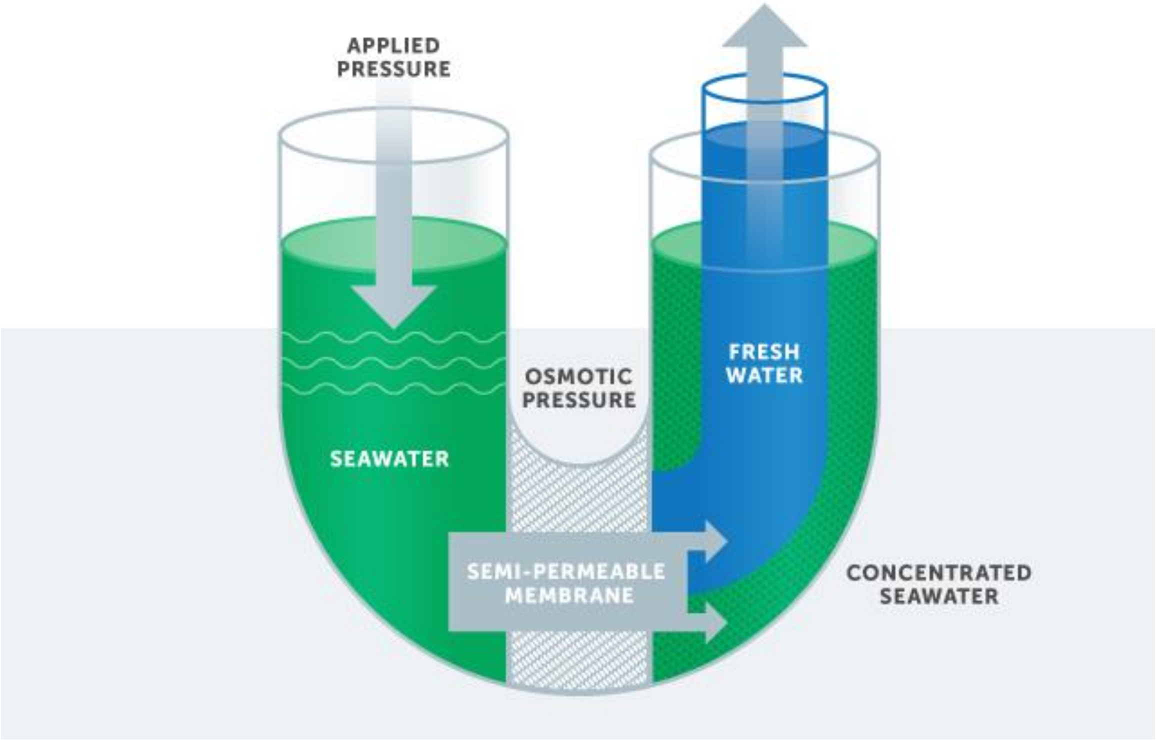


Figure 3: Simplified process diagram for reverse osmosis desalination (Poseidon Water LLC, 2015)

Membrane technologies that are pressure-driven and able to remove salinity from water include reverse osmosis and nanofiltration. According to the International Desalination Association, reverse osmosis currently makes up 60% of desalination capacity around the world (International Desalination Association, 2014). Reverse osmosis uses pressure to filter a saline solution through the use of a semi-permeable membrane. The membrane only allows freshwater to pass through, removing salt content from the water. One of the world's largest reverse osmosis plants is in Ashkelon, Israel and desalinates seawater at a rate of 100 MGD (Cooley, 2006). Nanofiltration is similar to reverse osmosis, but operates at lower pressures and uses filters with larger pores. These two differences limit the use of nanofiltration for desalination. However, nanofiltration is commonly used for the partial removal of water hardness and dissolved solids, or for the use in the pretreatment process before membranes as shown in Figure 4. Pretreatment methods are located prior to the reverse osmosis membranes and are being increasingly implemented in reverse osmosis plant construction (Cooley, 2006). These pretreatment methods allow for increased filter life by removing contaminants from the feed water.

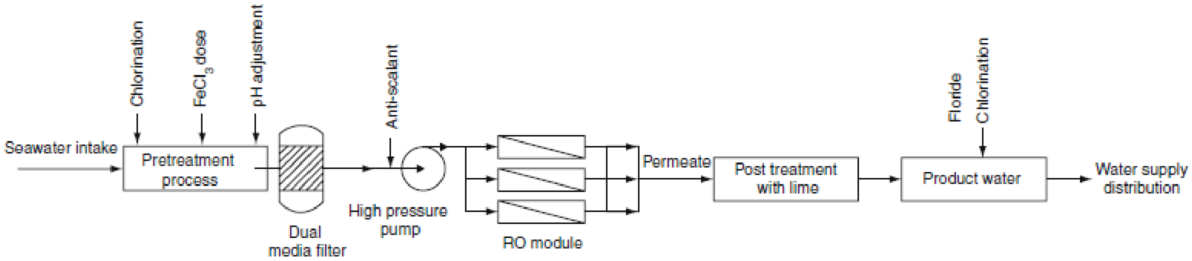


Figure 4: Process schematic of RO seawater desalination at Kwinana Desalination Plant (Saliby, 2009)

Electrical-driven processes of filtration are electrodialysis (ED) and electrodialysis reversal (EDR), shown in Figure 5. These processes incorporate a cathode and an anode placed on opposite sides of a membrane. The charge of the electrodes attracts the individual ions of the dissolved solids and deposits them on the surface of the electrode. An EDR system allows for the charges on each electrode to be swapped, preventing the buildup of scale. By swapping charge, ions that were once attracted to an electrode are now repelled, and attracted to the other electrode. By continuing this process, which can occur manually or on a timer, the ions and scale are extracted from the water and removed with the brine stream. This enables the EDR process to remove more salinity than ED processes. It is also important to note that, due to lower operational costs, ED processes are selected to treat water with lower amounts of dissolved solids than EDR.

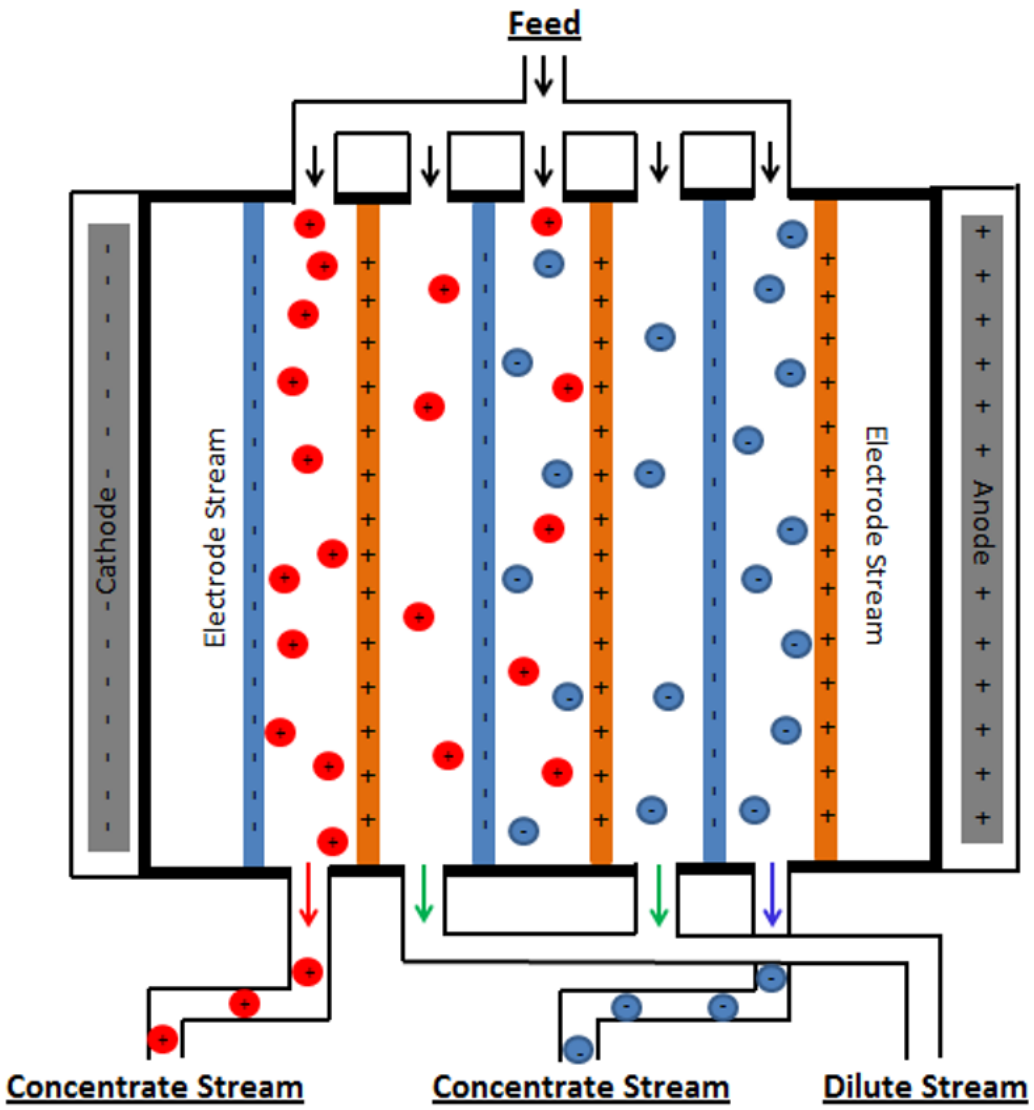


Figure 5: Filtration process of an electrodialysis desalination plant (Joyce River)

The two types of membrane technologies, pressure-driven and electrical-driven, operate in similar ways, but have unique dimensions that restrict their applications. Like reverse osmosis, the operational costs associated with ED are dependent on the concentration of dissolved solids in the feed water (Cooley, 2006). Unlike reverse osmosis, however, ED processes are not sensitive to pH or hardness levels of feed water. The processes also require minimal labor, resulting in lower maintenance costs. However, ED processes are only economical for lower concentrations of dissolved solids, and are not recommended for the processing of water with high concentrations of solids, such as saltwater, due to high energy costs. Pressure driven technologies, like reverse osmosis, are much more suited for treatment of water with higher concentrations of dissolved solids.

Desalination processes involving chemicals use ion exchange technologies. Specifically, dissolved solids are removed by the chemicals reacting with the ions of the contaminants, such as salt, produce potable water. This type of water desalination can be used in conjunction with other processes, such as reverse osmosis to provide increased water volume production (Younos & Tulou, 2005).

Thermal technologies use evaporation and distillation in the treatment of feed water. The process is commonly used when there is a local electrical power generation plant in order to utilize waste heat from the power plant to heat the water for distillation. The most common feed water used in thermal processes is saltwater (Younos & Tulou, 2005). Some common forms of thermal technologies include multi-stage flash and vapor compression.

Multi-stage flash and vapor compression are two technologies commonly used for freshwater production in the Middle East, an example of a multi-stage flash plant is shown in Figure 6 (Younos & Tulou, 2005). The multi-stage flash process, illustrated in Figure 7, preheats feed water before it is placed into a pool to evaporate. The vapor from the pool is then condensed on the incoming feed water piping, preheating the incoming water. This process is repeated in various stages as the dissolved solids' content in the water slowly increases as pure water is removed. The technology has produced high quantities of freshwater, but it is the most energy dependent of all thermal technologies. Vapor compression is similar to multistage-flash except the process pressurizes the steam into tubes, rather than condensing on the tubes. As the vapor in the tubes transfers heat to the feed water, the vapor condenses to produce freshwater.

Figure 6: Multi-stage flash plant, Saline Water Conservation Corp. Al Jubail, Phase II Saudi Arabia (Sasakura Engineering Co., LTD)

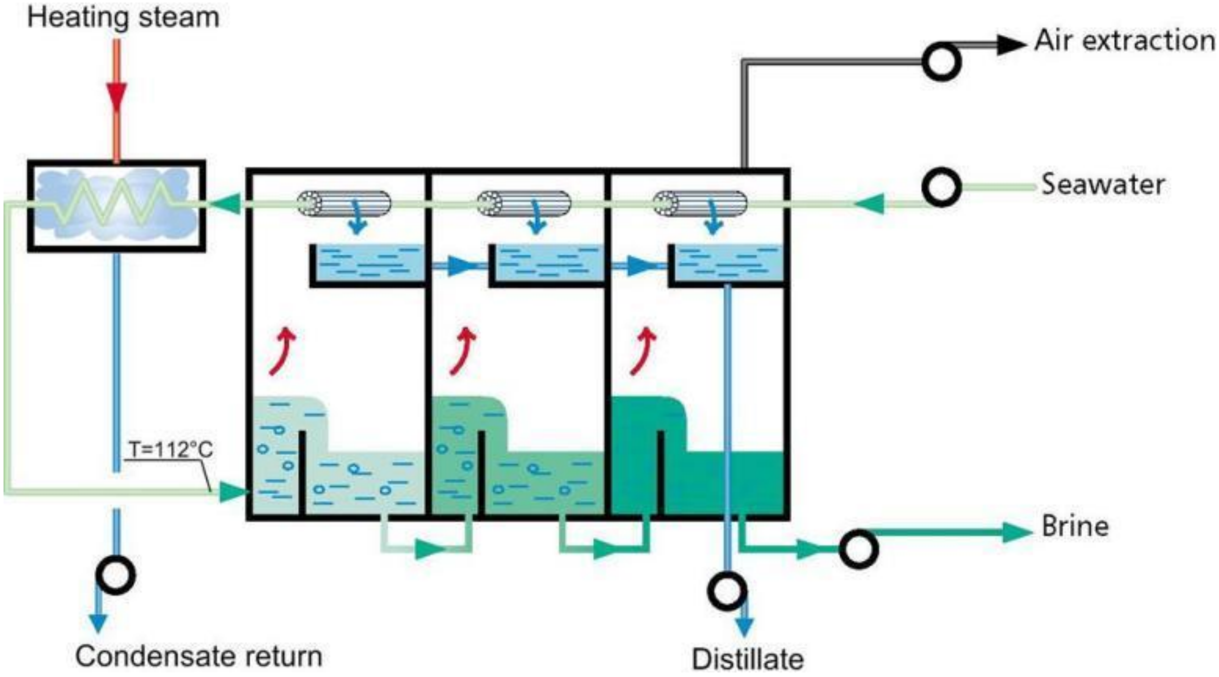
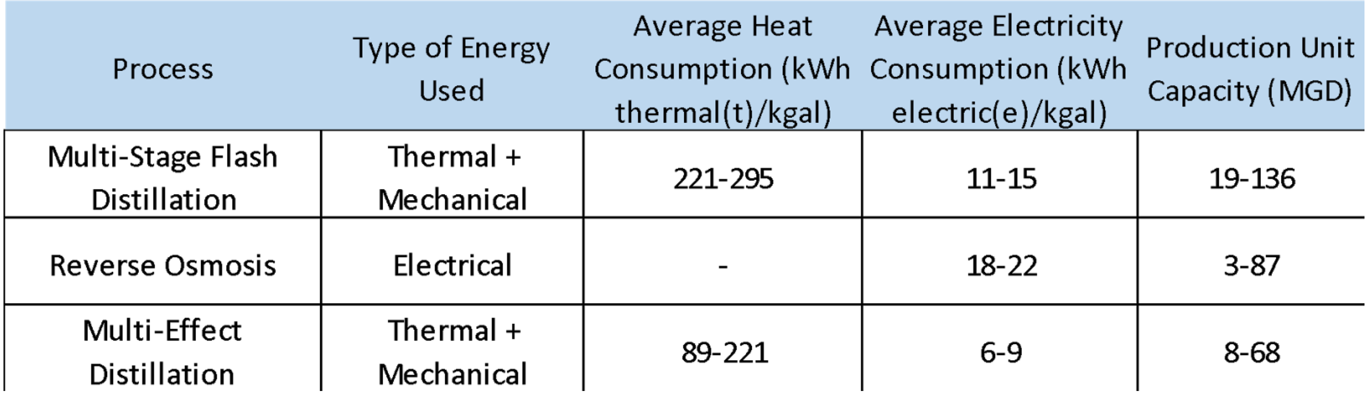


Figure 7: Process flow diagram of Multi-stage Flash desalination (Veolia Water Technologies, 2014)

Each desalination processes requires energy to produce freshwater as shown in Table 3. Multi-stage flash (MSF) primarily uses thermal and mechanical energy, while reverse osmosis (RO) uses electrical energy to drive the process. The amount of energy used as well as the type of energy used can affect the cost of the desalination process. For example, the total energy required by each process results in water produced through RO to be between 40-75% less expensive than water produced through MSF (Katsandri, 2011).



Process	Type of Energy Used	Average Heat Consumption (kWh thermal(t)/kgal)	Average Electricity Consumption (kWh electric(e)/kgal)	Production Unit Capacity (MGD)
Multi-Stage Flash Distillation	Thermal + Mechanical	221-295	11-15	19-136
Reverse Osmosis	Electrical	-	18-22	3-87
Multi-Effect Distillation	Thermal + Mechanical	89-221	6-9	8-68

Table 3: Energy use and typical capacity for desalination plants (Data converted from Katsandri, 2011)

In addition to different energy usages, MSF is not subject to the same costs as RO due to the absence of membrane elements; however MSF uses both electrical and thermal energy for production, representing about 23% and 26% of the production cost. The combined cost of the two energies is nearly twice that of RO in the Middle East, despite lower uses of electrical energy (Borsani, 2005). In addition, energy costs are variable, and unlike the cost of membranes, are expected to increase. Also, RO plants typically require 18 months to build, while an MSF plant will require a minimum of 24 months to construct (Katsandri, 2011). This reduced time frame in the construction process is an additional factor that could promote the use of one technology over another.

Cogeneration

Cogeneration is defined as "the production of electricity using waste heat (as in steam) from an industrial process or the use of steam from electric power generation as a source of heat" (Merriam- Webster, 2015). With respect to desalination, waste heat can be applied to the energy requirement of the production of freshwater from seawater or brackish water. Frequently, desalination plants are constructed with power plants in order to utilize the power plants waste heat while producing additional energy to be sold to the municipality (Tonner)

Technologies used

Thermal technologies can utilize waste heat by channeling it to heat the water for evaporation, whereas membrane technologies cannot. When used by themselves, thermal technologies are very energy intensive which prevents them from being cost effect methods of producing freshwater. However, when coupled with a waste heat source, the conceivability of MSF and MED increases.

Through reverse osmosis is the most commonly used stand-alone technology in the United States, it is not as effective in a cogeneration system. RO requires electrical energy and pressurize the feed water to filter it through the membranes rather than thermal.

When a community or geographic area is in need of both a power plant and a desalination plant, it is possible to have the two systems connected to supplement the supply of both energy and freshwater as outlined in Figures 8 and 9 below. A common method of power generation is to heat water to produce steam, which is then sent through a turbine to produce energy. With cogeneration, this high temperature steam can then be sent to a waste heat recovery boiler, also known as a brine heater, to heat the saltwater feed for the thermal desalination process. The heated saltwater feed can then proceed through the desalination process without requiring as much additional energy. The now cooled power plant water is then returned to a boiler to repeat the process. The power plant portion of the system has its own freshwater supply, while the desalination plant takes in saltwater from an outside source. This way, water is not transferred between the two, just heat.

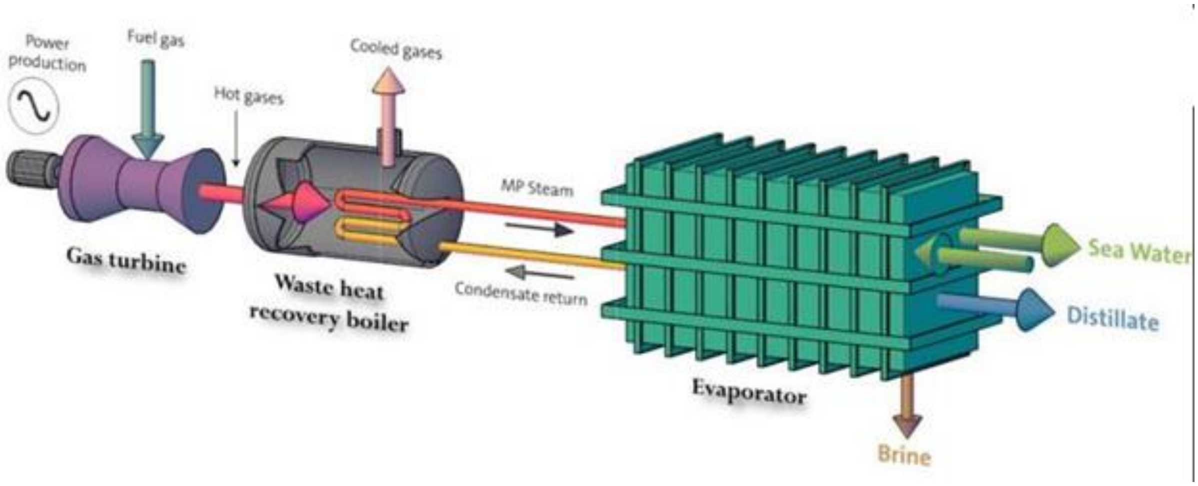


Figure 8: A gas turbine power plant with MSF desalination (Sidem Veolia, 2014)

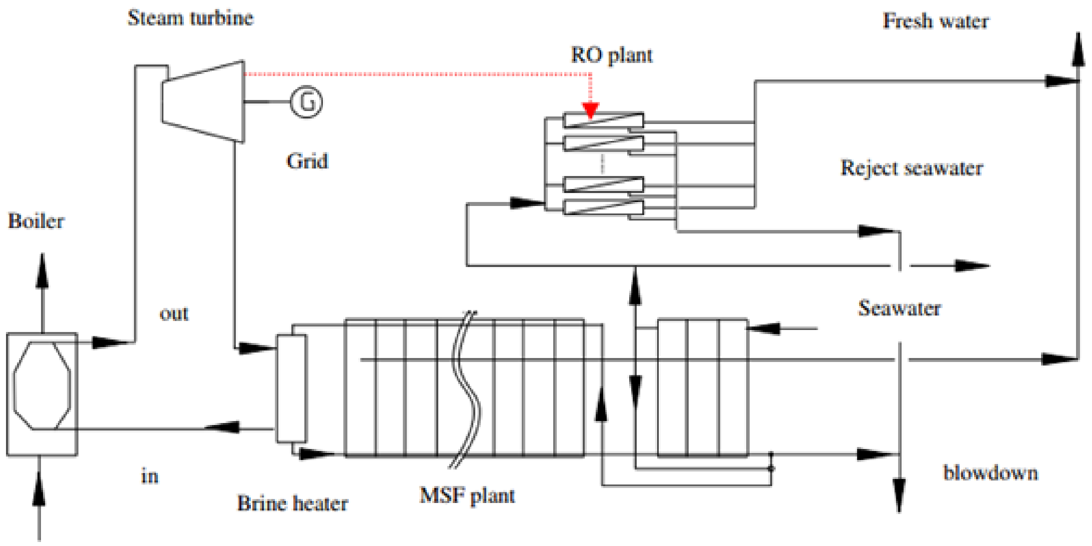


Figure 9: A steam turbine power plant with a MSF and RO desalination plant (Liangying, Yangdong, & Congjie, 2013)

Applications

Cogeneration has seen application worldwide. For example, a solid waste incinerator in the Netherlands uses resulting excess heat to power a seawater desalination plant. This allows the country to solve multiple problems at once: a lack of accessible fresh water and landfill space constraints. Similarly, large ships use heat given off by their engines to power the desalination of up to one million gallons of seawater every day to provide freshwater on long journeys (Tonner). This way, ships can remain at sea for longer periods of time without having to include large storage tanks for fresh water. In the mining industry, which is common in coastal and arid regions, sulfuric acid is used to dissolve copper ions from stone. The process of diluting sulfuric acid to the needed concentration is done by adding fresh water to concentrated acid. This reaction is exothermic, and the heat given off can be used in the desalination process to produce more freshwater. As a result of cogeneration, the production of sulfuric acid at the necessary concentration can be a continuous process, provided a saltwater source is easily accessible (Tonner). Other plants will be designed to have power generation and water desalination integrated if the surrounding area is in need of both.

The United States could benefit from this technique in very similar ways to those described above. Building a power plant and desalination plant together would be best suited for household uses, since both power production and water production can be predetermined by the needs of an area. Industrial needs can also be fulfilled by building an MSF plant that utilizes the waste heat of an industrial process. In this case, no excess power is generated, but previously unused heat can offset the cost and energy consumption of a desalination plant.

Efficiency

Overall, the cogeneration process is 10-20% more energy efficient than separately generating electricity and desalinating water (Tonner). There are two ways to measure the thermal efficiency of a desalination plant: the gained output ratio (GOR) and the performance ratio (PR). GOR is the mass flow rate of distilled water produced per mass flow rate of steam consumed in the process with the values typically ranging from 1 to 10 kg/kg (Kansas State University). PR is the amount of water produced per million joules of heat consumed. For a large scale MSF plant, GOR would range from 8-10 kg/kg and PR would range between 3.5 and 4.5 kg/MJ (Kansas State University). In most studies, GOR is the selected measure of efficiency. Cogeneration, increases energy efficiency due to the processes' direct connection. As shown in Figures 8 and 9, the heated steam leaving a turbine is sent directly to heat the saltwater feed of the desalination plant. This way, the steam is not air-cooled, and therefore does not lose heat to convection. The saltwater feed absorbs most of the heat energy, which is sufficient to operate a thermal technology plant. Additionally, excess energy produced by the turbine can be provided as electrical energy to a municipality or as a supplement the desalination process if necessary. A power plant operating alone would lose a majority of its thermal energy to the environment, and a stand-alone desalination plant requires power from the grid which is then converted to thermal energy, decreasing efficiency.

Cost Comparison

When comparing the costs of stand-alone desalination plants, reverse osmosis is the most cost effective and energy efficient technology. However, when coupled with an industrial process to utilize waste heat, MSF distillation has a lower cost and higher energy efficiency than stand-alone RO. One study analyzing the total costs of each of these processes is graphically represented in Figure 10. The graph shows MSF costs approximately $1.00 per m^3 of water produced for production rates ranging from 3000 to 12000 m^3/ hour. For water production rates from 3000 to 5000 m^3/ hour, RO and cogeneration both approximately cost $0.875 per m^3. As production rates rise, the cost of cogeneration lowers asymptotically to $0.80 per m^3 while RO's cost remains approximately $.0875 per m^3. This shows that cogeneration is the most cost effective option for freshwater production at rates greater than 5000 m^3/ hour (Liangying, Yangdong, & Congjie, 2013).

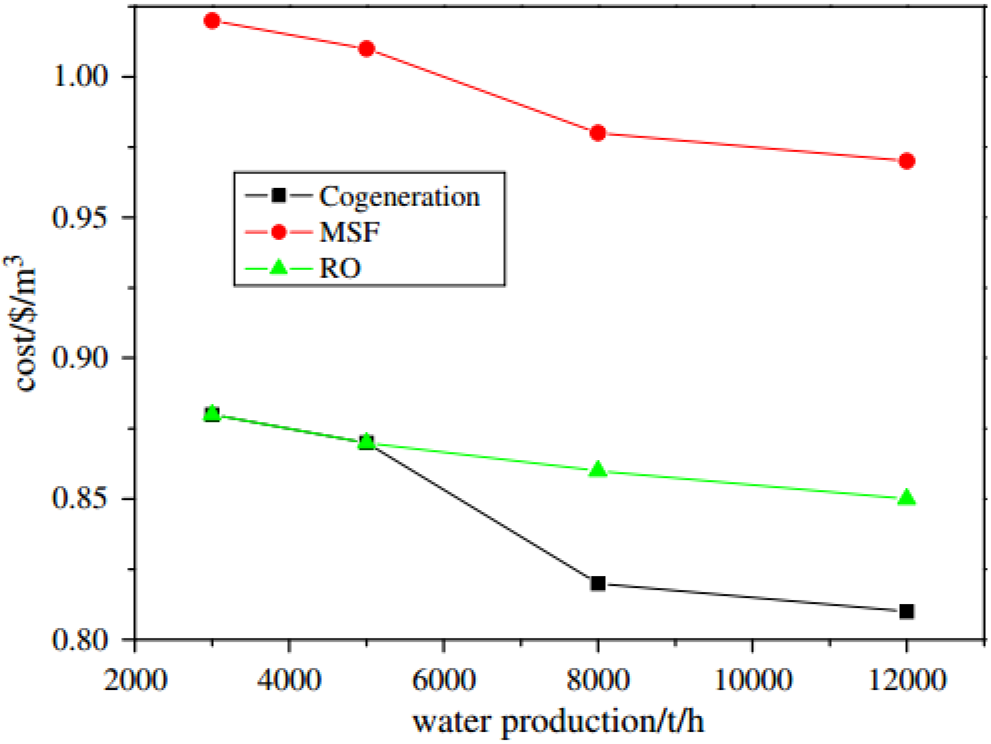


Figure 10: Cost vs. water production for different technologies (Liangying, Yangdong, & Congjie, 2013)

Production Cost Optimization

One problem that desalination plants have encountered is optimization of energy usage. Should a desalination plant produce more during the hours where demand is low and decrease production during peak energy demand they will be able to save money in addition to assisting the power plant by allowing them to not have to ramp up their production.

The optimization of energy usage in a desalination plant can be taken into consideration during the planning and construction phase of the plant. The energy consumed within an area or population varies depending on the time of day; during traditional work hours, 9am to 5pm, the majority of adults are at work so they are not consuming energy at home. This minimizes the demand on the electrical grid during this time period. At approximately 7pm, the energy consumed rises as adults arrive home from work and turn on their appliances. Figure 11 shows this energy demand over the course of a 24 hour period on an average spring day for the state of California. Additionally, the demand on the grid over the course of a day is also affected by renewables. Solar power is only effective when the sun is up, and people require more energy when the sun is setting, causing a large increase in demand.

According to Figure 11, by the year 2020 the energy demand will fall and rise at such steep rates that the grid and power plants may not be able to handle the differences. There is also the risk of over generation, where a plant produces more energy than is demanded. Specialized desalination plant design might solve this problem. Should a desalination plant desalinate more water during the hours where demand on the grid is low and slow down production during peak energy demand they will assist the power plants in leveling production rates and avoiding significant ramping. This would also benefit the desalination plant, as energy costs are lower when demand is lower.

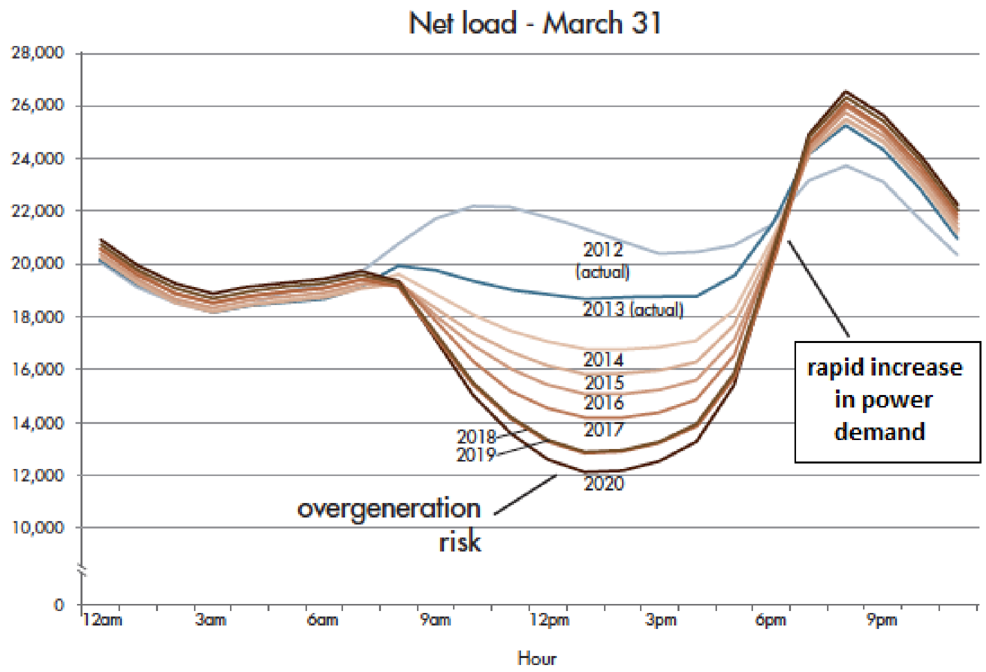


Figure 11: "The duck curve shows steep ramping needs and overgeneration risk" (Adapted from: California ISO, 2013)

As of 2015, few desalination plants are designed to have the capability to change production rates to compliment energy usage, while remaining cost effective. One plant that has implemented variability in hourly production is the Hadera desalination plant in Israel. The plant has a central pressure system; all of the piping feeds to the center of the plant. This allows for one or more pipes to be turned on and off during the day without affecting production from other pipes. During peak grid demand, only two specialized pumps are run, whereas, during low grid demand, the plant produces at full capacity: 20,000 m^3/hr.

Environmental Impacts of Desalination

Desalination plants and their effluents can have negative impacts on the environment and must be taken into account when determining a plant's feasibility. These environmental impacts are either directly related to the desalination process, such as the intake pipes and brine discharge, or indirectly related, such as the environmental changes caused by power plants that generate electricity for a desalination plant. All are a result of the process and should be taken into consideration when determining when to build a new plant.

The source water intake of a desalination plant negatively impacts the surrounding environment by increasing the salinity of the surrounding water and entrapping organisms existing in the piping. As illustrated in Figure 12, when groundwater is used in the desalination process the amount that is able to flow into rivers, lakes, and other above ground resources becomes limited. Desalination plants that draw from the groundwater can impact the ecosystems above ground, since the water level is lowered and salinity levels can increase. When large amounts of water are brought to the surface, the saltwater will typically fill the space created, bypassing the natural form filtration.

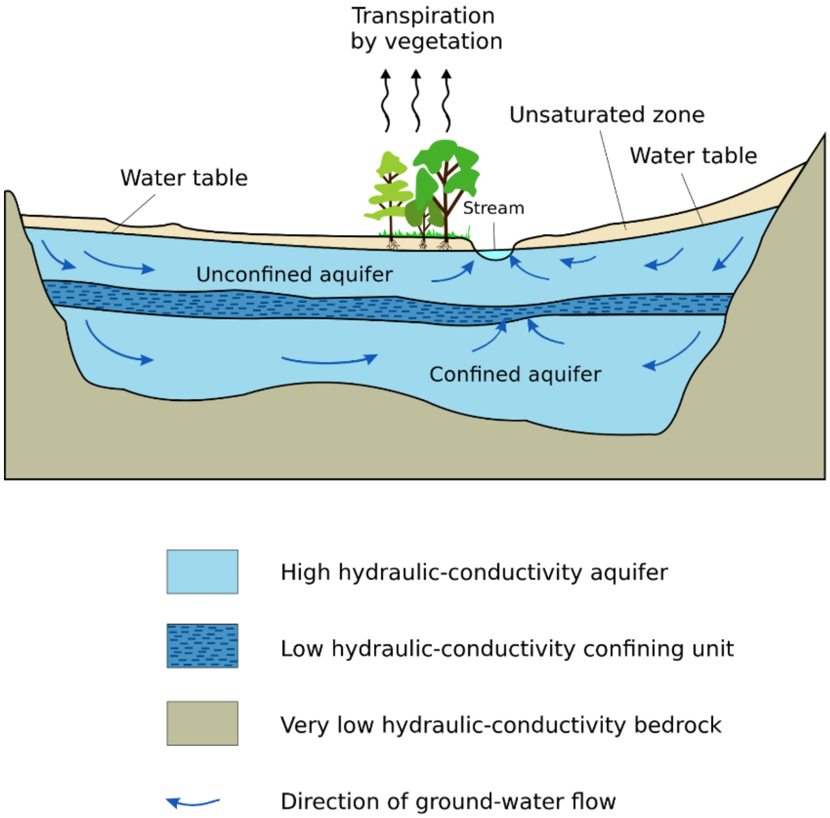


Figure 12: Aquifer cut-away (Wikipedia, 2014)

Open seawater intakes can cause multiple problems with marine ecosystems. Typically, the intake pipe will be covered by a screen similar to those shown in Figure 13, preventing any large organisms from entering the system. If the screen is not an appropriate size and material, organisms can collide with the screen and be injured or killed (impingement), while others can be drawn into the plant along with the feed water (entrainment). Additionally, when the pipes are installed sediments, nutrients and pollutants are mixed into the water, which disrupts the existing equilibrium. Overtime this can lead to interrupted water and sediment movement. Then as organisms begin to use the area as artificial reefs, shipping and boating routes are interrupted (Lattemann & Hopner, 2008).

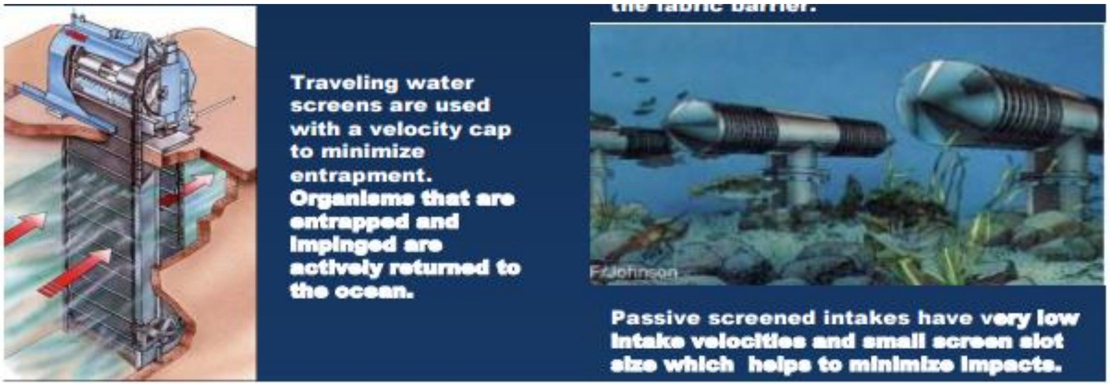


Figure 13: Water intake screens for desalination plants (Kennedy/Jenks Consultants, 2011)

After filtering seawater to produce freshwater, a high concentration of brine remains, which can be very harmful to the environment. Officially, there are no federal regulations regarding the disposal of the brine, although some states have their own policies, and there is an ongoing debate over whether it should be considered industrial waste or not (Mendeazza, 2005). For lack of laws enforcing proper disposal of brine water, desalination plants are more likely to dispose of the untreated brine back into the sea, since this method is the most cost effective.

The main problem involved with returning untreated brine in the ocean becomes clear when you look at the aquatic ecosystems nearby. Salinity and temperature levels are very important for marine species. However, most fish and marine plants can tolerate slight changes overtime, or even extreme differences for a small period of time. Desalination can cause increases to temperature and salinity to the surrounding seawater that is maintained for the duration of plant operation. The brine that is disposed of into the ocean typically has twice the salinity levels of the intake water and an increased temperature due to the processing with the degree of increase varying based on the desalination technology used and the intake temperature. The increase in temperature greatly impacts an organism's ability to regulate body temperature, reproduce, and obtain nutrients. These intake pipes are frequently found in shallow waters where nutrients, reproduction, marine life are abundant, causing these areas to experience the most severe negative impacts (Lattemann & Hopner, 2008). Due to the difference in concentration and temperature of the brine compared to the ocean water, the denser brine will sink to the ocean floor. On the bottom of the ocean, currents are weak and the solution will not be diluted by other ocean water as easily, causing extended damage to plant life, which jeopardizes habitats for other marine life (Cooley, 2013). The denser brine lying on the ocean floor contributes to the death of certain organisms, as a result others will move out of the area and new organisms will take over.

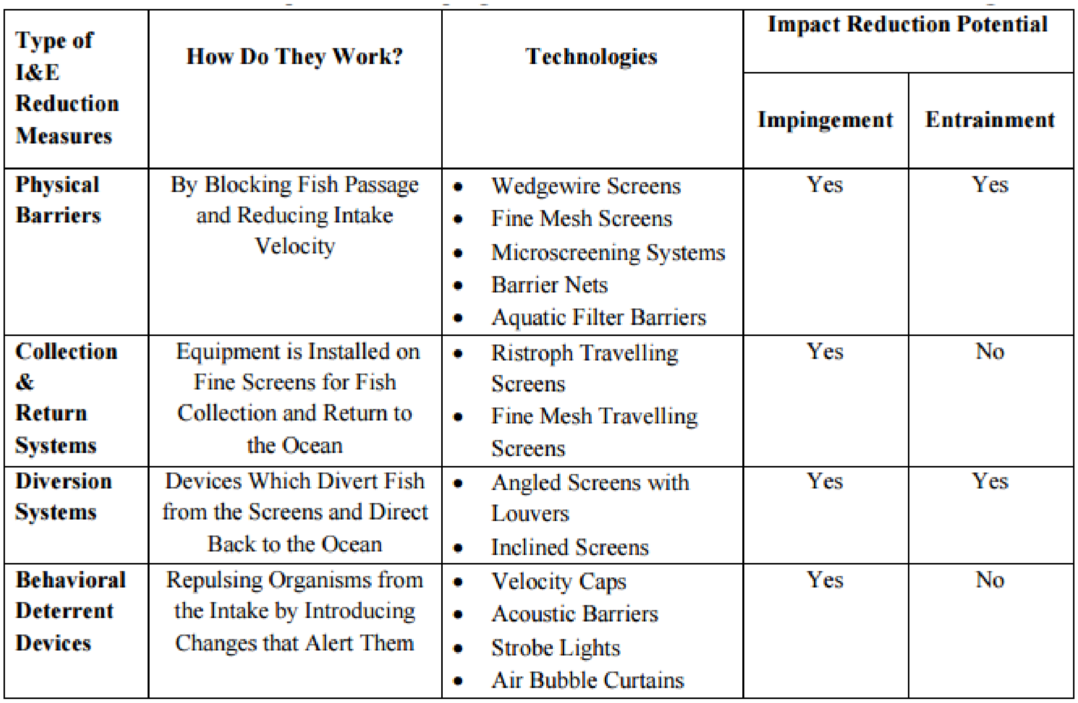
When seawater is put through the desalination process, there are typically some additional chemicals added to assist in the process. One of these chemicals is an anti-scalant which prevents the formation of scale on the equipment being used, but it is typically released into the environment with the brine. The anti-scalant used can disrupt the natural formation of chemical complexes that contribute to the marine environment (Lattemann & Hopner, 2008). Coagulants are also added to the feed water to assist with the filtration of suspended materials. When introduced to the water, they change the color, increasing turbidity and reducing light penetration (Lattemann & Hopner, 2008). Finally, cleaning chemicals such as chlorine, alkaline solutions, oxidants, and biocides are used to prevent fouling and to produce the cleanest water possible, but can be directly harmful or even lethal to organisms. The concentrations of these chemicals released to the ocean depend on the technology of the plant and the amount of water processed, but they continually have negative effects. Overall, the sudden and extended presence of new water conditions can make a region uninhabitable, or completely change the balance of the local environmental ecosystem.

The regulation of the environmental impacts is controlled by the state and city governments where each plant is being built. States where desalination is becoming more popular, such as California, Texas, and Florida, have implemented regulation and permit processes to protect the environment. For example, the California Coastal Act (CCA) includes policies to protect the state’s coastline regarding navigation, fishing, recreation, and ecosystem preservation. The CCA states that “where feasible, marine resources will be maintained, enhanced, and restored”, with the same principles applied to the biological productivity of coastal waters (Younos, 2005). In order to comply with this law, a company interested in building a desalination plant must show that the coast is the best location, as opposed to rivers or aquifers, and that the desalination plant will only cause minimal damage to the environment. There are similar regulations in states throughout the country.

In Australia where desalination has been implemented to augment a portion of the everyday water supply, the NSW *Environmental Planning and Assessment Act* is a part of the planning process. The act requires the declaration of a concept plan for a project and for the environmental impact to be defined. When considering a desalination plant the environmental factors that are considered include: seawater intakes, pipeline routes, plant sites, process chemicals, disposal sites, aboriginal issues, and social issues (El Saliby, 2009). In the case of a desalination plant in Kwinana, Australia the environmental impact assessment identified that marine habitat, emissions, noise, public safety, and aboriginal culture were all factors that needed to be addressed for the plant (El Sibley, 2009).

Mitigation

To prevent water intake systems from damaging to the environment, desalination plants should utilize mitigation methods such as controlled flow rates and intake screens. Limiting the intake flow for desalination plants can keep fish from become entrapped in the intake system (entrainment) and prevent significant salinity increases in underground aquifers. If the water is being pulled in too fast, fish and other aquatics animals may not be strong enough to swim away, leading them to be pulled into the intake pipes. Reducing the flow to less than 0.5 ft. per second will allow more fish to swim around the opening of the intake pipe without being pulled in (WateReuse Association, 2011). Another method to prevent fish from being pulled into the plant is to use screens to cover the pipes. The gaps in the screens vary in size and can exist in multiple layers. A common ocean water intake pipe will have the first screen with gaps 20 to 150 mm wide, followed by a second screen with openings 1 to 10 mm apart (WateReuse Association, 2011). Due to the presence of these screens, only small organisms like fish eggs and plankton are taken into the plant. The major drawback to this mitigation method is that fish and other marine organisms may become trapped on the screens, known as impingement. Other mitigation methods are shown in Table 4. If physicals barriers do not protect enough marine life from entrainment and impingement, a plant’s owners will typically restore wetlands to serve as a sanctuary for the species impacted by the plant. This way, aquatic animals can have a protected area for reproduction, to compensate for the eggs pulled into the desalination process.



Type of I&E Reduction Measures	**How Do They Work?**	**Technologies**	**Impact Reduction Potential**	
			Impingement	**Entrainment**
Physical Barriers	By Blocking Fish Passage and Reducing Intake Velocity	• Wedgewire Screens • Fine Mesh Screens • Microscreening Systems • Barrier Nets • Aquatic Filter Barriers	Yes	Yes
Collection & Return Systems	Equipment is Installed on Fine Screens for Fish Collection and Return to the Ocean	• Ristroph Travelling Screens • Fine Mesh Travelling Screens	Yes	No
Diversion Systems	Devices Which Divert Fish from the Screens and Direct Back to the Ocean	• Angled Screens with Louvers • Inclined Screens	Yes	Yes
Behavioral Deterrent Devices	Repulsing Organisms from the Intake by Introducing Changes that Alert Them	• Velocity Caps • Acoustic Barriers • Strobe Lights • Air Bubble Curtains	Yes	No

Table 4: Potential open intake impingement and entrainment reduction technologies (WateReuse Association, 2011)

Along with the production of freshwater, a high salinity brine must be disposed of following the desalination process. As discussed, the increased salinity and higher temperature can be intolerable to different forms of marine life, leading to the species relocating or dying. In order for the brine to have negligible effects on the environment, it should be diluted before returned to the ocean. Some plants will pump in additional seawater to mix with the brine, so that the salinity and chemical levels will be lower before disposal (WateReuse Association, 2011). There is also technology available to quickly mix the brine with the ocean water as it is being released. Alternatives include releasing the brine with changing tides, since the water closer to shore during high tide has a higher salinity than low tide, influencing a smaller impact. This can also be accomplished through colocation, where the output of the desalination plant is mixed with the output cooling water from a power plant.

Desalination around the World

There is a desalination plant on every human inhabited continent. As of 2013, there are a total of over 17,000 desalination plants worldwide combining for a total of 21.1 billion gallons of freshwater per day (International Desalination Association, 2014). As of 2019 it is predicted, 80% of the world's desalination freshwater production will be located in the MENA region. The

U.S. and Europe will combine for a total 12% of desalinated freshwater capacity (Katsandri, 2011). Plants not only differ in the quantity of water they desalinate but also in the technology used to desalinate that water. The United States and Europe typically select reverse osmosis as it is the least energy intensive option for seawater and brackish water desalination. As an example, RO accounts for 96% of the potential water production capacity of online desalination plants across the United States. In comparison, approximately 40 % of the desalination capacity around the world is from thermal technologies (Craig, 2010). Saudi Arabia commonly uses a process called multi-stage flash desalination. Though the process is much more energy intensive, the Jebel Ali M-station, as shown in Figure 14, uses cogeneration of power and desalinated water to optimize the overall efficiency of the plant, which was reported as 82% (Dubai Electricity and Water Authority, 2013).

Figure 14: The Dh10 billion gas-fired M Station at Jebel Ali, The National: UAE (Dea, 2013)

Australia's desalination efforts have seen mixed success in terms of operation post-completion. Perth, Australia has two desalination plants that service the city: the Southern Seawater Desalination Plant and the Perth Seawater Desalination Plant. Combined, the plants provide Perth with half of their water need (Water Corporation, 2015). Unfortunately, not every Australian plant has seen the same effectiveness as Southern Seawater and Perth. For example, the Victorian Desalination Plant was constructed during a time of drought, but upon its completion the drought had subsided and freshwater supplies had been replenished. Instead of running at full or partial capacity, the plant was given a zero water order until June 2016, meaning no water was needed from the plant but the city still has to pay for the plant's maintenance (Aquasure, 2015). Consumers are paying an average additional 200 dollars per year for their water because of the financial agreement Melbourne's government reached with Aquasure, the company contracted to build the plant (The Australian, 2014). Prior to the construction of the plant, one Australian organization "Your Water Your Say" protested the plant predicting that the plant would not run upon its completion, as shown in Figure 15. If the conditions under which a plant would not be operational are not accounted for, the desalination plant could place a heavy economic burden on the consumers without benefit.

Figure 15: 'Your Water Your Say' protests the Victorian Desalination Plant (ABC News, 2008)

Desalination in the U.S.

There are over 1,200 desalination plants in existence across the U.S. in a wide variety of locations and seven different climates. The majority of California plants are in the hot-dry climate indicated by Figure 16, due to the west coast drought conditions over the past 15 years. Though in generally hot-humid conditions, Florida has also constructed multiple desalination plants due to both drought and saltwater intrusion of underground aquifers (National Council for Public-Private Partnerships, 2008). Texas is classified as either a hot-dry or hot-humid climate, depending on the specific county being described. Northern U.S. is a cold climate and has not used desalination to the same extent as other areas of the country. The climate of each region is an important factor to consider in the implementation of desalination plants. The hot-dry climate typically does not have sufficient rainfall and generally faces drought which is the major reason for desalination in those areas. Residents of hot-humid climates take advantage of underground aquifers for freshwater, but saltwater intrusion has led to the use of desalination to supplement freshwater resources. The varying conditions across the country have influenced the need for desalination.

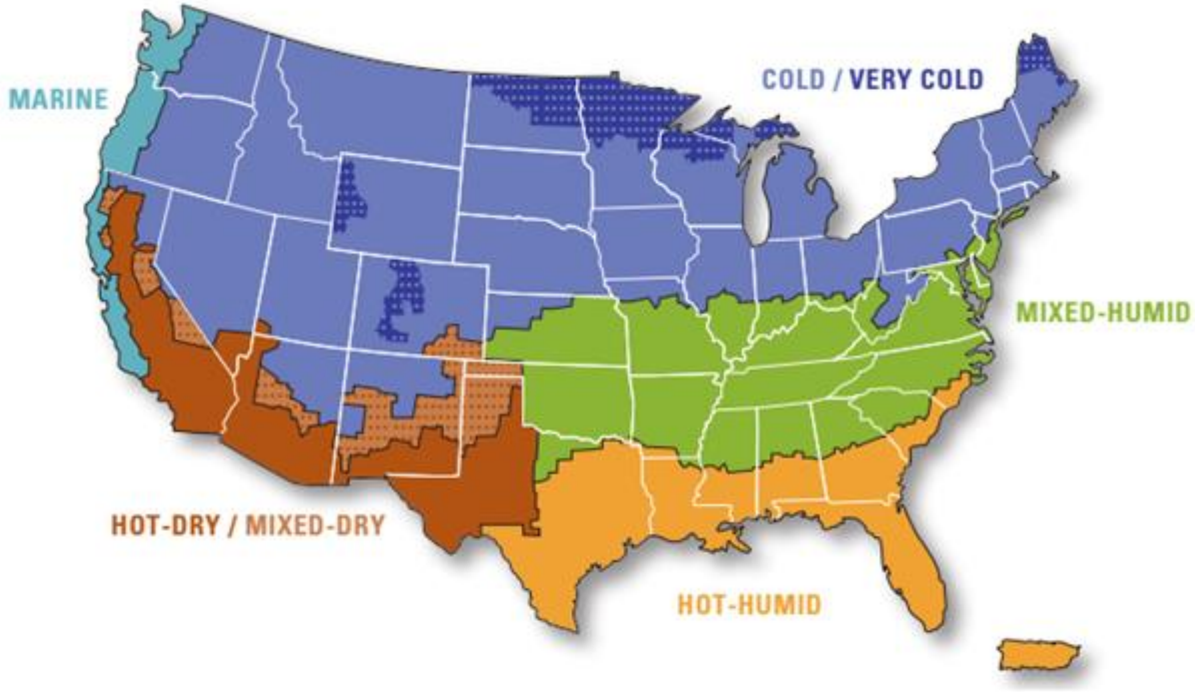


Figure 16: United States climate zones (U.S. DOE, 2015)

The use of desalination in the United States differs from that of the world, since brackish water is the primary source of water treated. Brackish water desalination provides 77% of desalination capacity in the United States while seawater desalination only makes up 8% (National Research Council, 2008). As of 2008, 96% of the desalination capacity in the United States was produced through membrane distillation, and only membrane technologies were used in the production of municipal desalination water capacity (Craig, 2010). In the U.S. thermal technologies are only used in industry, where ultrapure water is needed. These figures vary in a world where seawater is the largest source of desalination, and thermal technologies make up around 40% of desalination capacity in the world.

Key Desalination Plants in the U.S.

California's persistent drought has motivated the state and water experts to discuss different methods for supplementing freshwater, including using giant water balloons to collect water from the Northern part of the state (Potter, 2015). As a result of this ongoing discussion, there are 17 desalination plants undergoing construction as of 2014, the first of which is being developed by Poseidon Resources in Carlsbad, CA, which, upon completion in late 2015, will be able to provide 50 million gallons of freshwater a day (Boxall, 2013; Fagan, 2014). The plant will cost an estimated one billion dollars to construct and will provide fresh water to over 100,000 recipients in San Diego County, California.

Florida obtains freshwater from underground aquifers. However, saltwater intrusion has contaminated many of the aquifers because the state has overdrawn water as a result desalination is required to meet drinking water standards. The Southwest Cape Coral desalination plant was completed in 1977; the plant originally produced 3 million gallons a day, and then was upgraded over time so that it was producing an additional 15 million gallons per day by the year 1985 to meet the growing needs of the population (Aqua Care Water Treatment and Plumbing, 2011). Until 2010, the Southwest Cape Coral plant was desalinating 18 million gallons a day (City of Cape Coral, 2013) , and then the Northwest Cape Coral desalination plant was created to provide an alternate source of freshwater to compensate for the 35 year old Southwest plant beginning renovations (City of Cape Coral, 2012). The new Northwest desalination plant now produces 12 million gallons a day, with both of the desalination plants processing brackish groundwater (City of Cape Coral, 2012).

The desalination plants located in the northeastern United States are generally built as a result of saltwater intrusion. Specifically the desalination plant in Cape May, NJ was built after the town's wells salinity rose to unsafe levels. The plant desalinates two million gallons per day, servicing 60% of the small town's needs for freshwater. The desalination plant in Brockton, MA, built by Aquaria in 2008, was also constructed to combat saltwater intrusion; however, the demand for freshwater decreased through technological advancement during plant construction resulting in a completed plant that was no longer necessary. Even without requiring the plant's freshwater, the city is still on contract with Aquaria and must pay millions of dollars for the plant's operation and maintenance (Vedechalam, 2012).

Texan desalination plants concentrate on desalinating brackish groundwater, generally using RO to desalinate the water. One plant in El Paso, TX produces approximately 28 million gallons of water each day and has reduced its environmental impact by depositing its brine water 3,500 feet underground. Another plant in Brownsville, TX produces 11 million gallons a day and deposits its excess water in both a 7.5 million gallon storage tank and a 0.75 million gallon clearwell.

As of 1996, the United States enacted the Water Desalination Act to encourage the deployment of desalination in the country, the act has since been renewed multiple times (Craig, 2010). The act allows the investment of $30 million in desalination research, with an additional $25 million towards demonstration projects. The aim of the investments was to determine the most cost-effective and energy efficient means that usable water can be produced through desalination (U.S. Bureau of Reclamation, 1996). Some of the research topics include designs for different conditions of operation, methods of increasing economic efficiencies through collocated facilities, and the reduction of environmental impacts. The Desalination Act of 1996 shows as an example of the interest the United States has in the application of the technology.

Chapter 3: Methodology

The aim of this project was to provide the Department of Energy with the decision making landscape associated with the implementation of desalination. As shown in Figure 17, our project goal was accomplished by analyzing case studies of existing desalination plants, both domestically and internationally, and cataloguing characteristics of desalination plants to gain a full understanding of their function. This included: the reasons the plant was being used, the type of plant, the cost of developing the plant, the output and overall efficiency of the plant, and potential applications within the U.S.; As well as the impact of desalination on economics, ecosystems, and energy.

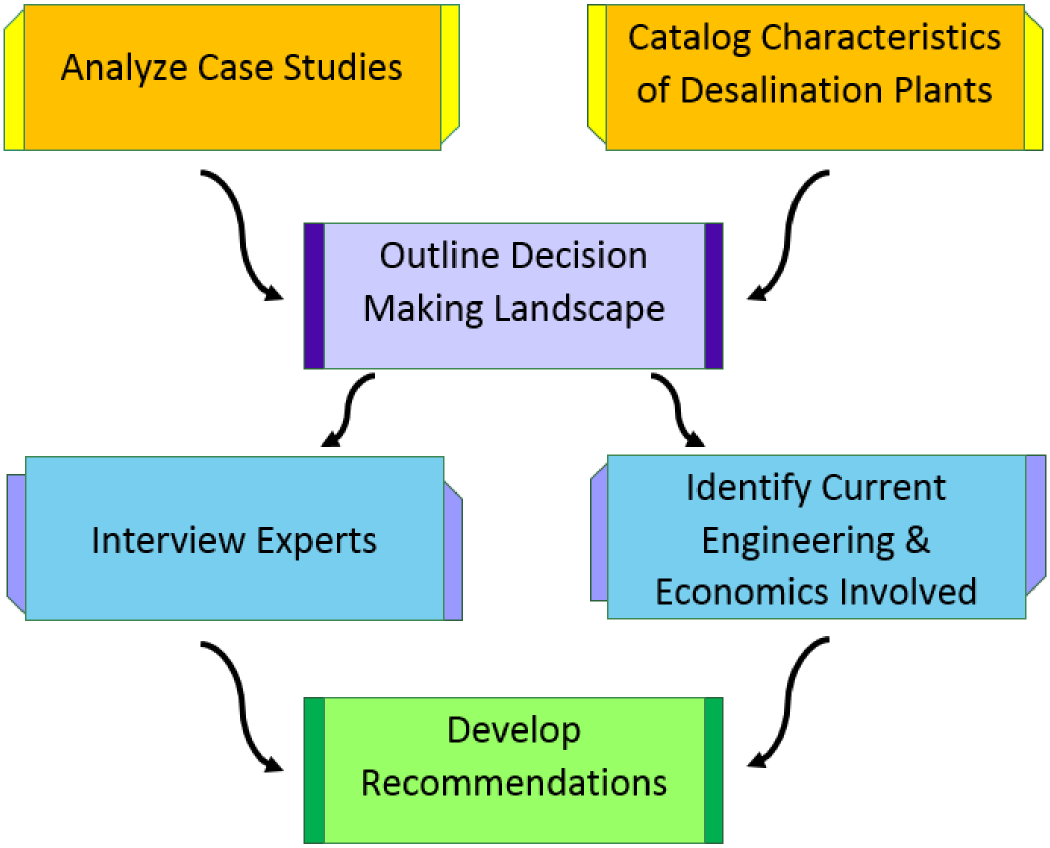


Figure 17: Project process flow diagram

The project was broken down into the following objectives:

- Catalogue the characteristics of international and domestic desalination plants considering variations in climate, location, and operational status.
- Research and describe the decision making landscape associated with the deployment of desalination plants by municipalities.
- Provide policy recommendations.

Objective 1: Catalogue the characteristics of international and domestic desalination plants considering variations in climate, location, and operational status.

Our first objective was to catalogue the characteristics of existing desalination plants around the world to gather information about their implementation. We selected eleven domestic and nine international plants, which produce a minimum of 150,000 gallons per day of freshwater, based on an overall variation in operational status, location and climate in order to gain a broad view of plant operations. Major regions we considered included: Europe, Australia, North America, Asia, and the MENA region. From the selected plants, we reviewed the characteristics and sorted them into a data matrix (see Appendix B). The team assigned a numerical value to each of the characteristics to allow quick access to data for meaningful comparisons. For example, the category of plant technology has been assigned a number between 1 and 4 based upon the technology used. The different characteristics we included in the table are: age, climate, cost, energy, feed water source, location, population served, size, technology applied, and uses for clean water. Certain characteristics of the plants have been defined as follows:

- Cost of the plant is associated with two distinct categories: cost to build and cost to maintain
- Energy considerations are divided into two categories, one for amount used and another for efficiency.
- Feed water sources include wastewater, brackish water, and saltwater.
- Size of a plant refers to the volume of freshwater the plant is able to produce in millions of gallons per day.
- Technology used can be classified as membrane, chemical, and thermal.
- Uses of the water range from industrial and agricultural use, to household use.

Additional paragraphs describing the plants in detail can be found in Appendix E. These paragraph outline information such as why the plant was constructed, issues addressed in the implementation, and unique features of the plant.

Objective 2: Research and describe the decision making landscape associated with desalination plants.

We determined the decision making landscape of desalination to be comprised of economic comparisons, motivating factors, risk factors, contract options, and permitting. This determination was made through discussion with our advisors, mentors, and desalination experts considering the multiple aspects pertaining to the implementation of desalination in order to accurately encompass all aspects of desalination in the decision making landscape.

The first step in determining whether desalination is a viable solution to the lack of available freshwater is to consider the economic viability of available sources of freshwater. These freshwater sources include conservation, desalination, and importation of water from surrounding areas. Motivating factors for the use of desalination are drought, saltwater intrusion, arid climates, and the diversification of a district's water portfolio. Examples of risk factors include varying levels of freshwater demand, drought cycles, and conservation. Contract options that are formed between municipalities and private companies can vary in their benefits and drawbacks for each group. The permitting process for a plant varies by state and addresses various areas of concern for the municipality.

Interviews were conducted with experts in the field of desalination to determine what qualities they believed to be important in the consideration of a desalination plant. These individuals were involved with research in the field of desalination or involved in the construction and operation of desalination plants from various regions in the United States and abroad. Interview questions can be found in Appendix C

The engineering and economics of desalination were identified based on reports of the cost of desalination technology. The cost of desalination technology is associated with the implementation of the desalination plant as well as the operation of the plant, and is broken down into capital and operational expenditures (CapEx and OpEx). The CapEx and OpEx were broken down into their individual components, which were then explained and identified with respect to their cost percentage of either the CapEx or OpEx of a desalination plant. The individual components of the CapEx and OpEx include, but are not limited to energy, equipment, chemicals, and maintenance.

Objective 3: Make policy recommendations

The final objective of the project was to make policy recommendations including research into innovative designs and operational schemes of desalination, specifically in relation to energy. These recommendations were based off of the information obtained in prior objectives relating to the decision making landscape of desalination implementation as well as the economics involved with desalination plants and information on problems associated with desalination. Additional recommendations for research were made based off of the process of gathering information on future technology and technological possibilities.

Chapter 4: Results

There are many steps a municipality must take into account before constructing a desalination plant. To ensure desalination is optimal, other forms of fresh water supply augmentation must be compared by identifying goals for additional supply, performing economic comparisons, and outlining different risk factors. Once desalination is chosen, additional steps such as creating a contract with a contractor and acquiring permits for the plant must be completed.

The Decision Making Landscape

Through the construction of the data matrix, interviews with desalination experts, and extensive research on desalination in the U.S. and internationally, the team discovered that there are commonalities in the decision process for desalination plants, but no two plants are identical.

Figure 18 provides a breakdown of the decision making process for desalination. The first aspect is to determine the reason there is a freshwater need for a region. These reasons vary from drought and arid climates, to population increases and saltwater intrusion, as discussed in Chapter 2. There are also other sources of freshwater to consider for supplementing a region's supply including new ground and surface water sources, importing water, recycling water, and conservation. A municipality would choose desalination as opposed to these alternatives for reasons such as an overall lower cost, a desire for a long term reliable source of freshwater, and diversification of an area's "water portfolio". Once desalination is determined to be the best option, decisions regarding financing, contracts, permits, technology, and energy sources must be made. These determinations will be made based on a plant's location and the organizations involved with the construction of the plant. Each of these steps in the decision making process will be explained in more detail below.

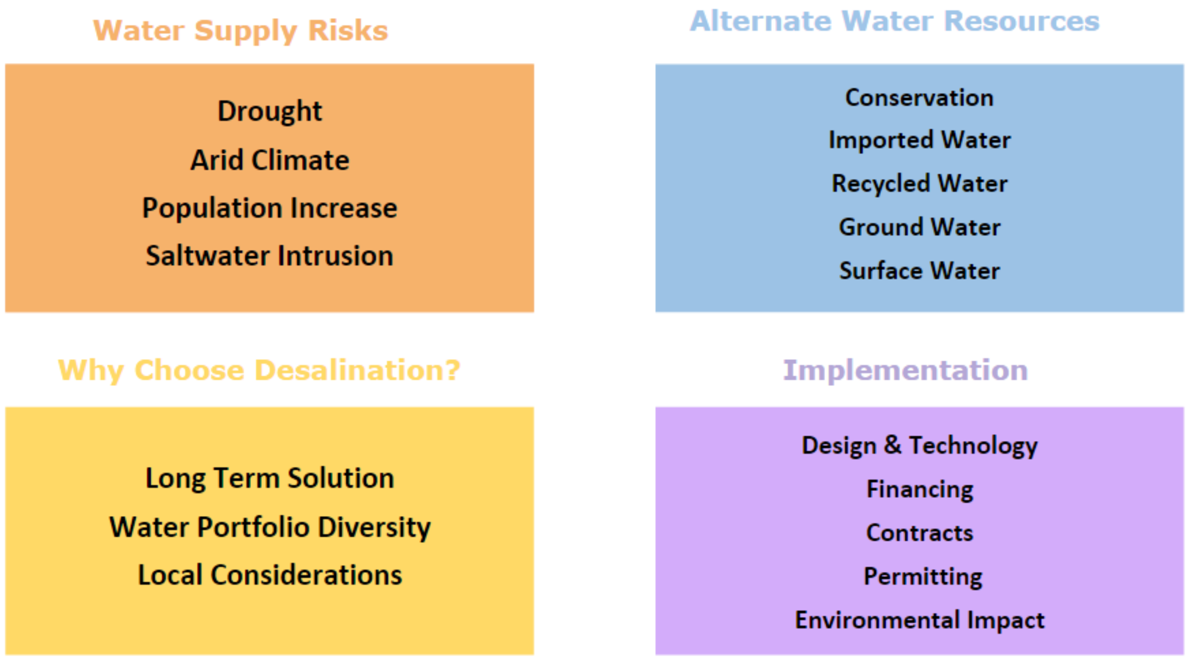


Figure 18: The decision making landscape of desalination

Supplemental Water Sources

There are several different water sources a municipality may consider for mitigating an insufficient freshwater supply including surface water, groundwater, imported water, water conservation, and desalinated wastewater. Locating and utilizing new sources of surface water and groundwater is the most direct way to increase the available freshwater supply. As of 2005 in the United States, 77% of freshwater came from surface water and 23% came from groundwater (Perlman, 2015b). This method is only applicable if other sources of freshwater are available; if the sources typically used by a municipality are depleted by drought or contaminated by saltwater intrusion, there may not be another sufficient natural source.

Conservation is generally an inexpensive alternative when compared to the implementation of the additional supply. As conservation is able to decrease the demand for water, it may also affect supply expansion projects if conservation is considered afterwards, as was the case in Brockton, MA. In Brockton, a 5 MGD reverse osmosis plant is now limited in operation due to conservation efforts post-construction. Methods of conservation may include infrastructure improvements, leak detection programs, fixture upgrades, and restrictions on use.

Leak detection programs may provide information on improvements to be made to increase control of water sources, thus reducing loss throughout a system. Fixture upgrades may include high-efficiency appliances and even alternative landscaping options that do not require watering. Rebates may be given to consumers willing to implement fixture upgrade options. Lastly, restrictions on water use may be put into place, such was the case when Poway, California faced a drought and imposed water bans, encouraging residents to conserve and minimize their water usage. The bans allowed the city to reduce their water consumption by about 32%; therefore, no further action was needed in reaction to the drought (Peterson, 2015). In some cases, conservation may be adequate for mitigating a water supply issue, and the municipality does not need to implement other methods of freshwater production.

The importation of water to where there is need may also be considered. While one region has insufficient amounts of freshwater, another may have excess. There may be the option for a municipality to purchase this excess supply. Transportation of the water may be achieved through systems of pipes or tank trucks (National Drought Mitigation Center, 2015). This method requires the cooperation of multiple municipalities, resulting in towns and cities to become dependent on others for water.

The reuse and treatment of wastewater is another way to mitigate limited freshwater supply. Wastewater is a water source that has been utilized and thereby had its quality diminished (Tatum, 2015). Examples include agricultural runoff, household waste, and rainwater diverted to sewers. Wastewater treatment plants are used to purify the water for reuse. The process uses different chemical and biological techniques, depending on the source of the wastewater, to remove contaminants in the water that could be harmful to human life or an industrial process. This method for obtaining freshwater is widely used in Israel, the world leader in recycling wastewater (Mandell, 2012). Israel treats approximately 105 billion gallons of wastewater each year, which is 80% of the country's wastewater (Mandell, 2012). For comparison, Spain is the second highest wastewater recycler, recycling 20% of their wastewater (Mandell, 2012). The majority of this water is used for agricultural and industrial purposes, but is purified enough to be potable (Mandell, 2012).

Municipality Considerations

In the selection of a mitigation method there may be specific goals or requirements put in place by a municipality including: determining whether a long-term or short-term solution is desired, locally based factors that affect the solution, and whether water diversification is an issue. Long-term solutions are less prone to sudden change and act more permanently. A long-term solution may be desired in areas where the problem affecting the freshwater supply is not expected to be relieved or may become worse, such as drought and saltwater intrusion. Saltwater desalination is a long-term solution unaffected by drought as the ocean can be thought of as an endless water supply.

Requirements and preferences may change by locality. In the selection of a desalination plant for Cape May, NJ, desalination was chosen because the city did not want to become dependent on another county for their water supply (Blair, 1999). By constructing a desalination plant producing up to two million gallons of freshwater a day, purifying their own aquifers and using dried up wells as a natural storage location to build up their freshwater supply, Cape May was able to keep their resources under local control, rather than relying on other communities for the importation of water.

Municipalities may be interested in adding solutions that are independent of their current sources of water. In Cape May, NJ past issues with saltwater intrusion increased support for desalination; the drilling of additional wells would have been prone to the same issues currently affecting the supply and therefore only a temporary solution (Blair, 1999). By using water from different sources, the city expands their “water portfolio”, introducing a more secure water supply to the area. With varying freshwater sources, an area has more security in knowing there is a backup source of freshwater should a method fail. In Mossel Bay, South Africa a severe drought sparked the construction of a 4 MGD reverse osmosis plant (Veolia Water). As of 2011, the plant is no longer needed to supply water for domestic use, but is still being paid for by increasing the price of water from other sources. The spokesperson for the Mossel Bay municipality, Harry Hill, has stated that they do not view the plant as a waste since it serves as insurance against future shortages (Van Rijswijck, 2011).

Risk Assessment and Identification

There are also specific risks involved with options like desalination, such as effects caused by drought and saltwater intrusion. Droughts, whether long or short term, pose a risk to the success and use of a desalination plant. During a drought, water supplies are depleted, causing a municipality to turn towards other sources, including desalination. If the drought ends during or immediately following construction, the municipality is left to pay for the plant, regardless of their need for water. This will increase the price residents are charged for water, even if it is coming from existing freshwater sources. This increased price does not typically receive favorable opinions from the general public, and the municipality would have invested time and money into a project that was unnecessary. The drought must be analyzed to determine if it will be long enough to validate the construction, or if droughts are frequent enough that the plant could be a beneficial long term investment.

Desalination plants constructed to combat saltwater intrusion by purifying brackish groundwater may encounter problems over time. As water is drawn out of an aquifer, seawater flows in to replace it. If water is removed at a high rate, such as with desalination, the seawater will not be naturally filtered to produce freshwater as previously discussed thereby increasing the salinity of the water in an aquifer over time. Water with increased salinity requires a higher pressure when used in membrane technologies, such as RO. The desalination plant in Cape May has seen the increase of the salinity of its feedwater from 1900 to 2400 ppm over a period of ten years (Vedachalam, 2012). Increases in pressures due to the increase in salinity leads to an increase in the cost to operate the plant.

Changes of water supply demands also pose a risk to the expansion of water supply. Future reductions in the need for water supply may change the need for implemented expansions in the supply, possibly causing them to not be needed. Reductions in water supply need are especially of concern when conservation is performed after expanding the water supply, as was the case in Brockton, MA. After implementation of a 5 MGD desalination plant, Brockton implemented water conservation and infrastructure improvements that lowered the total demand in the city by 3 MGD (Vedachalam, 2012). The change in demand has resulted in limited use of the desalination plant, but the city must continue to pay five million dollars per year for the supply of water regardless of use due to contractual obligations.

Freshwater Cost

The costs of different water supply and demand management options impact a municipality’s choices, as high cost solutions or prices may outweigh the benefits. With current desalination technology, desalinated water generally has the highest average cost of freshwater supply augmentation methods. For example, the marginal water costs for San Diego County as of 2010 are shown in Table 5 below. Water Conservation has the lowest cost, as low as $0.45 per 1,000 gallons, with desalination costing as much as $8.59 per 1,000 gallons (Cooley, 2012). This increase in cost can impact the feasibility of building a desalination plant as opposed to conservation or finding new sources of groundwater or surface water.

Water Type	Cost per 1,000 gallons of freshwater
Imported Water	$2.69-$2.99
Surface Water	$1.21-$2.46
Groundwater	$1.14-$3.37
Seawater Desalination	$5.53-$8.59
Recycled Water	$4.30-$6.61
Water Conservation and Efficiency	$0.45-$3.07

Table 5: Marginal water costs for San Diego County (Cooley, 2012)

The Cost of Desalination

In 2010, the Global Water Intelligence reported that $6.6 billion would be spent on the operational costs of all desalination plants worldwide. In the same year, an additional $6 billion would be spent in the form of capital costs for construction of new plants. As shown in Figure 19, the capital and operational costs will continue to grow as additional desalination capacity is added. In 2016, it is predicted that the global cost of operating the plants will exceed $11.8 billion and the capital costs will exceed $18 billion. Desalination is a growing industry with significant capital, energy, equipment, and labor costs (GWI, 2010).

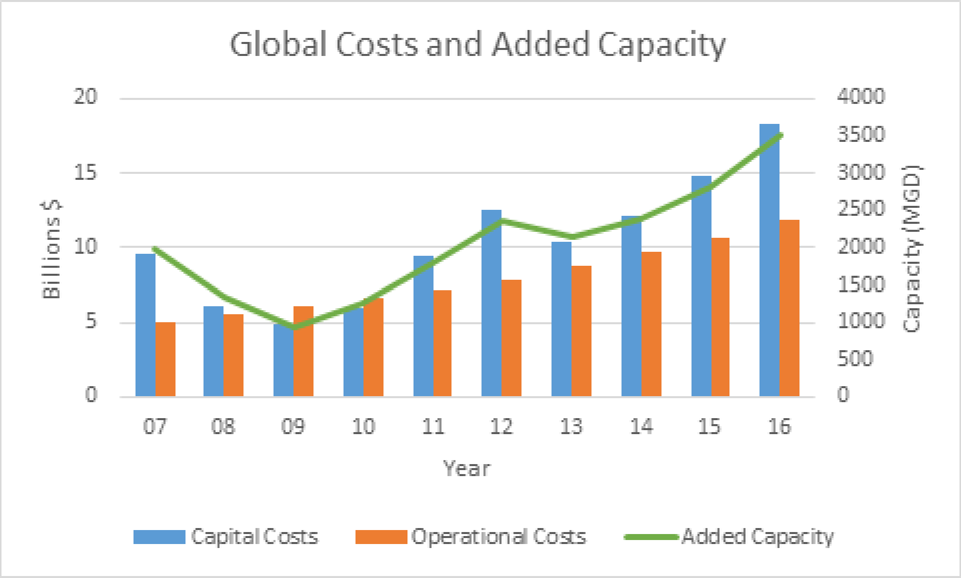


Figure 19: Added global capacity from 2007- 2016 compared with total operational costs and capital costs for newly constructed plants (data from: GWI, 2010)

In the United States reverse osmosis is the most prominent technology used for desalination. Thermal technologies do not have the same share of the country's market as they do in the world market, due to the large amounts of thermal energy required. The larger amounts of thermal energy combined with the high cost of fuel in the U.S. make current thermal technologies uneconomical when compared to reverse osmosis. Therefore, the current costs outlined are focused around the use of reverse osmosis and include capital and operational breakdowns of such.

Capital cost is a constant in the annual costs of a desalination plant. For a 50 MGD Seawater Reverse Osmosis (SWRO) plant, annualized capital costs make up approximately 37% of the annual cost breakdown of the plant (Cooley, 2012). As seen in Figure 20, the capital cost of a plant includes costs associated with the design, planning, and construction of a plant. Significant costs are present in the design, legal, and engineering costs associated with the construction of a plant. Other capital expenditures are related to the materials, equipment, and labor involved with the construction of a plant. To put the capital cost of desalination into perspective, the recently constructed desalination plant in Carlsbad, CA cost approximately a billion dollars to construct. The 50 MGD plant is co-located with a power plant, which helped to reduce the cost of the plant by using the existing intake and outfall structures of the power plant. Additional examples of capital costs breakdowns are shown in Appendix F.

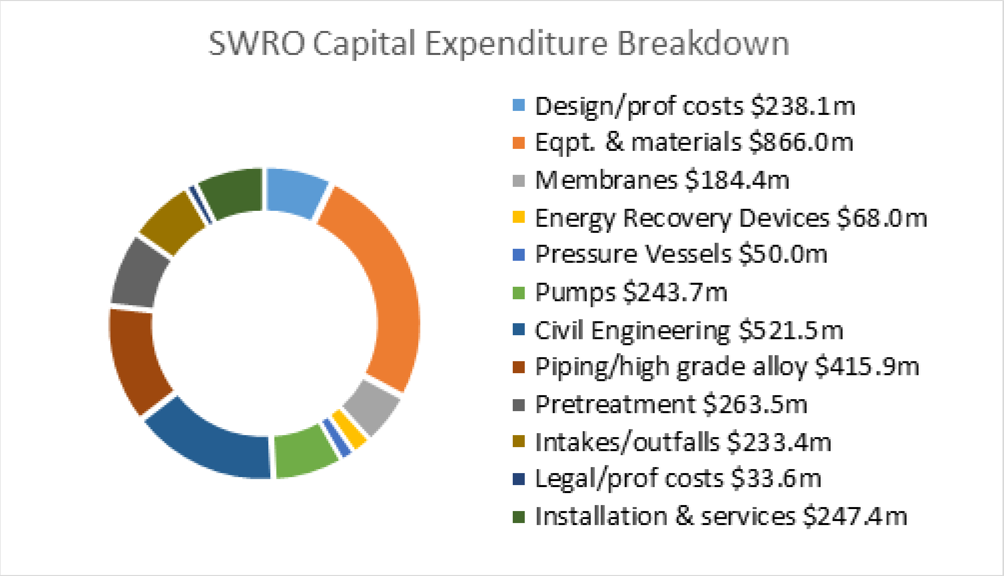


Figure 20: Global capital expenditures for SWRO plant construction in 2010, a total of $3.4 billion was spent (data from: GWI, 2010)

The operational costs of a SWRO desalination plant include energy, labor, maintenance, membranes, and chemicals. The operational costs can be further categorized as constant and variable costs. As shown in Figure 21, the largest operational costs are associated with energy requirements and chemicals, making up 36% and 12% of the total yearly cost of a 50 MGD SWRO plant respectively (Cooley, 2012). Energy and chemicals are also the two variable costs associated with the operation of a RO plant, meaning they are expected to fluctuate with the change in production of a plant as well as the cost of the resources. Chemicals used in the process are for the pretreatment of incoming water, maintain membrane elements, and mineral treatment after the desalination process (Cooley, 2012). Labor, maintenance and membranes are constant costs to a plant; they will remain constant through changes in production capacity. The replacement of membrane elements represent approximately 4% of a SWRO plants annual cost. A typical 38 MGD plant requires 840 membrane elements, which cost $450 each, though prices are expected to continue decreasing (Katsandri, 2011). Each element has a life of up to ten years, though they typically are replaced between years 5 and 7 to maintain higher water quality.

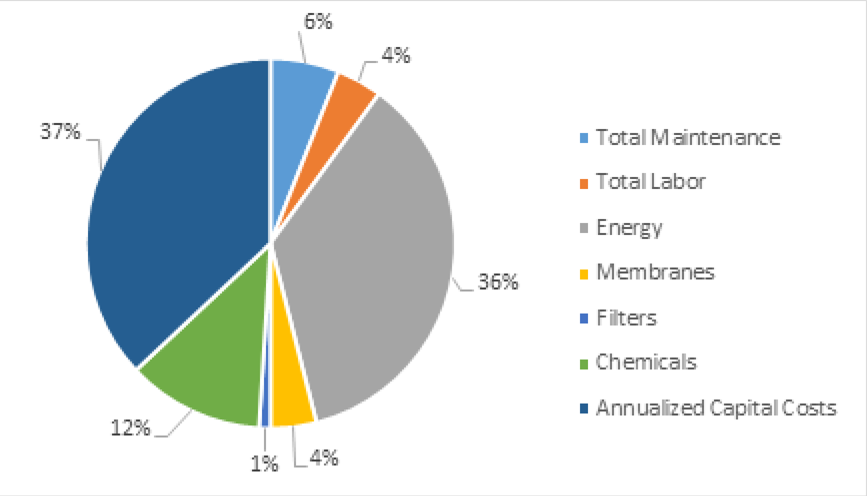


Figure 21: Annual operational expenditure breakdown for a 50 MGD SWRO plant. With constant energy costs of $0.07 per kWh; a membrane life of 5 years; 5% interest rates; and a depreciation over 25 years. (NRC, 2008)

The cost of electrical energy for a plant depends on local factors, such as the types of power plants used in the area. Nuclear and coal electrical power result in the least expensive power costs, while the use of oil for power production results in the most expensive energy costs, as shown in Figure 22 (Katsandri, 2011). By switching from oil and gas to nuclear power, the cost of water produced by RO can be cut 44%. Another advantage of nuclear power is the ability to operate with minimal CO_2 emissions, allowing for less expensive and cleaner energy when compared to other traditional power plants (Katsandri, 2011).

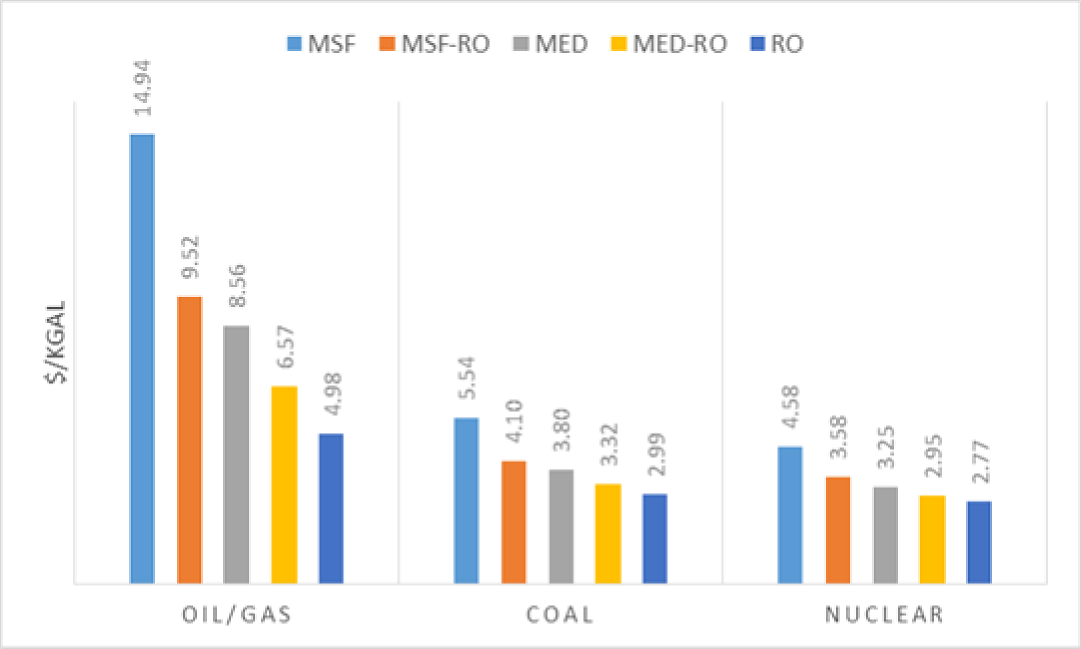


Figure 22: Cost of desalination for types of energy production. Data based off of 1,300 MW facilities with a capacity of 2.71 MGD. (Data converted from: Katsandri, 2011)

Costs of a reverse osmosis plant also relies on the salinity of the feed water. Brackish water (BW) plants are subject to less operational and capital costs, allowing their total process cost to be less than that of seawater (SW). The process cost over the lifetime of a SWRO plant will be nearly four times that of a BWRO plant (Appendix G). The difference in pricing of the two water types allows for a 50MGD BWRO plant to have operational expenditures of $0.29/kgal, while a similar SWRO would cost $0.70/kgal (see Appendix G for details).

The cost of desalination in the country is dependent on varying factors such as the size of a plant, feed water salinity, and the unit cost of variable costs. Appendix F gives a more detailed breakdown of the different costs associated with reverse osmosis desalination with regards to plant size as well as seawater and brackish water treatment. Currently, reverse osmosis is the least expensive and most economical desalination technology for mass production. Improvements in the process could allow for less expensive rates, which may allow for desalination to be competitive against other alternative water sources.

Contract Options

There are a variety of agreements that are formed between a municipality and a private construction company to manage the construction and operation of the plant. This process is initiated by either a municipality that decided to use desalination or a private company that believes a certain area is a good candidate for desalination. These options influence the distribution of risk between the municipality and the private company, along with different finance methods. “Key Issues for Desalination in California: Cost and Financing” describes the following five categories of contracts between a municipality and a private company or contractor (Cooley & Ajami, 2012).

Design-Bid-Build

A Design-Bid-Build (DBB) method for contracts between a municipality and a private company gives the municipality almost full control over the desalination plant and its construction process. In this case, a municipality or public water provider determines the need for a plant, obtains the funds for the plant, and runs the design process to meet the needs of their region. The municipality will then start accepting bids from contractors to build the designed desalination plant. The contractor or private company who is able to construct the plant the municipality desires for the lowest cost is given the job. The contractor only constructs the plant, before turning it over to the municipality to run. In this scenario, the municipality and the fresh water consumers have the highest risk of unforeseen costs and consequences involved in the operation of this plant. All possible variations in cost, due to changing energy markets or problems with the operation of the plant, are the responsibilities of the municipality to finance, potentially increasing the price of water significantly. Another drawback is that the plant may take longer to construct, since the contractor makes money off of the plant’s completion and not operation. This is a beneficial option when the municipality wants more control of the plant.

Design-Build

A similar contract design is Design-Build (DB). DB is similar to DBB with the only change being the removal of the bidding process. One contractor is brought in to construct the plant for a fixed price that meets the specifications the municipality has asked for. Some details of the plant, such as types of pumps used, are determined by the contractor. The lack of bids from private companies saves time throughout the design, construction, and operation process, since the municipality does not need to review and decide on a proposal. Also, allowing some of the details to be decided by the contractor might increase innovation and efficiency of the plant by allowing experts in the field of desalination determine the best way to meet specifications. A potential disadvantage to DB is that the cost to construct the plant will be higher, since contractors are not competing against one another to have the lowest cost to obtain the job. A region with a large budget, time constraints, and a need to maintain control of the desalination plant would benefit most from this contract.

Design-Build-Operate

Design-Build-Operate (DBO) is when a municipality determines a need for a desalination plant and obtains the grants and loans necessary to fund the project. From there, a company is hired to design and construct the plant. This group will also be in charge of the long term operation of the plant. DBO gives more control and risk to the contractor, and is frequently used when the owner does not have experience in the desalination process. The municipality maintains ownership of the plant, allowing flexibility of the quantity of freshwater produced, while providing an incentive for a high quality plant, since the contractor is in charge of operation and must produce the necessary amounts of freshwater. This scenario distributes risk relatively evenly between the municipality and contractor.

Design-Build-Own-Operate-Transfer

A contract option where the private company has more control is Design-Build-Own-Operate-Transfer (DBOOT). A private company will determine that an area is a good candidate for desalination, design a plant, and then discuss their proposal with the municipality. If the municipality agrees to buy the water from this proposed desalination plant, the private company obtains the finances for construction, builds and operates the plant. After a certain amount of time the desalination plant is transferred to the municipality on the predetermined date. Until the transfer, the plant is owned by the company, and the municipality simply purchases the water produced. Frequently, there is a set amount of money the municipality must pay the company every month, in order for the company to ensure they will be able to pay back the loans necessary to construct the plant. Every other aspect is controlled by the company, including any mechanical failures, damage from natural disasters, and everyday operation of the plant. This places a lot of risk onto the private company and contractors, since they are financially responsible for any unforeseen costs that arise. The major risk to the municipality is that if they do not need the water provided by a desalination plant, they still have to pay a fixed rate, increasing the amount of money consumers are charged for freshwater.

Design-Build-Own-Operate

One final common contract option is Design-Build-Own-Operate (DBOO). This is very similar to DBOOT, except the private company maintains ownership of the plant and there is not transfer to the municipality. This takes away even more control from the municipality and gives it to the company, putting greater long term risk with the private company. Figure 23 shows the five contracting options and their relative levels of public and private risk.

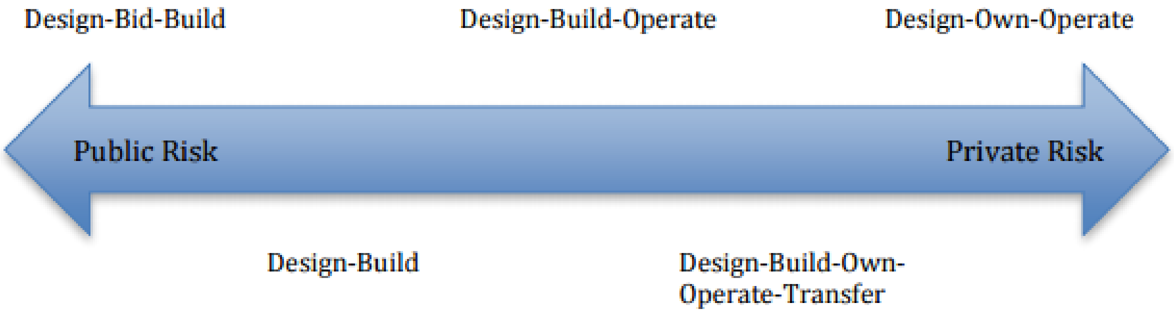


Figure 23: Risk allocation under various project delivery methods (Cooley & Ajami, 2012)

Financing

Initial construction of a desalination plant is a large investment, so a municipality or private company must secure the finances to build a plant before they can produce water to sell. This funding can be in the form of grants, bonds, loans, or private equity. Typically, due to the steep cost of the plant, the owner of the plant must apply multiple methods to fulfill their budget requirements.

"A grant is an award of financial assistance in the form of money with no expectation that the funds will be repaid" (Cooley & Ajami, 2012). Both federal and state governments have grant programs to provide funds for research and development, infrastructure improvements, to maximize the use of natural resources, and more. These include water security, clean drinking water, and desalination. Typically, grants will not cover all of the expenditures associated with the construction of a desalination plant, but can contribute to the overall costs. Federal grants typically are given to research and development as well as pilot plants, which assist in developing the technology used, but do not allow municipalities to build full scale desalination plants.

Another form of financing a desalination plant is bonds, which can either be provided by municipalities, corporate organizations, or the U.S. Government. Bonds are an agreement in which someone borrows money and agrees to pay back that amount on a specific date in the future, along with paying interest on the total amount periodically throughout the borrowing time frame. The bonds can either be repaid from a specific revenue source that the bond was issued for, “revenue bonds”, or payments can be independent of the success of the project, “general obligation bonds” (Cooley & Ajami, 2012). The U.S. government approves bonds for municipalities, while corporate bonds are sought after by private companies.

Loans are a similar to bonds, where a lender gives money to the municipality or contractor, who agrees to pay back the money and interest in the future. Both federal and state governments have low interest loans that can be obtained for desalination plant construction. Loans may also be provided by commercial lending institutions, where the money borrowed is backed by collateral.

Private equity is used by private desalination plant construction companies to fund their business ventures. Another firm gives money to the project in exchange for partial ownership of the desalination plant constructed. This allows the plant to be built, but decreases the profit that can be made by the construction company, since a portion belongs to their investors.

The types of funding a project is able to use are dependent on the borrower and the location. For example, grants and bonds are more frequently used for municipality-owned plants and, while private companies utilize private equity and investments. Additionally, states have different financial opportunities available, such as varying amounts of grants and different allowed uses for the funds.

Permits

The permits required for desalination plants in the United States are controlled by federal, state, and local governments. As a result, the permits required vary from plant to plant. The scope of the permits include areas such as land rights, construction regulations, intake water location and velocity, output brine concentrations, and the environmental impacts of the construction and operation of the plant. More specifically, federal regulations are observed in cases where endangered animals are in the area and can be negatively impacted by the plant.

The disparity between state and local regulations can cause delays in the construction of a plant. For example, in Carlsbad, California, the construction of a desalination plant was delayed ten years due to the long permitting process. Also, no two plants are exactly alike, so land use, energy consumption, water source, and the surrounding areas all have different rules and regulations. In areas such as the Northeast, where desalination is less prevalent, the process of submitting and filing for the permits is uncommon resulting in delays (Vedachalam, 2012). In the case of a plant built in Brockton, MA, the permitting process delayed the construction of the plant by nearly four years due to the Massachusetts Department of Environmental Protection being unfamiliar with the process for desalination plants (Vedachalam, 2012).

The permitting process can be a lengthy process required prior to construction. As many as thirty different permits from various levels in government may be required prior to breaking ground on construction (Vedachalam, 2012). The current permitting process involved with desalination plants plays a large role in the timeframe in which the plants can be implemented, due to eventual delays in the construction of a plant.

Advancements in Technology

Advancements in current technologies, as well as the introduction of new technologies will be needed to increase the value proposition of desalination. The value proposition can be increased through technological advancements resulting in reduced energy usage, cost reduction, and waste energy use. At the Energy Optimized Desalination Technology Development Workshop in 2015, a goal of \$0.50/m^3, or \$190/kgal, was outlined to allow desalination to be competitive in the water infrastructure. There are two possible ways to increase this proposition, one is through improvements in current desalination technology, and another is through research into alternative desalination methods and their commercialization.

Technology Improvements

Originally pioneered in the 1970’s and later commercialized in the 1980’s, reverse osmosis has seen dramatic energy use reductions. These improvements were due to the use of high-permeability membranes, the use of energy recovery devices, and use of more efficient pumps (Elimetech, 2011). In the seventies the energy use of desalination was over 15 kWh/m^3, this has since been reduced to as low as 1.8 kWh/m^3 in pilot-scale systems (Elimelech, 2011). Additional improvements are needed to maintain reverse osmosis’s place in the market, as well as increase its value.

One such way to increase the value of reverse osmosis is through advancements in membrane technology. Improvements are possible to reduce the capital costs of the membranes, as well as the operational costs associated with the process. Ultra-high permeability membranes are a new alternative that may be able to reduce pressures needed during the filtration process, reducing the energy demand, they also would help to reduce the capital costs of membranes as less element would be needed for a given water flux (Elimetech, 2011; GWI, 2010). Additional improvements into membranes with fouling resistance could help to reduce the energy use, reliability, and environmental impact of the process (Elimetech, 2011). Such membranes would reduce the amount of chemicals needed in the process of cleaning the membranes and pretreatment of the feed water. Large diameter membranes are also a viable option to reduce capital and operational costs (GWI, 2010). Improvements in membrane technology play a role in the entire system of reverse osmosis.

The pretreatment process of reverse osmosis is a possible area of improvement that could help to reduce the cost of desalination in both operations and capital. There is currently no standard method of pretreatment for the process; a standardized pretreatment method would result in reduced costs of the filters and membranes used in the pretreatment stage. Costs associated with the pretreatment stage could also be reduced due to the use of reverse osmosis membranes that require less chemical pretreatment.

The more widespread use of energy recovery systems as well as more efficient application would play a role in the overall energy use of a system as less energy is wasted. Though many new systems incorporate these systems, there is room for improvement (GWI, 2010). Additional energy reductions could be possible in the implementation of staged membrane operations, which incorporate two stages of reverse osmosis in series. The main advantage of the system is the use of less energy than a single stage osmosis plant due to bringing smaller amounts of water to high pressure. The first stage operates at a lower pressure and has less flux across the membrane, but the second stage operates using the brine from the first stage at a higher pressure. The energy use of the plant would theoretically decrease as more stages are implemented, but their implementation involves additional capital investments into the production of a plant.

There is room for improvement in reverse osmosis, but as energy prices rise these improvements may not be able to reduce overall costs. This was seen in the early 2000s as reverse osmosis was expected to see a continuous reduction in costs, but has yet to fall below \$0.50/m^3 (GWI, 2010). With minimal improvement since the Hyflux was contracted in 2003, achieving a cost of \$0.57/m^3 (GWI, 2010). Current uses of reverse osmosis are as little as 25% from the practical minimum energy required for an ideal reverse osmosis operation (Elimetech, 2011). There may be more opportunity to increase the value of desalination through the implementation of new technologies into the market, as reverse osmosis continues to reach practical minimum costs.

New Technology

As the current processes, such as reverse osmosis, inevitably reach a point of limiting returns and the cost of research into advancements outweighs the value of the advancements, new technologies can provide advancements in the desalination field. Research into new technologies may prove to be similar to the history of reverse osmosis, becoming more competitive over time as research when breakthroughs in the technology are discovered. These technologies include membrane distillation and forward osmosis, which are close to commercialization.

Membrane Distillation

Membrane distillation is a thermally driven process that incorporates a hydrophobic membrane for the support of a liquid-vapor interface (GWI, 2010). As shown in Figure 24, the membrane only allows vapor to pass through and condense on the other side; the passage of the vapor is driven by a temperature difference between the two sides of the membrane. There are currently four different types of membrane distillation systems, with two, Memstill and Memsys, being near the point of commercialization (GWI, 2010).

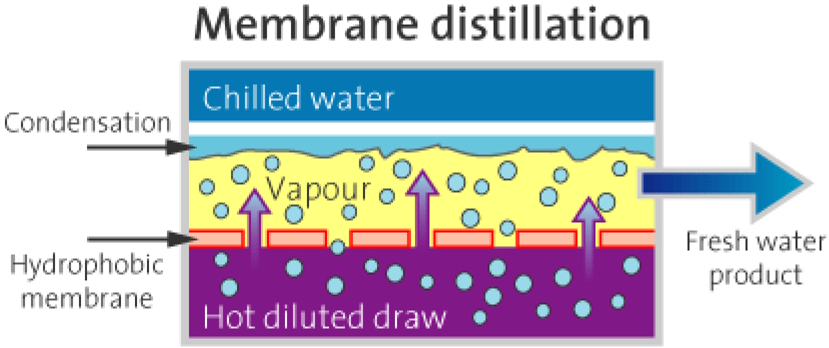


Figure 24: Cutaway of flow within the membrane distillation desalination process (bluetech)

Memstill uses warm and cold seawater on either side of a membrane to create a temperature difference, resulting in a pressure differential. The pressure differential works to pull the vapor from the warm seawater through the membrane. One advantage of this system is the ability to use low-grade waste steam and heat from sources such as power plants, refuse incineration plants, and other heat generating plants (GWI, 2010). The use of waste heat energy allows for less use of electrical energy in the operation of the plant, and is an option to decrease the grid demand of desalination.

Memsys is different from Memstill through the inclusion of multiple distillation effects, or stages. At each stage in the process the brine from a previous effect is distilled at a lower pressure through all effects. At each effect the heat energy is recovered from the preceding effects. An advantage of the system is the ability to operate without the need for chemicals, a large cost of desalination processes such as reverse osmosis, and a 100 µm filter being the only required pretreatment. Reduction in the required pretreatment would relate to significant decreases in energy required for the process, which currently accounts for large amounts of the energy used in reverse osmosis (Elimetech, 2011).

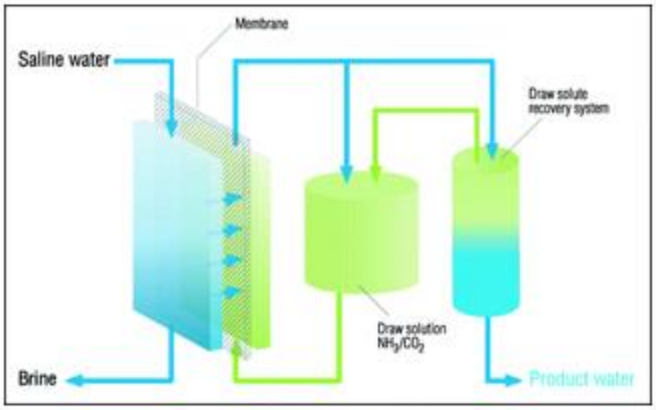
Memstill and Memsys share other advantages in their process design such as the ability to be driven by solar energy when waste heat is not available. Also, they operate at much lower temperatures, when compared to conventional distillation techniques, of around 140 degrees Fahrenheit. Other advantages of the technology are as follows (GWI, 2010):

- Lower operating pressures than conventional pressure-driven membrane processes
- Low sensitivity to variations in process variables, such as pH and salinity
- Reduced facility volume when compared to conventional distillation
- 100% rejection of ions, macromolecules, cells, and other non-volatiles

The process also contains some drawbacks including low yield rates when compared to the conventional desalination techniques, the required separate treatment of undesirable volatiles in the water, and the dependency on a waste heat source. Membrane distillation is promising due to its ability to use waste heat from various processes in the production of desalinated water. However, improvements in the yield of the process will help to reduce costs by requiring less raw water for the same amount of production.

Forward Osmosis

Forward osmosis works off the same idea as reverse osmosis, through the inclusion of membrane to desalinate water. Unlike RO, forward osmosis uses osmotic pressure, rather than hydraulic pressure, to create a pressure differential across the membrane. As shown in Figure 25, the process uses a concentrated high osmotic pressure draw solution to pull the lower concentrated saline water through the membrane, where salinity is removed. This step results in a diluted draw solution. To produce freshwater, the solute must be removed from the diluted draw solution; how the solute is removed is dependent on the type of solute used.



Forward Osmosis (FO) Diagram

Figure 25: Forward Osmosis process flow diagram (Wasserman, 2013)

When dissolved gases are used as the solute, it is possible to use thermal energy to remove the solute. Low-grade waste heat can be used for separation of the gases to produce fresh water. The use of high molecular weight solutes are able to be removed through physical means, this results in lower energy costs than the filtration methods used in reverse osmosis (GWI, 2010). As the solute is removed, it can be recycled in a closed loop within the forward osmosis process.

The forward osmosis process shows promise as a technology to allocate waste heat for the purpose of desalination. Specific improvements in the area of membranes could help to increase the value of the technology. More robust membranes that meet the requirements of forward osmosis would allow for lower concentrations of the draw solution, resulting in lower energy requirements (Elimelech, 2011). The commercial availability of forward osmosis membranes is a current limitation in the commercialization of the process, with current systems featuring limitations due to the adaptation of reverse osmosis membranes (GWI, 2010).

Forward osmosis also has the ability to be combined with reverse osmosis to create a hybrid. One such combination incorporates a forward osmosis system followed by reverse osmosis. In the forwards osmosis system, pure salt is used as the draw solution. The diluted ultra-high salinity solution can then be processed by a reverse osmosis stage. Advantages of this hybrid include reduced risk of fouling and scaling of membranes.

Alternative desalination methods to those already widely used in the world, may serve as a way to increase the value of desalination. These alternatives may serve as a way to reduce the cost of production for desalination, as well as to incorporate waste heat into the desalination process. The use of waste heat would allow for the use of available energy, which would otherwise not be used, to supplement the production of desalinated water. The use of the waste heat would result in less demand on the electrical grid compared to current desalination practices.

Desalination and the Energy Problem

As mentioned prior, power plants are having difficulty managing the load on the grid. The plants are not designed to produce the low amount of energy during the dip in demand in the middle of the day, nor able to ramp up with the demand around 5pm. Storing the energy during the day is currently unviable, but running a desalination plant more during the hours of low grid demand might help mitigate the problem. Desalination plants may be designed with variable production capacity by the hour; this way a plant can maximize economic and energy efficiency by producing the maximum amount of water during low costs for energy and less over the rest of the day. This also benefits the power plants, creating a more level grid demand with a higher minimum value.

Social Implications

In addition to the technical aspects of desalination, there are social implications of building a desalination plant that must be considered. Environmental impacts and increased water prices have led to backlash from citizens living in areas utilizing desalination. Protests and lawsuits can impede the progression of desalination plant construction and new research as well as negatively impact the local opinion of desalination.

Should the public protest or petition against a plant, the required time to finish construction might increase, thus increasing the time the community will lack the freshwater provided by the desalination plant. For example, multiple protests occurred during the construction of the Victorian desalination plant in Melbourne, Australia. These protests included beachfront signs, signs outside the plant’s property and people chaining themselves inside the plant’s property (ABC News, 2008; Gray, 2009; Water-Technology). In addition, a petition containing over 3000 signatures was given to the Victorian parliament requesting the plant not be constructed (ABC News, 2009). The government was also pursued in court by the activist group “Your Water Your Say”; “Your Water Your Say” lost the proceedings and were forced to pay reparations (Water-Technology).

The Victorian plant is still experiencing public backlash because it is not producing any water until, at very least, June 2016. The price of the water in Melbourne has increased due to the government’s debt to Aquasure, the company hired to build the desalination plant. This backlash might pressure the government to shut down the plant, effectively wasting the large sum of money invested in the plant. The government would still have to pay Aquasure the agreed amount of money per year, despite not using the desalination plant. The public’s opinion on the plant is heavily influenced by the economics, environmental impact, and politics of the plant, and can be examined as a model for future reactions to plants. Some citizens are upset about having to pay more money per year for their water despite heavily petitioning against the desalination plant’s construction. Others are concerned about the environment and the impact that desalination could have on the surrounding ecosystem. Further, some are claiming that the plant is merely a political move and has little significance for the community despite its significant cost.

In the United States, multiple lawsuits were filed against California’s Carlsbad desalination plant prior to construction. Poseidon Water could not begin construction until they won all fourteen lawsuits, significantly delaying the completion of the plant (Perry, 2015; Rogers, 2014). The lawsuits were by environmentalist groups such as the Surfrider Foundation, with both environmental and economic concerns. One attorney suing for the Surfrider foundation claims “this is going to be the pig that will try for years to find the right shade of lipstick. [The Carlsbad desalination] project will show that the water is just too expensive” (Rogers, 2014).

Recommendations

With the research that has been completed and discussed in this document, the team has developed the following recommendations.

1. **Conservation should serve as the primary response to a lack of freshwater.**

When facing an increased demand for freshwater, the primary mitigation method a municipality should implement is conservation. Conservation efforts, such as water bans, infrastructure improvements, and leak detection, typically cost less than alternative water sources. These efforts have also proven to be effective in eliminating the freshwater deficit a region may face. If conservation begins after a desalination plant begins construction, the conservation efforts may be successful enough to no longer require desalination. For this reason, it is best to implement conservation tactics prior to desalination and other high cost, energy intensive strategies.

2. **Investments should be made into developing desalination technology, with the focus on both new methods of desalination, improving those already used, and the potential use of renewable energy.**

It is clear that the current state of desalination will not allow for the technology to compete with other means of water sourcing based on cost and energy usage. Improvements in current technologies, as well as emerging technologies such as forward osmosis, membrane distillation, freeze distillation, and humidification-dehumidification desalination. Research in these areas could prove useful to not only decreasing the cost of desalination, but to also take advantage of sources of waste heat within the country, run off of renewable energies, and reduce energy usage. Funding can go towards laboratory research or pilot plants, depending on the progression of the technology. Technologies currently being researched can be found in Appendix I.

3. **The United States should work with countries from all over the world that also have experience with desalination.**

Other nations around the world have been more reliant on desalination as a water source and thus have made significant improvements in energy efficiency and equipment effectiveness. Working with other countries, such as Israel and Australia, who are currently leading the way in desalination may help to expedite improvements to the technology used within the United States. Joint ventures, such as research competitions, teams of researchers from all different backgrounds, and international conferences, can help both the U.S. and the world advance the field of desalination to benefit those in need of freshwater.

4. **Design desalination plants with flexible production capacity.**

By designing desalination plants with flexible production capacities, desalination plants would be able to maintain economic feasibility through different production capacities. The changes in production capacity may be based off of changes in feedwater salinity, as well as changes in demand from the desalination plant.

In the case of saltwater intrusion, as water is drawn out of a well the salinity of the water increases. The increased salinity from saltwater intrusion requires higher pressure for reverse osmosis membranes to filter the water. Should the salinity become higher than anticipated, water pumps may need to be replaced to achieve the new pressure, and infrastructure may need to be replaced to accommodate the higher pressure and potential for additional scaling. In order to desalinate water for as long as possible, the plant would need to accommodate a range of salinities, without having to change out pumps, piping, or other equipment.

With drought cycles, the need for freshwater fluctuates over time, meaning the demand on a desalination plant also changes. Typically, a plant producing as much water as possible decreases the cost of production and allows the plant to make a profit. If a plant is operating below maximum capacity, the plant would need to charge more for the water to cover the cost differential. Further research and development into variable desalination technology which would allow a plant to run below full capacity will optimize cost and energy usage. Power plants may also be able to benefit from hourly variable desalination as a way to level the demand on the power grid, allowing the power plants to reduce changes in production and overgeneration risk.

5. **Develop mutually beneficial schemes between power plants and desalination plants.**

As of 2015, the desalination plant receives the majority of benefits from colocation, mainly through bypassing the permitting and construction of intake and outfall pipes. However, little benefit is given to the power plant. There is opportunity for innovation of methods for colocation to be mutually beneficial for a desalination plant and a power plant. Having the situation become mutually beneficial may provide more incentive for power plants to work with the construction and implementation of desalination. One idea previously mentioned may include the use of desalination plants as a means of leveling the electrical grid demand. This would have long-term advantages as areas switching to renewable energies increase the risk of over-generation.

6. **A database of desalination plants should be created, since desalination is a large consumer of energy.**

Due to the amount of time spent collecting data on desalination plants, it is recommended that a database be created containing pertinent information about the plants. This database could be similar to the one currently in place for electrical power plants, which can be found here: http://www.eia.gov/electricity/data/eia860/. A database will be useful in tracking the various components of desalination plants, allowing quick access to desalination plant data. This information curated inside the database will allow interested parties, such as the Department of Energy, to track the amount of energy used by desalination, among other plant characteristics, and inform potential future research and development in the area. Based upon our research and interviews with desalination experts, we recommend the following information be included:

- Location
- Year Completed
- Operational Status: Max Capacity, Partial Capacity, Non-operational
- Desalination Technology Implemented: RO, MSF, etc.
- Physical Size
- Freshwater Production Rate
- Feed water Source
- Feed water Salinity
- Brine Output Salinity
- Ownership
- Capital Expenditures
- Operational Expenditures
- Energy Requirement

Chapter 5: Conclusion

The world water crisis is a formidable problem lacking a clear, definitive solution. In order to mitigate the negative effects of the water crisis, the freshwater supply must be augmented in regions affected by a lack of freshwater. There are multiple mitigation methods to consider including conservation, finding alternative freshwater sources, and desalinating high salinity water. Prior to implementing desalination, determinations must be made on design, technology, contracting, and financing. These qualities are outlined in the decision making landscape of desalination presented in this report.

Reflections

Allison—Working at the Department of Energy was a great experience and a once in a lifetime opportunity. It was interesting to see how a government organization operates and to communicate with professionals from all areas of the DOE who contribute to the field of desalination. Our sponsors were always available to provide feedback and answer any questions we had about our project, the DOE in general, or just about the D.C. area. Having the chance to attend and take part in weekly staff meetings along with controlling our own schedule for completion was great experience for future work. This was the largest project I had worked on, and it was nice to see it all come together at the end. By far my favorite aspect of our project was the fascinating research involved in defining the interconnectivity of water and energy involved in desalination, with such a broad topic area we were able to expand into many relevant fields. As opposed to being a technical project with one specific answer, our project was thought oriented, with the final product being the “story” of desalination, allowing for a lot of interpretation. This is not a typical project at WPI, so this topic was interesting to explore.

Alex—Working with the Department of Energy brought significant experience in working within a group environment, as well as with the advisors and mentors involved. Within the team it was helpful to gain experience working over the long-term and discovering how the different personalities of each member produced a successful team dynamic. Experience with advisors and mentors gave insight into the importance of receiving and providing clear expectations and explanations, and what affects the absence of these can create. The experience I had working with the Department of Energy is something I can take into other projects, such as the Major Qualifying Project, and into future work experience.

Ian-I enjoyed adapting to the new environment of the Department of Energy as well as the city of DC itself. In the office we were constantly challenged to coordinate the conflicting desires of our sponsors and advisors; if we could do it all over again we would have straightened out expectations at start. Outside the office I enjoyed the many streets to explore and the astounding trails to hike along from cliffside views to pounding waterfalls.

Shaun—The IQP process allowed me to develop my skills in a group format whilst working towards a deliverable applicable to my future career. I learned how to identify and balance a team dynamic while setting deadlines and working through complex ideas. Working for the Department of Energy, learning about government work, and meeting individuals excited to hear about what our project was an experience I won’t soon forget. IQP has opened me to the idea of jobs I might want to pursue upon my completion of college and how to change my working styles to fit into a team dynamic. There’s not much I would change if I went through the process again except for increased communication between ourselves, our advisors, and our mentors for optimal project understanding.

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Appendix A: Organization of the DOE

The Department of Energy is a cabinet level organization; the Secretary of Energy is appointed by the President and sworn in by Congress, with all activities directly reported to the White House. The current Secretary of Energy is Dr. Ernest Moniz, who was appointed following his previous work as an MIT professor and service as Under Secretary of the DOE (U.S. DOE, 2015). The Department employs approximately 13,000 federal workers and 93,000 contract workers (U.S. DOE, 2015). The DOE is also the parent agency of many companies including: Energy Efficiency and Renewable Energy; Energy Information Administration; Environmental Management; Fossil Energy National Laboratories (energy department); National Nuclear Security Administration; Nuclear Energy, Science and Technology; Power Administration; Federal Energy Regulatory Commission (U.S. DOE, 2015). The companies and offices that make up the DOE are shown in the organization chart below (U.S. DOE, 2015).

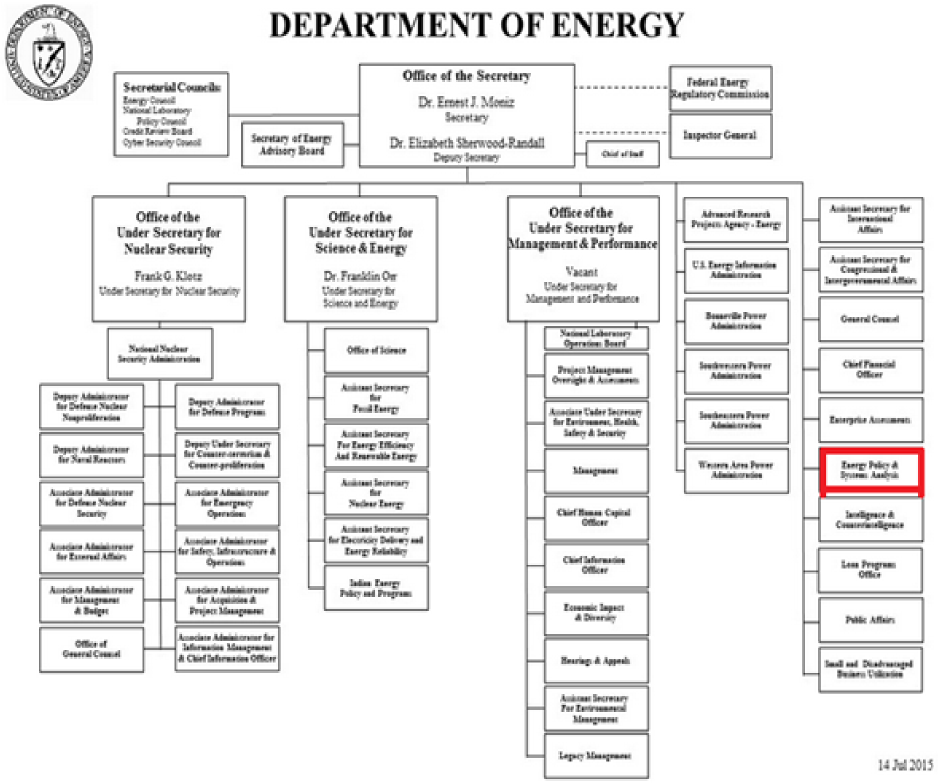
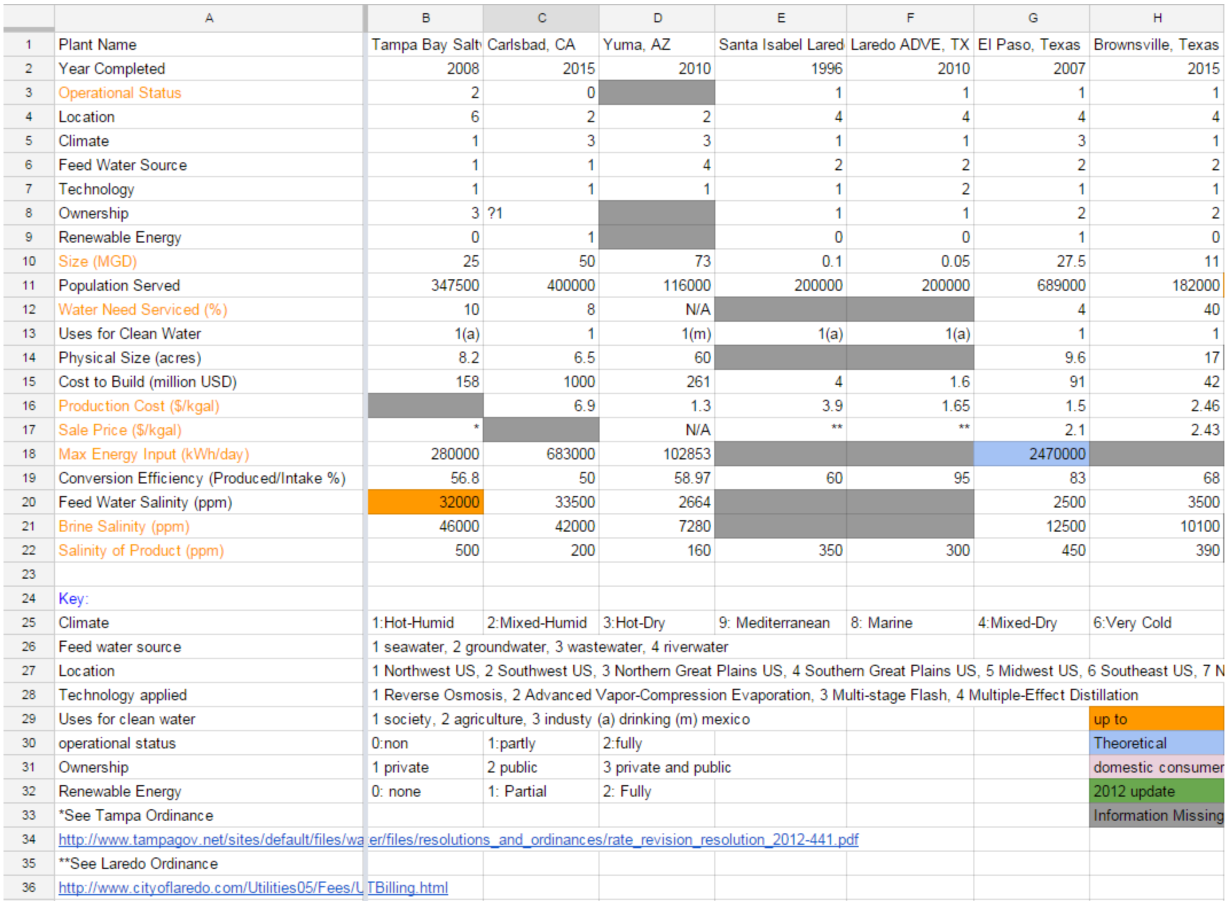


Figure 26: Department of Energy offices organization chart with EPSA highlighted in red (U.S. DOE, 2015)

The DOE has an annual budget of approximately $28 billion in the 2015 fiscal year, funded by taxpayers. The budget is distributed within the organization to fund areas such as: nuclear security, energy and environmental divisions, and research and development (U.S.DOE, 2014a). Specifically, the Office of Energy Policy and Systems Analysis (EPSA) has a budget of $38,545,000. Some of the funds distribution is predetermined, while a significant amount goes to grants for advancements in science and renewable energy (U.S. DOE, 2014a). The EPSA is focused on analyzing domestic energy policies, both existing and planned, and how they can be improved and applied. Our project is to identify characteristics necessary for optimal deployment of desalination plants domestically, considering the energy intensity of existing desalination technologies.

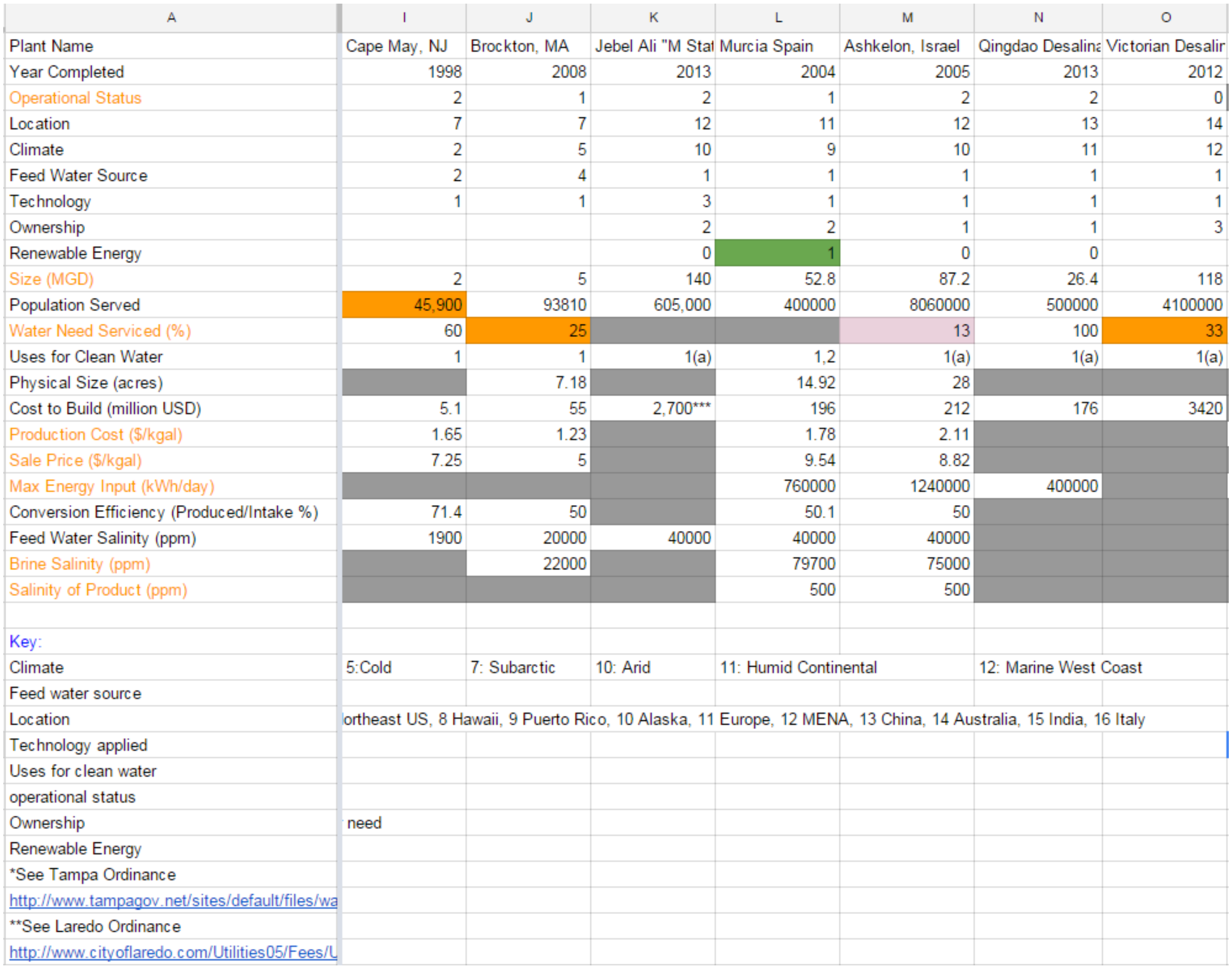
Appendix B: Plant Characteristic Data Matrix

Originally, the team was going to use the data matrix created to perform a detailed economic analysis to determine the viability and success of desalination in the U.S. Due to a change in the direction of the project to look at the decision making landscape of desalination, the matrix was used alongside Appendix E to gain an understanding of desalination plant and the different characteristics, such as technology, ownership, and water source, that a municipality must decide upon before construction. As a result, the team learned that there are very few correlations between the plants. Every plant studied was unique and had its own set of characteristics. For example, there is a slight trend with the energy input and the production of water, but there are multiple outliers. Overall, the matrix allowed the team to learn about areas of desalination, such as contract options, that should be further researched.



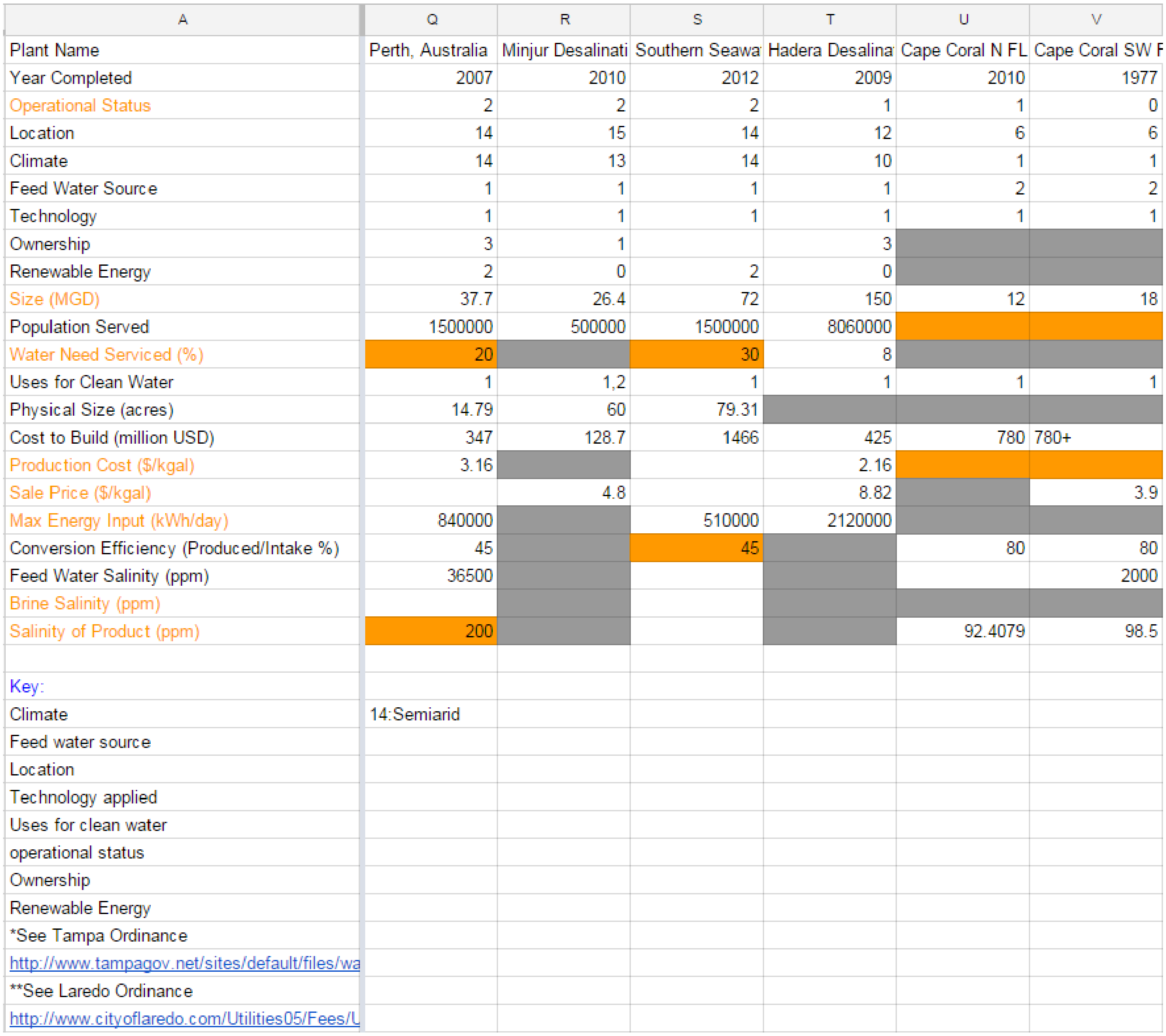
	A	B	C	D	E	F	G	H
1	Plant Name	Tampa Bay Salt	Carlsbad, CA	Yuma, AZ	Santa Isabel Lared	Laredo ADVE, TX	El Paso, Texas	Brownsville, Texas
2	Year Completed	2008	2015	2010	1996	2010	2007	2015
3	Operational Status	2	0		1	1	1	1
4	Location	6	2	2	4	4	4	4
5	Climate	1	3	3	1	1	3	1
6	Feed Water Source	1	1	4	2	2	2	2
7	Technology	1	1	1	1	2	1	1
8	Ownership	3	?1		1	1	2	2
9	Renewable Energy	0	1		0	0	1	0
10	Size (MGD)	25	50	73	0.1	0.05	27.5	11
11	Population Served	347500	400000	116000	200000	200000	689000	182000
12	Water Need Serviced (%)	10	8	N/A			4	40
13	Uses for Clean Water	1(a)	1	1(m)	1(a)	1(a)	1	1
14	Physical Size (acres)	8.2	6.5	60			9.6	17
15	Cost to Build (million USD)	158	1000	261	4	1.6	91	42
16	Production Cost ($/kgal)		6.9	1.3	3.9	1.65	1.5	2.46
17	Sale Price ($/kgal)	*		N/A	**	**	2.1	2.43
18	Max Energy Input (kWh/day)	280000	683000	102853			2470000	
19	Conversion Efficiency (Produced/Intake %)	56.8	50	58.97	60	95	83	68
20	Feed Water Salinity (ppm)	32000	33500	2664			2500	3500
21	Brine Salinity (ppm)	46000	42000	7280			12500	10100
22	Salinity of Product (ppm)	500	200	160	350	300	450	390
23								
24	Key:							
25	Climate	1:Hot-Humid	2:Mixed-Humid	3:Hot-Dry	9: Mediterranean	8: Marine	4:Mixed-Dry	6:Very Cold
26	Feed water source	1 seawater, 2 groundwater, 3 wastewater, 4 riverwater						
27	Location	1 Northwest US, 2 Southwest US, 3 Northern Great Plains US, 4 Southern Great Plains US, 5 Midwest US, 6 Southeast US, 7 N						
28	Technology applied	1 Reverse Osmosis, 2 Advanced Vapor-Compression Evaporation, 3 Multi-stage Flash, 4 Multiple-Effect Distillation						
29	Uses for clean water	1 society, 2 agriculture, 3 industy (a) drinking (m) mexico						up to
30	operational status	0:non	1:partly	2:fully				Theoretical
31	Ownership	1 private	2 public	3 private and public				domestic consumer
32	Renewable Energy	0: none	1: Partial	2: Fully				2012 update
33	*See Tampa Ordinance							Information Missing
34	http://www.tampagov.net/sites/default/files/wa	er/files/resolutions_and_ordinances/rate_revision_resolution_2012-441.pdf						
35	**See Laredo Ordinance							
36	http://www.cityoflaredo.com/Utilities05/Fees/U	TBilling.html						

Figure 27: Part one of the data matrix



A	I	J	K	L	M	N	O
Plant Name	Cape May, NJ	Brockton, MA	Jebel Ali "M Stat	Murcia Spain	Ashkelon, Israel	Qingdao Desalina	Victorian Desalin
Year Completed	1998	2008	2013	2004	2005	2013	2012
Operational Status	2	1	2	1	2	2	0
Location	7	7	12	11	12	13	14
Climate	2	5	10	9	10	11	12
Feed Water Source	2	4	1	1	1	1	1
Technology	1	1	3	1	1	1	1
Ownership			2	2	1	1	3
Renewable Energy			0	1	0	0	
Size (MGD)	2	5	140	52.8	87.2	26.4	118
Population Served	45,900	93810	605,000	400000	8060000	500000	4100000
Water Need Serviced (%)	60	25			13	100	33
Uses for Clean Water	1	1	1(a)	1,2	1(a)	1(a)	1(a)
Physical Size (acres)		7.18		14.92	28		
Cost to Build (million USD)	5.1	55	2,700***	196	212	176	3420
Production Cost ($/kgal)	1.65	1.23		1.78	2.11		
Sale Price ($/kgal)	7.25	5		9.54	8.82		
Max Energy Input (kWh/day)				760000	1240000	400000	
Conversion Efficiency (Produced/Intake %)	71.4	50		50.1	50		
Feed Water Salinity (ppm)	1900	20000	40000	40000	40000		
Brine Salinity (ppm)		22000		79700	75000		
Salinity of Product (ppm)				500	500		
Key:							
Climate	5:Cold	7: Subarctic	10: Arid	11: Humid Continental		12: Marine West Coast	
Feed water source							
Location	ortheast US, 8 Hawaii, 9 Puerto Rico, 10 Alaska, 11 Europe, 12 MENA, 13 China, 14 Australia, 15 India, 16 Italy						
Technology applied							
Uses for clean water							
operational status							
Ownership	need						
Renewable Energy							
*See Tampa Ordinance							
http://www.tampagov.net/sites/default/files/wa							
**See Laredo Ordinance							
http://www.cityoflaredo.com/Utilities05/Fees/L							

Figure 28: Part two of the data matrix



A	Q	R	S	T	U	V
Plant Name	Perth, Australia	Minjur Desalinati	Southern Seawa	Hadera Desalina	Cape Coral N FL	Cape Coral SW F
Year Completed	2007	2010	2012	2009	2010	1977
Operational Status	2	2	2	1	1	0
Location	14	15	14	12	6	6
Climate	14	13	14	10	1	1
Feed Water Source	1	1	1	1	2	2
Technology	1	1	1	1	1	1
Ownership	3	1		3		
Renewable Energy	2	0	2	0		
Size (MGD)	37.7	26.4	72	150	12	18
Population Served	1500000	500000	1500000	8060000		
Water Need Serviced (%)	20		30	8		
Uses for Clean Water	1	1,2	1	1	1	1
Physical Size (acres)	14.79	60	79.31			
Cost to Build (million USD)	347	128.7	1466	425	780	780+
Production Cost ($/kgal)	3.16			2.16		
Sale Price ($/kgal)		4.8		8.82		3.9
Max Energy Input (kWh/day)	840000		510000	2120000		
Conversion Efficiency (Produced/Intake %)	45		45		80	80
Feed Water Salinity (ppm)	36500					2000
Brine Salinity (ppm)						
Salinity of Product (ppm)	200				92.4079	98.5
Key:						
Climate	14:Semiarid					
Feed water source						
Location						
Technology applied						
Uses for clean water						
operational status						
Ownership						
Renewable Energy						
*See Tampa Ordinance						
http://www.tampagov.net/sites/default/files/wa						
**See Laredo Ordinance						
http://www.cityoflaredo.com/Utilities05/Fees/U						

Figure 29: Part three of the data matrix

Sources: Abengoa, 2013; Androphile, 2015; Arroyo & Shirazi, 2012; Baker, 2013; Bar-Eli, 2014; CDM Smith, 2015; Cape Coral, 2014; Crawford, 2013; University of Texas Dallas, 2010; Degener, 2012; Degremont; Dubai Electricity and Water Authority, 2014; El Paso Water Utilities, 2007; Els et. All, 2005; Genasci Smith; General Electric, 2008; Guevara, 1998; IDE Technologies, 2015; U.S. Department of the Interior, 2012; Kever, 2011; Kurmelovs, 2015; Lapuente, 2012; Madhavan, 2014; March, 2014; Melbourne Water, 2015; Murcia Today, 2013; National Oceanic and Atmospheric Administration, 2015; Norris; Palomar &Losada, 2010; Florida Department of environmental Protection, 2010; San Diego Couty Water Authority, 2015; Simpson, 2013; South Florida Water Management District, 2014; Starsend, 1993; Sturdivan et. All, 2009; Tampa Bay Water, 2008; 2010; 2011; Tenne, 2010; Texas Water Development Board, 2010; The Hindu, 2010; Vmenkov, 2010

Appendix C: Sample Interview Questions

The following is a list of sample interview questions for our interview process.

What population does your desalination plant service?

In what ways do those people use the water?

How clean is the water you provide/are there different levels of cleanliness?

How much freshwater do you produce per day?

What is the energy efficiency of your plant?

Is there anything that could make your plant more effective: location, type, efficiency?

What are the capital and operational expenditures of the plant?

Does the plant operate year round?

Are there seasonal differences for plant operations?

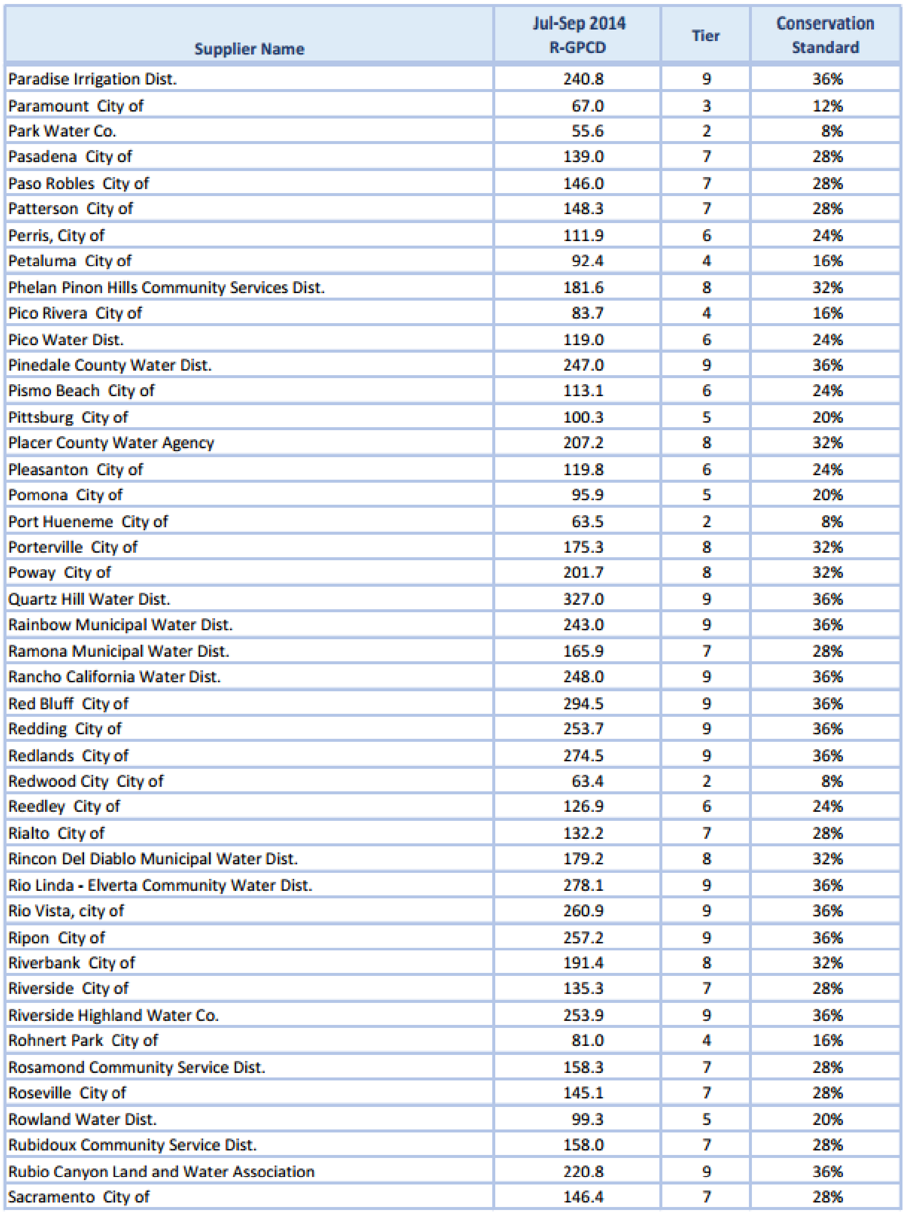
What do you do with the salt once it is removed from the water?

How do you reintroduce the remaining water back into the environment?

How many employees work at the plant?

Appendix D: Water Conservation Ratings

This table shows the conservation tier achieved by various cities in California, including Poway, and their R-GPCD scores for July-September 2014. (Table retrieved from State Water Resources Control Board, 2015a)



Supplier Name	Jul-Sep 2014 R-GPCD	Tier	Conservation Standard
Paradise Irrigation Dist.	240.8	9	36%
Paramount City of	67.0	3	12%
Park Water Co.	55.6	2	8%
Pasadena City of	139.0	7	28%
Paso Robles City of	146.0	7	28%
Patterson City of	148.3	7	28%
Perris, City of	111.9	6	24%
Petaluma City of	92.4	4	16%
Phelan Pinon Hills Community Services Dist.	181.6	8	32%
Pico Rivera City of	83.7	4	16%
Pico Water Dist.	119.0	6	24%
Pinedale County Water Dist.	247.0	9	36%
Pismo Beach City of	113.1	6	24%
Pittsburg City of	100.3	5	20%
Placer County Water Agency	207.2	8	32%
Pleasanton City of	119.8	6	24%
Pomona City of	95.9	5	20%
Port Hueneme City of	63.5	2	8%
Porterville City of	175.3	8	32%
Poway City of	201.7	8	32%
Quartz Hill Water Dist.	327.0	9	36%
Rainbow Municipal Water Dist.	243.0	9	36%
Ramona Municipal Water Dist.	165.9	7	28%
Rancho California Water Dist.	248.0	9	36%
Red Bluff City of	294.5	9	36%
Redding City of	253.7	9	36%
Redlands City of	274.5	9	36%
Redwood City City of	63.4	2	8%
Reedley City of	126.9	6	24%
Rialto City of	132.2	7	28%
Rincon Del Diablo Municipal Water Dist.	179.2	8	32%
Rio Linda - Elverta Community Water Dist.	278.1	9	36%
Rio Vista, city of	260.9	9	36%
Ripon City of	257.2	9	36%
Riverbank City of	191.4	8	32%
Riverside City of	135.3	7	28%
Riverside Highland Water Co.	253.9	9	36%
Rohnert Park City of	81.0	4	16%
Rosamond Community Service Dist.	158.3	7	28%
Roseville City of	145.1	7	28%
Rowland Water Dist.	99.3	5	20%
Rubidoux Community Service Dist.	158.0	7	28%
Rubio Canyon Land and Water Association	220.8	9	36%
Sacramento City of	146.4	7	28%

Appendix E: Selected Desalination Plant Summaries

Along with cataloging characteristics of 20 desalination plants, the team wrote descriptions of each plant. These descriptions include why the plant was built, any issue or obstacles faced in the construction process, unique plant characteristics, and any other fact that could not be categorized accurately.

Domestic Desalination Plants

Cape May, NJ-

The Cape May desalination plant employs reverse osmosis technology to supply 2MGD of fresh water to the community; the water is used by up to 45,900 residents in the summer months and 7,200 in the winter. During the winter the filtered water is stored in wells for future use during the peak demands of the summer. The plant was employed to filter groundwater in the region as previous wells and aquifers became affected by saltwater intrusion in the area (Vedachalam, 2012).

The need for the plant started as the Cohansey Aquifer had continued to fall victim to salt-water intrusion. Resulting in the slow loss of freshwater supply, and the need for more. Economic analysis were done on possible solutions, resulting in the use of desalination due to the communities need to stay in control of their own resources, long-term capability of the project, and the ability to lessen the use of the Cohansey Aquifer (Blair, 1999). The currently installed plant was built in two phases; this helped allow the immediate use of the plant. The current plant is able to supply 60% of the communities water need (Vedachalam, 2012).

Due to the complexity of the project, the first of its kind in the state, the project was assigned a permit coordinator to help expedite the process. Even with these efforts, the process took several months longer than expected and affected the budgeting of the project (Blair, 1999).

Brockton, MA-

The area of Brockton has been experiencing water shortages since the 1800s and they intensified after WWII. In 1986 restrictions were placed on the city prohibiting new business and residential connections due to the lack of water, later being removed in 1992 due to new water use restrictions and infrastructure improvement. The plant required 30 federal state and local permits before construction could begin, causing a delay of 4 years due to the state not being used to the desalination permitting process. The 5 MGD plant was built for $55 million and finished in June 2008. The plant takes water from the Taunton River, and disposes of the brine in the same place. Water is taken during low tide, and disposed during high tide due to TDS levels (allows for lower salinity water to be treated, and the disposal to be into higher salinity water).the cost of production is $1.23/kgal but the company in charge, Aquaria, charges Brockton $5/kgal. The plant is currently barely used due to conservation improvements lowering the demand in the town, although the city must still pay Aquaria 5 million per year due to contract obligations. The water conservation improvements reduced the average demand from 12 MGD to 9 MGD. In the fall of 2011, less than a percent of the water used in the city came from the plant. (All data from Vedachalam, 2012).

El Paso, Texas-

In 2007, the Kay Bailey Hutchison Desalination plant began operation in El Paso, Texas. The plant cost $91 million to construct and has the capacity to purify brackish water to produce up to 27.5 million gallons of fresh water a day through reverse osmosis (CDM Smith, 2015). This water is used by the citizens of El Paso and those at the Fort Bliss Army post (Kever, 2011). The brackish water is retrieved from underground aquifers, specifically the Mesilla Bolson and the Hueco Bolson nearby (Kever, 2011). The brine produced from this process is then placed 3,500 feet underground through a process called deep well injection to minimize negative environmental impacts, which is powered by solar energy (CDM Smith, 2015). The cost of this desalinated water is $2.10 per 1,000 gallons, compared to $0.45 per 1,000 gallons of natural fresh water and $1.85 per 1,000 gallons of purified river water (Kever, 2011). The plant itself is approximately ⅓ the size of a football field, and requires 14 people to maintain operation 24 hours a day (Kever, 2011).

Brownsville, Texas-

The Southmost Regional Water Authority desalination plant in Brownsville, Texas was originally completed in 2004, producing up to 7.5 mgd, but was updated in 2014 to allow up to 11mgd. This reverse osmosis plant purifies brackish groundwater and cost a total of $42 million (Gomez, 2014). It cost $2.46 per kgal to produce this water, and is sold to society for prices ranging from $1.87 to $3.85 per kgal, depending on the amount of water consumed. When this water is not directly needed, there is a 7.5 million gallon storage tank and a 0.75 million gallon clear well on site. The city has an additional 13 million gallon storage capability (Sturdivant, 2009).

Carlsbad, CA-

The Carlsbad desalination plant will be operational distributing water to the businesses and residents in San Diego County, CA by late 2015 (Carlsbad Desalination Project, 2015). This desalination plant takes in ocean water and supplies 8% of San Diego County's freshwater (Poseidon Water, 2015). The main idea behind the implementation of this plant is to compensate for California's ongoing drought. The desalination plant's had an initial cost of $1 billion. The Carlsbad plant will cost about $7 to produce a thousand gallons and will produce 25 million gallons a day, for a rough total cost of $175,000 a day (San Diego County Water Authority, 2015).

Yuma, AZ-

The Yuma plant is designed to recover 75% of the runoff lost to the Wellton Mohawk Irrigation District river system (Lohman, 2003), it cleans the water and sends it through the Colorado river and then on its way to Mexico (U.S. Department of the Interior, 2015). The remaining 25% of now highly concentrated salts is discharged into the Gulf of California (Lohman, 2003). The plant's production cost is $1.30 per thousand gallons (Montgomery, 2011) and the plant produces around 73 million gallons a day (Perry, 2010), for a rough total cost of $94,900 a day.

Cape Coral, FL-

Florida obtains freshwater from underground aquifers, but, due to their overdrawing of these aquifers, saltwater intrusion has contaminated many of these sources, requiring desalination to meet drinking water standards. The Southwest Cape Coral desalination plant was completed in 1977; the plant originally produced 3 million gallons a day, and then was upgraded over time so that it was producing an additional 15 million gallons per day by the year 1985 to meet the growing needs of the population (Aqua Care Water Treatment and Plumbing, 2011). Until 2010 the Southwest Cape Coral plant was desalinating 18 million gallons a day (City of Cape Coral, 2013) , and then the Northwest Cape Coral desalination plant was created to provide an alternate source of freshwater to compensate for the 35 year old Southwest plant beginning renovations (City of Cape Coral, 2012). The new Northwest desalination plant now produces 12 million gallons a day and just like the Southwest desalination plant the Northwest also takes in brackish ground water (City of Cape Coral, 2012).

Tampa Bay, FL-

The Tampa Bay SWRO plant opened two years after its original intended date due to multiple changes in contractor. In July 1999 S&W Water, a joint venture between Stone and Webster and Poseidon Resources was selected for plant construction, but in 2000 Stone and Webster filed for bankruptcy causing Poseidon to create a new company with Covanta Energy in order to begin the project. In 2002, Tampa Bay Water bought out Poseidon's share in the plant, leaving just the new company, Covanta Tampa Construction, to finish the plant. After failing the performance tests in 2003, Covanta Tampa Construction also filed for bankruptcy. American Water/Pridesa was contracted in 2004 and finished the plant in 2007 (Water-Technology). The plant is collocated with Big Bend Power Station and "catches" a portion of the intake water from the power station to desalinate. The brine solution is mixed with the outflow of the power station to dilute the solution to an acceptable salinity (Tampa Bay Water, 2010).

Laredo, TX-

The Santa Isabel Desalination Plant was established in 1996 and desalinates 100,000 gallons per day of brackish groundwater for the population of Laredo, TX. In 2010, an experimental Advanced Vapour-Compression Evaporation pilot segment was added to the plant to test the effectiveness of a new type of desalination. The project, developed by a Texas A&M University professor, was a joint venture between the city of Laredo and Terrabon (Bentz, 2012). The results of the pilot testing were inconclusive due to a leakage of heat causing the heat exchanger to not operate at maximum efficiency.

International Desalination Plants

Murcia, Spain-

The Valdelentisco Desalination Plant in Murcia, Spain began operation in 2004. 52.8 million gallons of freshwater are produced by reverse osmosis of seawater every day (Water-Technology, 2015). The cost of production is $1.78/kgal, but the freshwater is sold for $9.54/kgal (Murcia Today, 2013). Spain first began use of desalination when a plant utilizing multi stage flash technology was opened on the island of Lanzarote in 1964. However, starting in 2012, only 16% of the total capacity of desalination plants in Spain was used. There are two main factors that led to the lack of use: there were a few years of rain that filled reservoirs and aquifers, and the expected population growth slowed down and was not as large as anticipated.

Increases in electricity cost in 2008 and some reduction in water use due to conservation efforts may have influenced the change as well. The Valdelentisco plant stopped all production in 2012, but then restarted a year later, below full capacity (March, 2014).

Ashkelon, Israel-

The MENA region is known for their use of desalination due to their lack of fresh water. Israel is no exception, opening a desalination plant in 2005 in Ashkelon. It can produce up to 87.2 MGD of fresh water, servicing 13% of the country's domestic consumer demand. It utilizes reverse osmosis to purify seawater from the Mediterranean at a cost of $2.11 per 1000 gallons, which is then sold for $8.82/ kgal. The plant cost $212 million to build, but has continued to provide water to over one million people since it began operation (Water- Technology, 2015). Israel is also the world leader in recycling waste water, reusing over 400 million m^3/year of treated waste water. Drip irrigation provides fresh water to over 90% of their agricultural sector. Children are educated on the importance of water conservation, to remind parents of water conservation techniques (Mandell, 2012).

Perth, Australia (Kwinana)-

The 38 MGD plant is able to provide up to 20% of the water for Perth, and is entirely powered by renewable energy. A 10MW solar farm and 55MW Wind farm provide power to the plant. The plant operates using reverse osmosis and filters seawater in the process. The plant was built to supplement the dam supplies which have decreased to around 25% in size since their implementation. The plant in Kwinana is one of two plants supplying Perth with desalinated water as a source of freshwater.

Perth, Australia (Binningup)-

The plant is built in a two stage development/expansion, each stage allows for the production of 36MGD of freshwater for a total of 72 MGD. Like the other plant supplying water to Perth, the entire plant operates off of renewable energy from the nearby solar and wind farms. The plant is able to supply up to 30% of the water need for its service area. The plant was implemented for the same reasons as the other Perth plant.

Trapani, Sicily-

Built in 1995, the desalination plant in Trapani, Sicily runs on thermal vapor compression multiple effect distillation technology (TVC-MED). The plan's production cost is a little over $7 per thousand gallons and the plant produces upwards of 9 million gallons a day for a rough per day cost of $63,000. The desalination plant serves 3% of the 5 million Italians living in Sicily. (Cipollina, 2005)

Dubai, United Arab Emirates-

The Jebel Ali compound in Dubai is segmented into different "stations" each containing a power plant and a MSF desalination plant. The desalination plants utilize the waste heat from the power plants to heat up the seawater for distillation. The desalination intake pipes are located unusually close to shore to avoid taking in oil in case of an oil spill in the Arabian Gulf (Simpson, 2013).

Appendix F: World Capital Expenditure Breakdowns

The following tables are taken from the Global Water Intelligence's report Desalination Markets 2010. They include historical data from 2007 to 2009, while the data from 2010 to 2016 is a forecast for the market. The information is useful in separating the construction related capital costs to the design and legal costs. The tables are sorted as groupings of all technologies, multiple technologies, as well as individual technologies. Data in the tables is listed in the order of millions of USD spent in the world each year for new infrastructure.

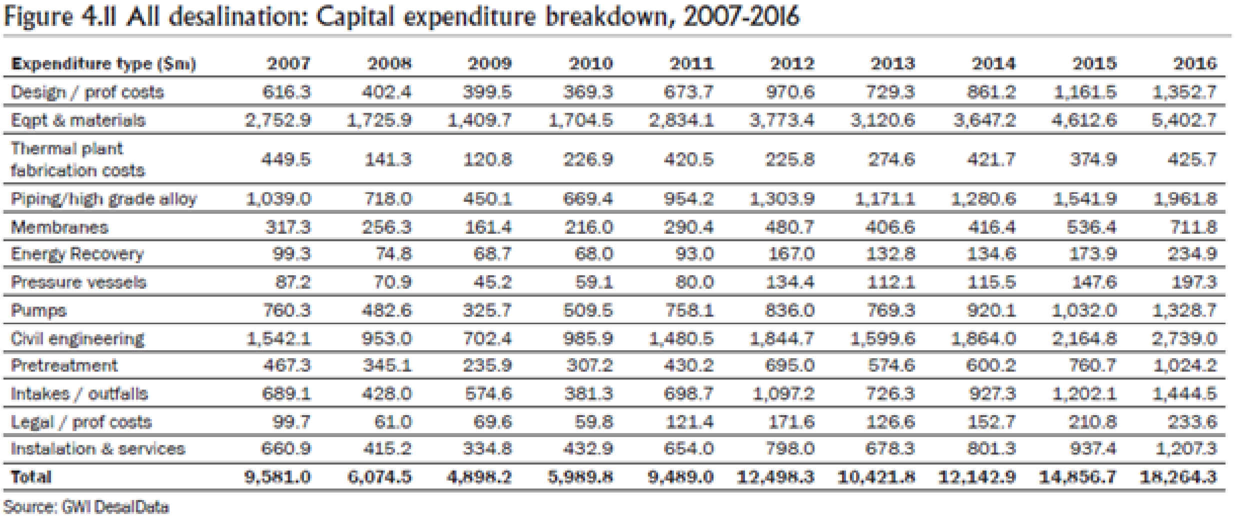


Figure 4.11 All desalination: Capital expenditure breakdown, 2007-2016

Expenditure type ($m)	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Design / prof costs	616.3	402.4	399.5	369.3	673.7	970.6	729.3	861.2	1,161.5	1,352.7
Eqpt & materials	2,752.9	1,725.9	1,409.7	1,704.5	2,834.1	3,773.4	3,120.6	3,647.2	4,612.6	5,402.7
Thermal plant fabrication costs	449.5	141.3	120.8	226.9	420.5	225.8	274.6	421.7	374.9	425.7
Piping/high grade alloy	1,039.0	718.0	450.1	669.4	954.2	1,303.9	1,171.1	1,280.6	1,541.9	1,961.8
Membranes	317.3	256.3	161.4	216.0	290.4	480.7	406.6	416.4	536.4	711.8
Energy Recovery	99.3	74.8	68.7	68.0	93.0	167.0	132.8	134.6	173.9	234.9
Pressure vessels	87.2	70.9	45.2	59.1	80.0	134.4	112.1	115.5	147.6	197.3
Pumps	760.3	482.6	325.7	509.5	758.1	836.0	769.3	920.1	1,032.0	1,328.7
Civil engineering	1,542.1	953.0	702.4	985.9	1,480.5	1,844.7	1,599.6	1,864.0	2,164.8	2,739.0
Pretreatment	467.3	345.1	235.9	307.2	430.2	695.0	574.6	600.2	760.7	1,024.2
Intakes / outfalls	689.1	428.0	574.6	381.3	698.7	1,097.2	726.3	927.3	1,202.1	1,444.5
Legal / prof costs	99.7	61.0	69.6	59.8	121.4	171.6	126.6	152.7	210.8	233.6
Instalation & services	660.9	415.2	334.8	432.9	654.0	798.0	678.3	801.3	937.4	1,207.3
Total	**9,581.0**	**6,074.5**	**4,898.2**	**5,989.8**	**9,489.0**	**12,498.3**	**10,421.8**	**12,142.9**	**14,856.7**	**18,264.3**

Source: GWI DesalData

Table 6: Capital expenditure breakdown for all desalination (GWI, 2010)

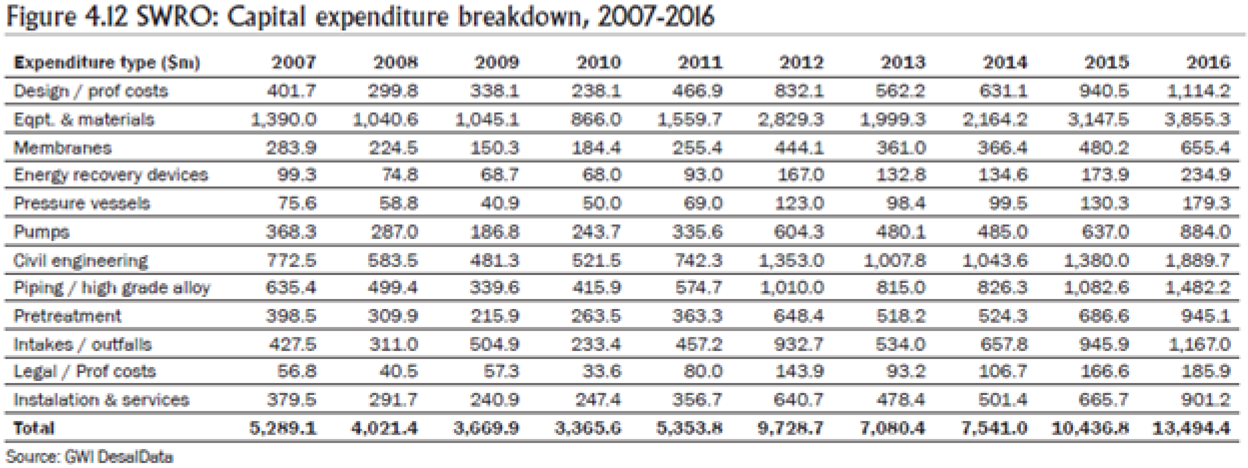


Figure 4.12 SWRO: Capital expenditure breakdown, 2007-2016

Expenditure type ($m)	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Design / prof costs	401.7	299.8	338.1	238.1	466.9	832.1	562.2	631.1	940.5	1,114.2
Eqpt. & materials	1,390.0	1,040.6	1,045.1	866.0	1,559.7	2,829.3	1,999.3	2,164.2	3,147.5	3,855.3
Membranes	283.9	224.5	150.3	184.4	255.4	444.1	361.0	366.4	480.2	655.4
Energy recovery devices	99.3	74.8	68.7	68.0	93.0	167.0	132.8	134.6	173.9	234.9
Pressure vessels	75.6	58.8	40.9	50.0	69.0	123.0	98.4	99.5	130.3	179.3
Pumps	368.3	287.0	186.8	243.7	335.6	604.3	480.1	485.0	637.0	884.0
Civil engineering	772.5	583.5	481.3	521.5	742.3	1,353.0	1,007.8	1,043.6	1,380.0	1,889.7
Piping / high grade alloy	635.4	499.4	339.6	415.9	574.7	1,010.0	815.0	826.3	1,082.6	1,482.2
Pretreatment	398.5	309.9	215.9	263.5	363.3	648.4	518.2	524.3	686.6	945.1
Intakes / outfalls	427.5	311.0	504.9	233.4	457.2	932.7	534.0	657.8	945.9	1,167.0
Legal / Prof costs	56.8	40.5	57.3	33.6	80.0	143.9	93.2	106.7	166.6	185.9
Instalation & services	379.5	291.7	240.9	247.4	356.7	640.7	478.4	501.4	665.7	901.2
Total	**5,289.1**	**4,021.4**	**3,669.9**	**3,365.6**	**5,353.8**	**9,728.7**	**7,080.4**	**7,541.0**	**10,436.8**	**13,494.4**

Source: GWI DesalData

Table 7: Capital expenditure breakdown for saltwater RO (GWI, 2010)

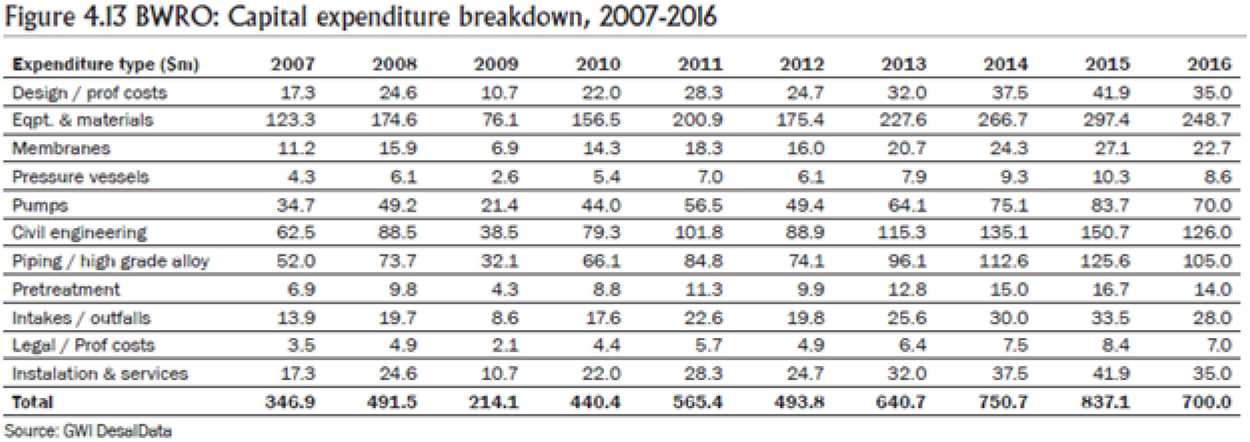


Figure 4.13 BWRO: Capital expenditure breakdown, 2007-2016

Expenditure type ($m)	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Design / prof costs	17.3	24.6	10.7	22.0	28.3	24.7	32.0	37.5	41.9	35.0
Eqpt. & materials	123.3	174.6	76.1	156.5	200.9	175.4	227.6	266.7	297.4	248.7
Membranes	11.2	15.9	6.9	14.3	18.3	16.0	20.7	24.3	27.1	22.7
Pressure vessels	4.3	6.1	2.6	5.4	7.0	6.1	7.9	9.3	10.3	8.6
Pumps	34.7	49.2	21.4	44.0	56.5	49.4	64.1	75.1	83.7	70.0
Civil engineering	62.5	88.5	38.5	79.3	101.8	88.9	115.3	135.1	150.7	126.0
Piping / high grade alloy	52.0	73.7	32.1	66.1	84.8	74.1	96.1	112.6	125.6	105.0
Pretreatment	6.9	9.8	4.3	8.8	11.3	9.9	12.8	15.0	16.7	14.0
Intakes / outfalls	13.9	19.7	8.6	17.6	22.6	19.8	25.6	30.0	33.5	28.0
Legal / Prof costs	3.5	4.9	2.1	4.4	5.7	4.9	6.4	7.5	8.4	7.0
Instalation & services	17.3	24.6	10.7	22.0	28.3	24.7	32.0	37.5	41.9	35.0
Total	**346.9**	**491.5**	**214.1**	**440.4**	**565.4**	**493.8**	**640.7**	**750.7**	**837.1**	**700.0**

Source: GWI DesalData

Table 8: Capital expenditure breakdown for brackish water RO (GWI, 2010)

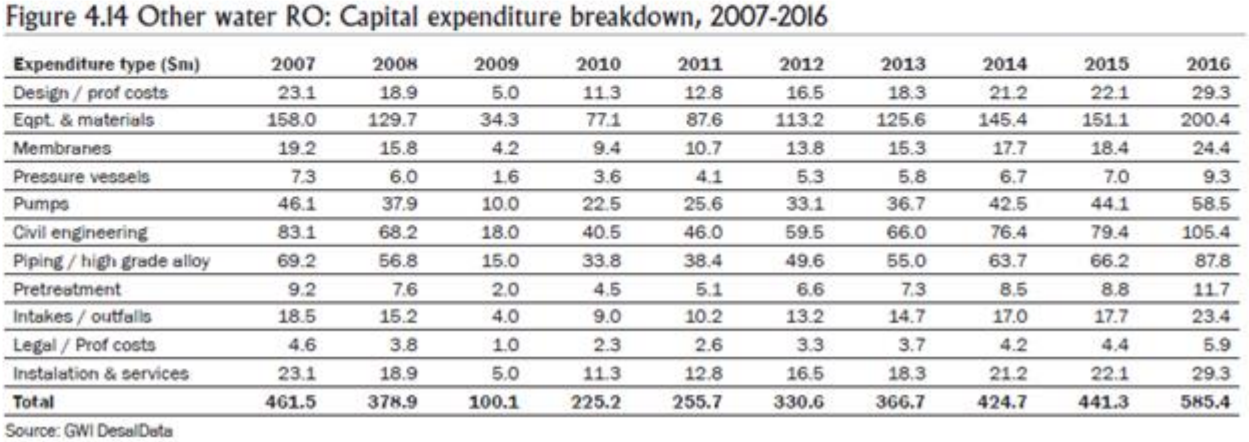


Figure 4.14 Other water RO: Capital expenditure breakdown, 2007-2016

Expenditure type ($m)	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Design / prof costs	23.1	18.9	5.0	11.3	12.8	16.5	18.3	21.2	22.1	29.3
Eqpt. & materials	158.0	129.7	34.3	77.1	87.6	113.2	125.6	145.4	151.1	200.4
Membranes	19.2	15.8	4.2	9.4	10.7	13.8	15.3	17.7	18.4	24.4
Pressure vessels	7.3	6.0	1.6	3.6	4.1	5.3	5.8	6.7	7.0	9.3
Pumps	46.1	37.9	10.0	22.5	25.6	33.1	36.7	42.5	44.1	58.5
Civil engineering	83.1	68.2	18.0	40.5	46.0	59.5	66.0	76.4	79.4	105.4
Piping / high grade alloy	69.2	56.8	15.0	33.8	38.4	49.6	55.0	63.7	66.2	87.8
Pretreatment	9.2	7.6	2.0	4.5	5.1	6.6	7.3	8.5	8.8	11.7
Intakes / outfalls	18.5	15.2	4.0	9.0	10.2	13.2	14.7	17.0	17.7	23.4
Legal / Prof costs	4.6	3.8	1.0	2.3	2.6	3.3	3.7	4.2	4.4	5.9
Instalation & services	23.1	18.9	5.0	11.3	12.8	16.5	18.3	21.2	22.1	29.3
Total	**461.5**	**378.9**	**100.1**	**225.2**	**255.7**	**330.6**	**366.7**	**424.7**	**441.3**	**585.4**

Source: GWI DesalData

Table 9: Capital expenditure breakdown for non- brackish/ saltwater RO (GWI, 2010)

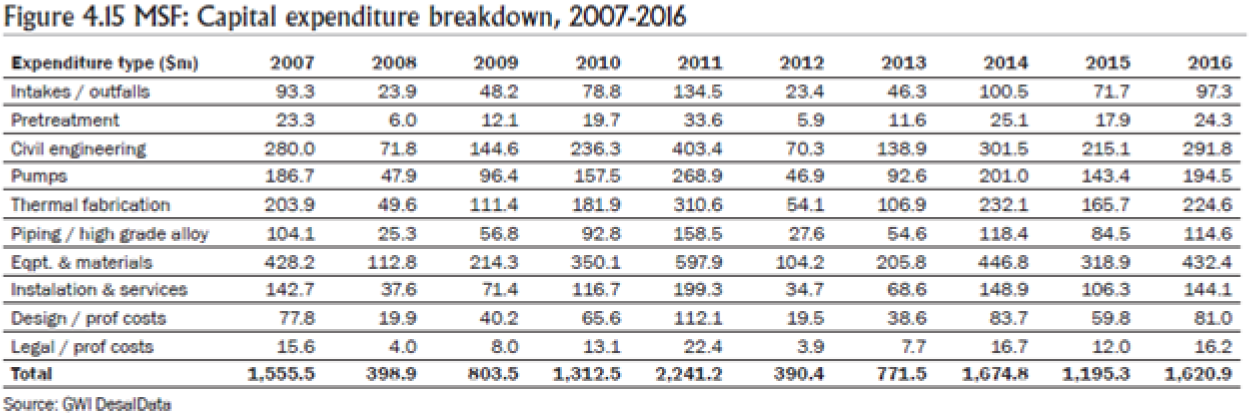


Figure 4.15 MSF: Capital expenditure breakdown, 2007-2016

Expenditure type ($m)	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Intakes / outfalls	93.3	23.9	48.2	78.8	134.5	23.4	46.3	100.5	71.7	97.3
Pretreatment	23.3	6.0	12.1	19.7	33.6	5.9	11.6	25.1	17.9	24.3
Civil engineering	280.0	71.8	144.6	236.3	403.4	70.3	138.9	301.5	215.1	291.8
Pumps	186.7	47.9	96.4	157.5	268.9	46.9	92.6	201.0	143.4	194.5
Thermal fabrication	203.9	49.6	111.4	181.9	310.6	54.1	106.9	232.1	165.7	224.6
Piping / high grade alloy	104.1	25.3	56.8	92.8	158.5	27.6	54.6	118.4	84.5	114.6
Eqpt. & materials	428.2	112.8	214.3	350.1	597.9	104.2	205.8	446.8	318.9	432.4
Instalation & services	142.7	37.6	71.4	116.7	199.3	34.7	68.6	148.9	106.3	144.1
Design / prof costs	77.8	19.9	40.2	65.6	112.1	19.5	38.6	83.7	59.8	81.0
Legal / prof costs	15.6	4.0	8.0	13.1	22.4	3.9	7.7	16.7	12.0	16.2
Total	**1,555.5**	**398.9**	**803.5**	**1,312.5**	**2,241.2**	**390.4**	**771.5**	**1,674.8**	**1,195.3**	**1,620.9**

Source: GWI DesalData

Table 10: Capital expenditure breakdown for Multi-Stage Flash (GWI, 2010)

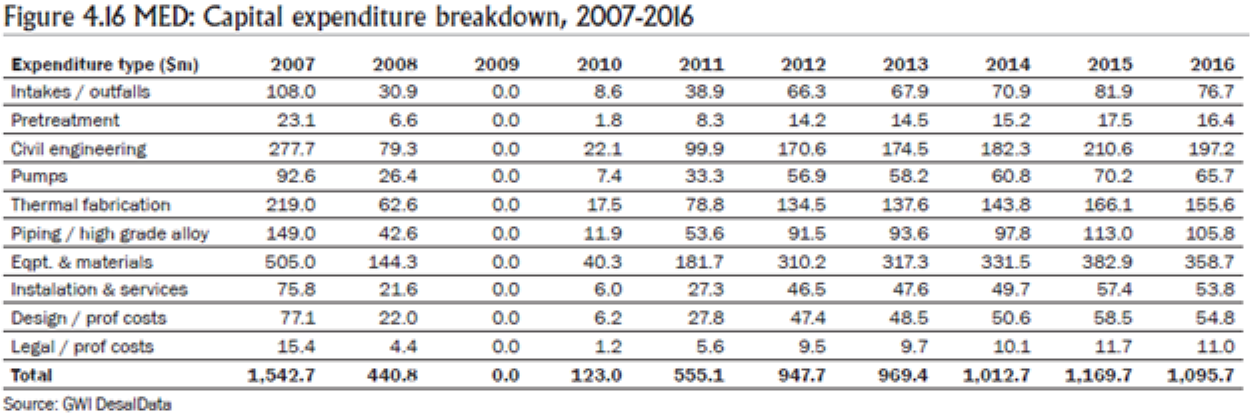


Figure 4.16 MED: Capital expenditure breakdown, 2007-2016

Expenditure type ($m)	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Intakes / outfalls	108.0	30.9	0.0	8.6	38.9	66.3	67.9	70.9	81.9	76.7
Pretreatment	23.1	6.6	0.0	1.8	8.3	14.2	14.5	15.2	17.5	16.4
Civil engineering	277.7	79.3	0.0	22.1	99.9	170.6	174.5	182.3	210.6	197.2
Pumps	92.6	26.4	0.0	7.4	33.3	56.9	58.2	60.8	70.2	65.7
Thermal fabrication	219.0	62.6	0.0	17.5	78.8	134.5	137.6	143.8	166.1	155.6
Piping / high grade alloy	149.0	42.6	0.0	11.9	53.6	91.5	93.6	97.8	113.0	105.8
Eqpt. & materials	505.0	144.3	0.0	40.3	181.7	310.2	317.3	331.5	382.9	358.7
Instalation & services	75.8	21.6	0.0	6.0	27.3	46.5	47.6	49.7	57.4	53.8
Design / prof costs	77.1	22.0	0.0	6.2	27.8	47.4	48.5	50.6	58.5	54.8
Legal / prof costs	15.4	4.4	0.0	1.2	5.6	9.5	9.7	10.1	11.7	11.0
Total	**1,542.7**	**440.8**	**0.0**	**123.0**	**555.1**	**947.7**	**969.4**	**1,012.7**	**1,169.7**	**1,095.7**

Source: GWI DesalData

Table 11: Capital expenditure breakdown for Multiple Effect Distillation (GWI, 2010)

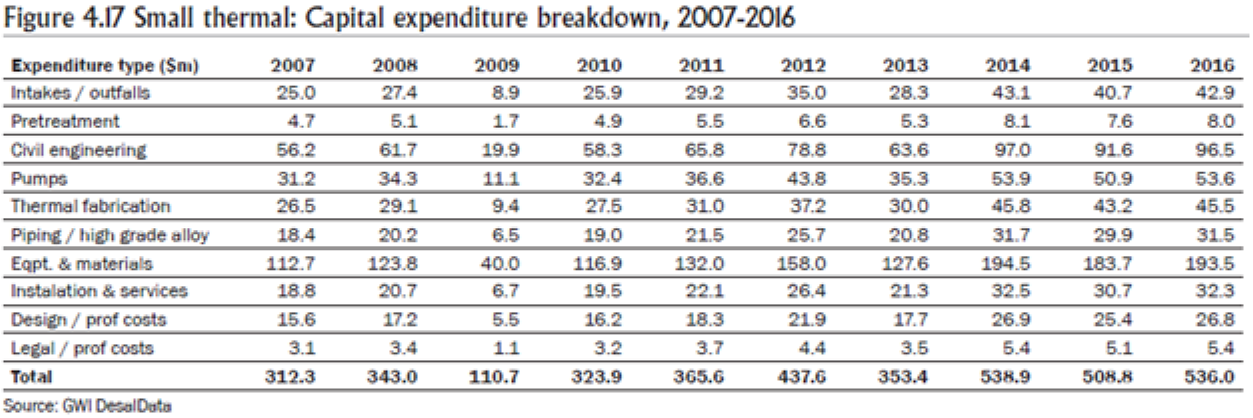


Figure 4.17 Small thermal: Capital expenditure breakdown, 2007-2016

Expenditure type ($m)	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Intakes / outfalls	25.0	27.4	8.9	25.9	29.2	35.0	28.3	43.1	40.7	42.9
Pretreatment	4.7	5.1	1.7	4.9	5.5	6.6	5.3	8.1	7.6	8.0
Civil engineering	56.2	61.7	19.9	58.3	65.8	78.8	63.6	97.0	91.6	96.5
Pumps	31.2	34.3	11.1	32.4	36.6	43.8	35.3	53.9	50.9	53.6
Thermal fabrication	26.5	29.1	9.4	27.5	31.0	37.2	30.0	45.8	43.2	45.5
Piping / high grade alloy	18.4	20.2	6.5	19.0	21.5	25.7	20.8	31.7	29.9	31.5
Eqpt. & materials	112.7	123.8	40.0	116.9	132.0	158.0	127.6	194.5	183.7	193.5
Instalation & services	18.8	20.7	6.7	19.5	22.1	26.4	21.3	32.5	30.7	32.3
Design / prof costs	15.6	17.2	5.5	16.2	18.3	21.9	17.7	26.9	25.4	26.8
Legal / prof costs	3.1	3.4	1.1	3.2	3.7	4.4	3.5	5.4	5.1	5.4
Total	**312.3**	**343.0**	**110.7**	**323.9**	**365.6**	**437.6**	**353.4**	**538.9**	**508.8**	**536.0**

Source: GWI DesalData

Table 12: Capital expenditure breakdown for Small Thermal (GWI, 2010)

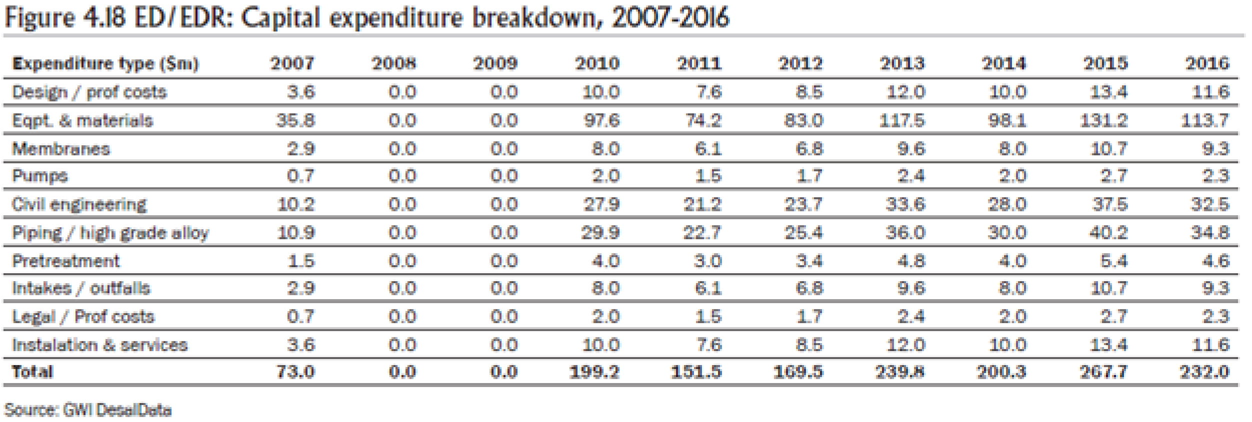


Figure 4.18 ED/EDR: Capital expenditure breakdown, 2007-2016

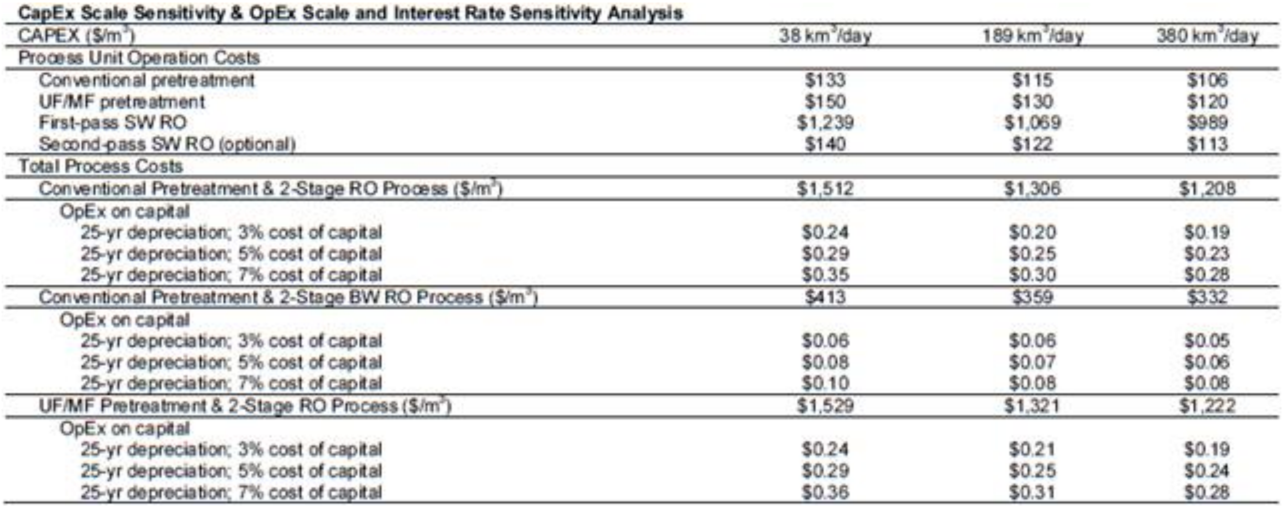
Expenditure type ($m)	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Design / prof costs	3.6	0.0	0.0	10.0	7.6	8.5	12.0	10.0	13.4	11.6
Eqpt. & materials	35.8	0.0	0.0	97.6	74.2	83.0	117.5	98.1	131.2	113.7
Membranes	2.9	0.0	0.0	8.0	6.1	6.8	9.6	8.0	10.7	9.3
Pumps	0.7	0.0	0.0	2.0	1.5	1.7	2.4	2.0	2.7	2.3
Civil engineering	10.2	0.0	0.0	27.9	21.2	23.7	33.6	28.0	37.5	32.5
Piping / high grade alloy	10.9	0.0	0.0	29.9	22.7	25.4	36.0	30.0	40.2	34.8
Pretreatment	1.5	0.0	0.0	4.0	3.0	3.4	4.8	4.0	5.4	4.6
Intakes / outfalls	2.9	0.0	0.0	8.0	6.1	6.8	9.6	8.0	10.7	9.3
Legal / Prof costs	0.7	0.0	0.0	2.0	1.5	1.7	2.4	2.0	2.7	2.3
Instalation & services	3.6	0.0	0.0	10.0	7.6	8.5	12.0	10.0	13.4	11.6
Total	**73.0**	**0.0**	**0.0**	**199.2**	**151.5**	**169.5**	**239.8**	**200.3**	**267.7**	**232.0**

Source: GWI DesalData

Table 13: Capital expenditure breakdown for Electrodialysis and Electrodialysis Reversal (GWI, 2010)

Appendix G: U.S. Capital and Operational Expenditures

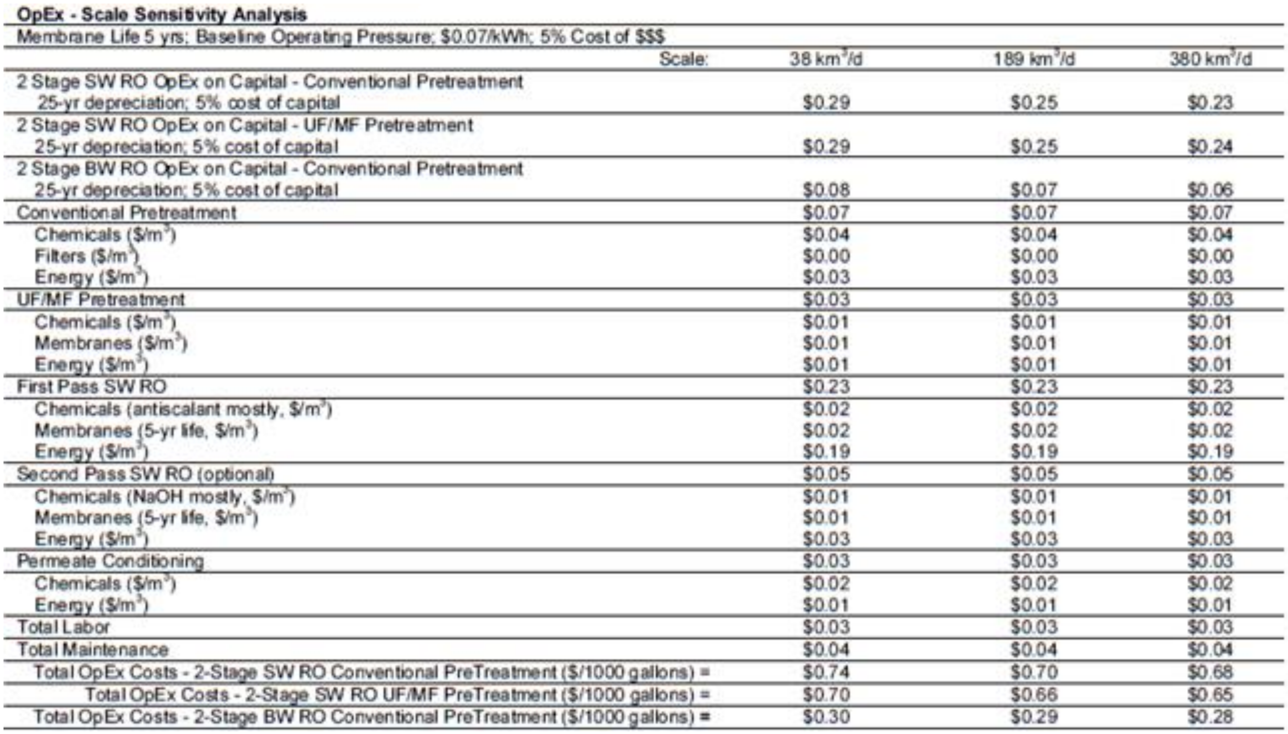
Tables G-1 and G-2 from *Desalination: A National Perspective*, show individual capital and operational expenditures for reverse osmosis power plants. The different plant types include seawater reverse osmosis with conventional pretreatment, seawater reverse osmosis with ultrafiltration/nanofiltration pretreatment, and brackish water reverse osmosis with conventional pretreatment. The plants are also outlined in sizes of 38 km^3/day (10 MGD), 189 km^3/day (50 MGD) and 380 km^3/day (100 MGD). The operational expenditure breakdown shows the resulting price of treated water per thousand gallons.



CapEx Scale Sensitivity & OpEx Scale and Interest Rate Sensitivity Analysis

CAPEX ($/m^3)	38 km^3/day	189 km^3/day	380 km^3/day
Process Unit Operation Costs			
Conventional pretreatment	$133	$115	$106
UF/MF pretreatment	$150	$130	$120
First-pass SW RO	$1,239	$1,069	$989
Second-pass SW RO (optional)	$140	$122	$113
Total Process Costs			
Conventional Pretreatment & 2-Stage RO Process ($/m^3)	$1,512	$1,306	$1,208
OpEx on capital			
25-yr depreciation; 3% cost of capital	$0.24	$0.20	$0.19
25-yr depreciation; 5% cost of capital	$0.29	$0.25	$0.23
25-yr depreciation; 7% cost of capital	$0.35	$0.30	$0.28
Conventional Pretreatment & 2-Stage BW RO Process ($/m^3)	$413	$359	$332
OpEx on capital			
25-yr depreciation; 3% cost of capital	$0.06	$0.06	$0.05
25-yr depreciation; 5% cost of capital	$0.08	$0.07	$0.06
25-yr depreciation; 7% cost of capital	$0.10	$0.08	$0.08
UF/MF Pretreatment & 2-Stage RO Process ($/m^3)	$1,529	$1,321	$1,222
OpEx on capital			
25-yr depreciation; 3% cost of capital	$0.24	$0.21	$0.19
25-yr depreciation; 5% cost of capital	$0.29	$0.25	$0.24
25-yr depreciation; 7% cost of capital	$0.36	$0.31	$0.28

Table 14: Capital expenditure scale sensitivity and operation expenditure scale and interest rate sensitivity analysis (National Research Council, 2008)



OpEx - Scale Sensitivity Analysis

Membrane Life 5 yrs; Baseline Operating Pressure; $0.07/kWh; 5% Cost of $$$

Scale:	38 km^3/d	189 km^3/d	380 km^3/d
2 Stage SW RO OpEx on Capital - Conventional Pretreatment 25-yr depreciation; 5% cost of capital	$0.29	$0.25	$0.23
2 Stage SW RO OpEx on Capital - UF/MF Pretreatment 25-yr depreciation; 5% cost of capital	$0.29	$0.25	$0.24
2 Stage BW RO OpEx on Capital - Conventional Pretreatment 25-yr depreciation; 5% cost of capital	$0.08	$0.07	$0.06
Conventional Pretreatment	$0.07	$0.07	$0.07
Chemicals ($\$/m^3$)	$0.04	$0.04	$0.04
Filters ($\$/m^3$)	$0.00	$0.00	$0.00
Energy ($\$/m^3$)	$0.03	$0.03	$0.03
UF/MF Pretreatment	$0.03	$0.03	$0.03
Chemicals ($\$/m^3$)	$0.01	$0.01	$0.01
Membranes ($\$/m^3$)	$0.01	$0.01	$0.01
Energy ($\$/m^3$)	$0.01	$0.01	$0.01
First Pass SW RO	$0.23	$0.23	$0.23
Chemicals (antiscalant mostly, $\$/m^3$)	$0.02	$0.02	$0.02
Membranes (5-yr life, $\$/m^3$)	$0.02	$0.02	$0.02
Energy ($\$/m^3$)	$0.19	$0.19	$0.19
Second Pass SW RO (optional)	$0.05	$0.05	$0.05
Chemicals (NaOH mostly, $\$/m^3$)	$0.01	$0.01	$0.01
Membranes (5-yr life, $\$/m^3$)	$0.01	$0.01	$0.01
Energy ($\$/m^3$)	$0.03	$0.03	$0.03
Permeate Conditioning	$0.03	$0.03	$0.03
Chemicals ($\$/m^3$)	$0.02	$0.02	$0.02
Energy ($\$/m^3$)	$0.01	$0.01	$0.01
Total Labor	$0.03	$0.03	$0.03
Total Maintenance	$0.04	$0.04	$0.04
Total OpEx Costs - 2-Stage SW RO Conventional PreTreatment ($/1000 gallons) =	$0.74	$0.70	$0.68
Total OpEx Costs - 2-Stage SW RO UF/MF PreTreatment ($/1000 gallons) =	$0.70	$0.66	$0.65
Total OpEx Costs - 2-Stage BW RO Conventional PreTreatment ($/1000 gallons) =	$0.30	$0.29	$0.28

Table 15: Operational expenditure scale sensitivity analysis (National Research Council, 2008)

Appendix H: Poway Water Use Restrictions

On July 21, Poway City Manager Dan Singer declared a Level 2 Water Shortage Alert, with mandatory conservation measures that took effect on August 1, 2014. The City Council ratified the declaration at its meeting on August 5, 2014. The conservation measures associated with a Level 2 Declaration, as defined in Poway Municipal Code Chapter 8.94, are as follows:

1. Do not wash down paved surfaces, including but not limited to sidewalks, driveways, parking lots, tennis courts, or patios, except when necessary to alleviate safety or sanitation hazards.
2. Do not allow water waste from inefficient landscape irrigation, such as runoff, low head drainage, or overspray and do not allow water flows onto non-targeted areas, such as adjacent property, non-irrigated areas, hardscapes, roadways, or structures.
3. Irrigate residential and commercial landscape before 8:00 a.m. and after 8:00 p.m. only.
4. Use only a hand-held hose equipped with a positive shut-off nozzle or bucket to water landscaped areas, including trees and shrubs located on residential and commercial properties that are not irrigated by a landscape irrigation system.
5. Irrigate nursery and commercial grower’s products before 8:00 a.m. and after 8:00 p.m. only. Watering is permitted at any time using a hand-held hose equipped with a positive shut-off nozzle, a bucket, or when a drip/micro-irrigation system/equipment is used. Irrigation of nursery propagation beds is permitted at any time. Water for livestock is permitted at any time.
6. Use only recirculated water to operate ornamental fountains.
7. Wash vehicles only using a bucket and a hand-held hose with positive shut-off nozzle, mobile high pressure/low volume wash system, or at a commercial site that recirculates (reclaims) water on site. Do not wash vehicles during hot conditions when additional water is required due to evaporation.
8. Offer guests in hotels, motels, and other commercial lodging establishments the option of not laundering towels and linens daily.
9. Do not use single-pass cooling equipment in new commercial applications, including, but not limited to, air conditioners, air compressors, vacuum pumps, and ice machines.
10. Use a water recirculation system for commercial conveyor car washes and all new commercial laundry systems.

11. Run only fully loaded dishwashers and washing machines.
12. Use recycled or non-potable water for construction purposes to the fullest extent possible when available.
13. Reset irrigation clocks as necessary to water once per week in winter, and not more than two times per week in summer.
14. Add water to maintain the level of water in swimming pools and spas only when necessary (to ensure proper operation of the pool filter). A pool cover is encouraged, but not required.
15. Serve and refill water in restaurants and other food service establishments only upon request.
16. Landscape watering shall be conducted only in conformance with landscape watering schedules and restrictions for commercial and residential properties approved by the City Manager. The watering schedule and restrictions may address factors such as how many days during the week, which days of the week, the amount of time per watering station, and other pertinent details. Watering of landscaped areas that are not irrigated by a landscape irrigation system shall be subject to the same watering schedule and restrictions, using a bucket, hand-held hose with positive shut-off nozzle, or low-volume non-spray irrigation. City-maintained parks, landscaped areas, and facilities; golf courses; and commercial growers and nurseries are exempt from the schedule restrictions.
17. All leaks shall be repaired within 72 hours of notification by the City of Poway, unless other arrangements are made with the City Manager.

The landscape watering schedule and restrictions are as follows:

- Irrigation will be allowed only before 8:00 a.m. and after 8:00 p.m.
- Landscape irrigation is limited to no more than two assigned days per week:
- Homes with street addresses ending in an odd number can water Sunday and Thursday;
- Homes with street addresses ending in an even number can water Saturday and Wednesday;
- Apartments, condos and businesses can water Monday and Friday.
- Landscape irrigation using sprinklers is limited to no more than ten minutes maximum per watering station per assigned day. This requirement does not apply to drip, micro-irrigation, or stream rotor systems.

- Watering of landscaped areas that are not irrigated by a landscape irrigation system may occur no more than two assigned days per week by using a hand-held container, hand-held hose with positive shut-off nozzle, or low-volume soaker hose.
- Watering is not permitted during or within 48 hours after a measurable rain event.

Poway’s Water Conservation Plan allows flexibility with these watering schedule restrictions for properties that have installed new low water-use landscaping. Recognizing that California-friendly plants need water to establish, the City Manager may grant an exemption or modification to these restrictions as necessary.

Appendix I: New Desalination Technology

Name	Description	Advantages	Disadvantages	Development/ Use
Cogeneration	A desalination plant and a power plant are constructed together to produce both freshwater and energy.	-Fulfills two different needs of a region (water and energy) -Utilizes waste heat -Energy is directly produced for desalination	-Higher cost to construct than one process alone -Must be run together -The desalination plant must use thermal technologies	-Studies of cost benefits are being conducted -Used all over the world
Colocation	The cooling water used in an existing power plant is used by a desalination plant.	-No new intake pipes must be built/ the desalination plant does not need to go through this permitting process -Slightly higher water temperature -Use power plant water for brine dilution -Only one set of intake pumps	-New laws prohibiting once through cooling for power plants	-Fully developed, but now being phased out of use - Common in the U.S. and the MENA region
Concentrated Solar Power	Curved mirrors focus the sun's energy onto a receiver in the center. This heats water to produce steam that moves a turbine and generates electricity that can be used for desalination.	-A source of renewable energy -Takes more advantage of the sun's energy than traditional solar panels	-Limited to MSF -Energy could be used for the grid -Limited to areas with little clouds, fog, and rain to make financial sense	-Currently being developed by the DOE
Deionization	Two porous electrodes attracted ions out of the water.	-Good for pre/post treatment -Energy efficient for brackish water	-not efficient for large scale, high salinity water treatment	-Used for brackish water <10,000 ppm
Directional Solvent Extraction	Directional solvents, like decanoic acid, are used to dissolve water at a slightly	-Low temperatures so it can capitalize on waste heat -No membranes	-Still in development	-Developed by MIT

	higher temperature and leave salts behind. Once cooled, the water is recovered and solvent is reused.	-Low cost		
Forward Osmosis	Uses an osmotic pressure gradient to filter water across a membrane.	-Potential for lower energy costs than RO -Can use waste energy	-No commercial FO membranes available, so they are adapted form RO membranes and are not as effective	-One of the closest technologies to commercialization
Freeze- Thaw	The temperature of saltwater is reduced so that freshwater freezes and can be removed. The ice is then melted, providing a freshwater source.	-Minimal scaling and corrosion of materials	-Difficult on a large scale	-Research is being conducted
Geothermal Energy	Heat from the earth is used to generate steam to run a turbine and produce power.	-Renewable -Cheap to maintain	-Expensive initial cost -Fracking/holes in the ground -groundwater contamination -Thermal technologies must be used	-Some pilot plants have been studied
Humidification-Dehumidification	A gas, such as air, absorbs pure water from the feed saline water (humidifying) and then condenses it out (dehumidifying), leaving only freshwater.	-Similar to MSF, but does not require a large temperature increase -Less energy input required	-May not be plausible on a large scale	-Still in development by a company called Gradient
Membrane Distillation	Vapor is passed through a hydrophobic membrane, leaving behind impurities	-Can use waste energy -limited use of chemicals -Little pretreatment required -Low operating pressures -Low sensitivity to pH and salinity -Reduced process volume compared to traditional	-Not commercially successful -Thermal energy driven -lower yield rates compared to conventional desalination techniques	-Still in development

Solar and Wind Energy	Solar and wind energy (renewables) can be used to power desalination plants.	-Does not use fossil fuels/ less harmful to the environment -Can be used with all forms of desalination technologies -Renewable energy	-This energy could also be added to the grid instead (the same amount of energy would be used) -Can be viewed as a PR stunt	-Fully developed technology -Used in Australia
Variable Run Times	The rate of water production by the desalination plant changes based on time of day and the amount and cost of energy from the grid.	-Lowers the cost of energy used by the plant -Can even out the duck curve/ be used to manage the demand on the grid	-Plant will not be able to run at full capacity to get the benefits -must ensure the plant produces enough each day to be cost effective	-In use, but only in select countries - Highly used and successful in Israel (see the Ashkelon and Hadera plants) -Poseidon Water looking to build one in Huntington Beach, CA
Waste Heat	An industrial process that gives off waste energy that can be used to power a desalination plant.	-Utilize the heat instead of wasting it -Do not need to produce more heat and burn fossil fuels -reduces energy pulled from the grid, leading to less energy production	-Only works with thermal technologies	-fully developed - Typically used in the MENA region where thermal technologies are more common
Wave Energy	Flaps that are tethered to the bottom of the sea, where they are moved from the pressure of the waves, producing energy.	-Renewable energy source that can directly fuel desalination	-Could have more environmental impacts	-Still very early in development -Has been attempted in Australia

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