REVERSE OSMOSIS IN DESALINATION PLANTS

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Abstract*—This paper will explore the process of desalination by reverse osmosis (RO) and the benefits that it can contribute to society. RO may offer a sustainable solution to the water crisis, a global problem that is not going away without severe interference and innovation. This paper will go into depth on the processes involved with RO and how contaminants are removed from sea-water. Additionally, the use of significant pressures to force water through the semi-permeable membranes, which only allow water to pass through them, will be investigated. Throughout the paper, the topics of environmental and economic sustainability will be covered. Subsequently, the two primary methods of desalination, RO and multi-stage flash distillation (MSF), will be compared. It will become clear that RO is a better method of desalination when compared to MSF.*

This paper will study examples of RO in action, including; the Carlsbad Plant, the Sorek Plant, and applications beyond the potable water industry. It will be shown that The Claude "Bud" Lewis Carlsbad Desalination Plant (Carlsbad), located in San Diego, California is a vital resource in the water economy of the area. The impact of the Sorek Plant, located in Tel Aviv, Israel will also be explained. Both plants produce millions of gallons of fresh, drinkable water and are vital resources for the people that live there.

Key Words - Carlsbad, Desalination, Potable, Reverse Osmosis, Sorek, Water Crisis

THE WATER CRISIS

The global water crisis is a very substantial and relevant issue throughout the world. Water scarcity is defined as the insufficient availability of water in comparison to the demand for water usage [1]. This widespread problem is unlikely to go away on its own, as increasing population correlates to growing demand for clean water. As mentioned in a research article by the American Association for the Advancement of Science, 1.8 to 2.9 billion people are facing severe water scarcity for at least four months per year [1]. The billions of people who suffer from this crisis each day are spread across the globe, but certain regions are most heavily affected. Specifically, the two regions most affected by the water crisis are North Africa and the Middle East. A startling 61% of the combined population in these two regions are exposed to high or very high-water stress, as mentioned in the book *Beyond Scarcity* [2]. This disproportionate access to clean water is caused by a combination of the region's poor climate and economy. In these regions, government instability and civil turmoil further exacerbate the water crisis.

However, the large-scale problem does not only affect third-world countries but also nearly every nation, including the United States of America. In the USA, millions have issues with water scarcity, impacting their everyday lives [3]. California has faced multiple year-long droughts, limiting their water availability and usage. With rising water usage and climate change, California faces a long-term issue with water scarcity [3]. The problem of water scarcity may not be to the same extent in California as it is in in the Middle East, but it will have a tremendous impact on the agricultural industry in the state, which in turn will harm the state's economy. The spread of water scarcity reaches much closer to the University of Pittsburgh, where there have been local problems with availability of clean water. In the past year, several counties in the Pittsburgh area have been on flush and boil advisories [4].

The problem of water scarcity is one that can affect any area, and it only seems to be getting worse. By the year 2007, about 1.2 billion people lived in areas of physical scarcity, and by 2025, 1.8 billion people will be living in regions with absolute scarcity [5]. As demonstrated by these figures, the current trend projects an increase in water scarcity, leading to a decrease in quality of life for hundreds of millions of people. An economically sustainable solution must be implemented to combat the far-reaching problem of water scarcity.

One possibly viable solution is desalination plants, which can produce massive amounts of clean, drinkable and agriculture-friendly water. These desalination plants offer a sustainable solution through the process of RO.
The water supply is no longer restricted to the limited amount of freshwater. Instead, clean water can be produced from the vast supply of sea-water. The sustainability of RO can give future generations the ability to produce clean water, which is of great importance due to the increasing severity of the water crisis [6].

THE SOLUTION: REVERSE OSMOSIS

Pre-treatment

The process of RO begins with ocean water flowing into the plant's uptake through trash racks and traveling screens to remove any debris that the ocean water may contain [7]. The water then goes through a multimedia gravity filter which typically consists of anthracite, silica, and granite or only sand and anthracite [7]. This will remove any particles larger than 10 microns [7]. The removal of these particles provides protection to the high-pressure pumps and the RO section of the plant [7]. Pre-treatment is required to remove any unwanted constituents from the water. If pre-treatment is ignored, then the constituents in the water would cause membrane fouling, resulting in contamination of the membrane [7]. According to a well-renowned engineer, Akili Khawaji, "A typical pretreatment includes chlorination, coagulation, acid addition, multi-media filtration, micron cartridge filtration, and dechlorination. The type of pre-treatment to be used largely depends on the feed water characteristics, membrane type and configuration, recovery ratio, and product water quality" [7]. The differing feed water characteristics require various chemicals to be added to the intake water. Sodium hypochlorite is added to prevent the growth of microorganisms, sulfuric acid adjusts the pH and assists in the control of hydrolysis and scale formation, and sodium bisulfate to dechlorinate [7].

Membrane pressure required

Following pre-treatment, feedwater must be raised to the appropriate pressure for the contaminants to be filtered out by the membranes [8]. The osmotic pressure is overcome by applying a higher external pressure, which forces water to flow in the reverse direction to the natural flow across the membrane. The permeate is encouraged to flow through the membrane because of the pressure differential created between the pressurized feedwater and product water [8]. The feedwater that remains then continues to the pressurized side of the reactor as brine. The initial pressurization of feedwater is the most significant energy requirement through the process [8].

The tendency for water to flow through the membrane is known as osmotic pressure (π), which is directly related to the dissolved solute concentration as shown in equation 1.

$$\pi = iMR$$

Figure 1 [9]
Osmotic Pressure Equation

In the van't Hoff equation above, osmotic pressure has units of kPa; R is the universal gas constant with units of J/mol*K; T is the absolute temperature in Kelvins; i is the van't hoff factor; and M is molarity of the dissolved salt. Equation 1 proves that a higher concentration of NaCl corresponds to higher osmotic pressure [9]. For the variations of seawater used in desalination plants, the osmotic pressure ranges from 5500 to 7000 kPa, and for the less concentrated brackish water, the osmotic pressure ranges from 1500 to 2500 kPa [8]. This difference in osmotic pressure is due to the varying concentration of the inputs.

Hollow fine fiber membrane

Depending on the desalination plant, different types of membranes may be used. The hollow fiber module is typically used for cellulosic derived membranes [10]. It was first developed by Dow chemical in 1966 [10]. A review on RO membrane technology states, "In this module, thousands of hollow fibers are bundled together into an element making the pressure vessels" [10]. The configuration provides a very dense packing of fibers in each vessel, along with uniform permeate flow with minimal pressure drop [10]. The hollow fiber module produces up to ten times more permeate water than the spiral wound membrane, due to high membrane surface area. The difficulty in applying the technology to the more widely used polyamide membranes on a commercial scale has limited their use to only cellulosic membranes [10]. In Figure 2 below depicts a typical hollow fiber membrane. In it, it displays the sea water intake as well as the brine and product water outlet streams. Further, the figure shows how tightly packed each hollow fine fiber bundle is.

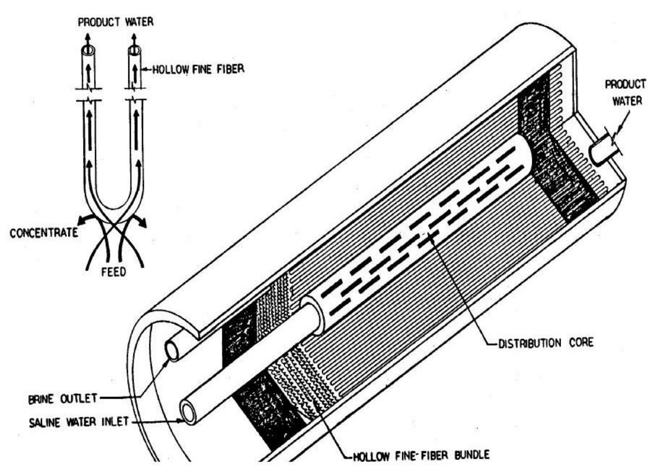

Figure 2 [11]
Hollow Fine Fiber Module

Spiral Wound Membrane

Spiral wound module is an advanced version of the plate and frame model of module [10]. The structure of the plate and form module consists of, "Two membranes with their active side are placed facing each other separated by a feed channel spacer and centrally connected to perforated permeate collection coil" [10]. Over the years the design and materials have been slightly modified. Desalinated water passes through the membrane surface into the permeate channel in a spiral fashion toward the center of the module and exits the module through the collection tube [10].

Different numbers of spiral wound elements may be contained in single pressure vessels depending upon the requirement. Recently the focus of spiral wound membrane research has gone to maximizing the membrane area to increase the capacity for desalination [10].

Additionally, "Studies indicate reduction up to nearly 20% of the total desalination cost by use of large modules (16 in.. and 18 in..) compared to the conventional 8-inch element" [10]. The MegaMagnum RO element created by Koch Membrane Systems is one of the only elements to have an 18 in diameter compared to most other manufacturers who provide a 16 in diameter element [10].

The spiral wound module uses polyamide thin film composite membranes [10]. Although the hollow fiber module has an advantage over the spiral wound regarding packing density, most hollow fiber modules have been swapped out for spiral wound modules [10]. The main cause is the fouling resistance of the spiral wound module, which results in fewer requirements for pretreatment [10].

Membrane Separation

In the membrane separation process of RO, the semi-permeable membrane prevents dissolved salts from passing through. The membrane must be capable of withstanding the drop of the pressure across it. Currently, there are membranes available for pump operation up to 84 kg/cm discharge pressure [7].

From applying feed water to the membrane assembly, the result is a desalinated water product stream, permeate, and a brine reject stream as shown below in Figure 3. The figure shows the different features of the module that feedwater is applied through. Upon viewing the figure, the separation of the two product streams become clear. However, this membrane filter process does not have perfect efficiency, so a small percentage of salt can pass through the membrane and stay in the product stream [8].

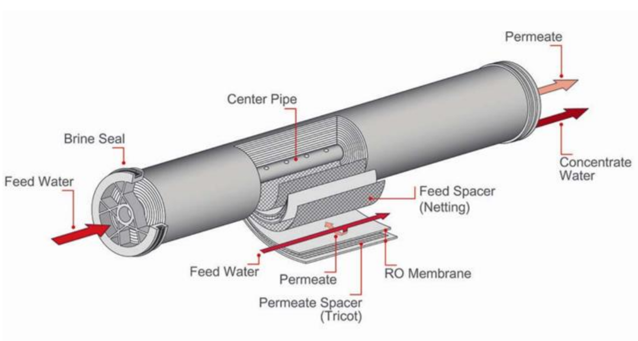

Figure 3 [12]
Spiral Wound Membrane Module

Later in the paper, the efficiency of RO will be compared to a different desalination technique. With this in mind, the performance of the RO membrane is affected by various parameters; flow rate, permeate flux, salt rejection, recovery rate, and differential pressure [12]. Feedwater flow rate is the rate of water entering the RO system whereas permeate flow rate is the rate of water moving through the membranes [12]. The permeate flux describes the amount of permeate produced during membrane separation per unit of time and RO membrane area [12]. The salt rejection is the percentage of solute retained by the RO membrane. The recovery rate is the fraction of feed flow that passes through the membrane. Differential pressure is the difference between feed and concentrate pressure during water flow through one or more RO membrane elements [12].

Post-Treatment

After passing through the membrane, the product water is then ready for the post-treatment process. This entails adjustments of the water's pH and removal of dissolved gas disinfection [13]. According to Lenntech, a water treatment company, "Desalination Reverse Osmosis permeate has a slightly acidic pH after Pass-1, a TDS of 70 to 350 mg/L, 2 to 6 mg/L of Ca+ Mg and Boron concentration between 0.5-1.2 mg/L based on the raw water salinity and temperature" [13]. With these concentrations, the water is not yet usable for drinking, process, or irrigation. To become clean drinking water, the sodium chloride and boron concentration can be reduced by making a second run through the RO process [13]. After passing through the membrane a second time, residual calcium and magnesium concentration are close to zero, which is a requirement for drinking water. To attain irrigation water, there must be an equilibrium between calcium and magnesium which is beneficial for the soil. Additionally, boron is poisonous to plants and should be removed from the water [13]. A second pass through the RO system is usually avoided for irrigation water because there must be a sufficient level of calcium and magnesium still present. Process water is a somewhat generic term that encompasses many different types of water. Requirements vary depending on the manufacturer's guidelines, so the treatment process also ranges [13].

Sustainability and Environmental Impact of RO

Similar to any modern engineer, after analyzing a process, one must thoroughly examine its sustainability. Concerning RO, engineers investigate how desalination plants and the process will meet their definition of sustainability. The definition of sustainability that will be used in this paper coincides with that of the United Nations Conference on sustainability, which is, “Sustainable development emphasizes a holistic, equitable and far-sighted approach to decision-making at all levels. It emphasizes not just strong economic performance but intragenerational and intergenerational equity. It rests on integration and a balanced consideration of social, economic and environmental goals and objectives in both public and private decision-making”

[14]. When engineers consider the sustainability of a project, they must look at the long-term effects generations down the line, in addition to it's immediate economic, environmental, and quality of life impact.

Although there are benefits associated with RO, negative environmental impacts may ensue. To illustrate, desalination processes are commonly powered by energy from the combustion of fossil fuels which release greenhouse gases, in addition to other harmful emissions. These emissions contribute to acid rain and climate change, negatively impacting the environment [6]. As previously mentioned, desalination plants generate clean water and concentrate brine. The concentrate is made of liquid substances containing up to 20% of the treated water. When the brine is disposed of into waters of lower salinity, the concentrate will normally sink to the bottom layers [15]. This creates problems for the marine environment because the brine may contain damaging chemicals. However, to reduce the harm, desalination plants dilute the concentrate in a process known as blending [7].

Other environmentally harmful issues with desalination plants are noise pollution, visual pollution, reduction in recreational fishing and swimming areas [16]. Even though the process of RO has negative environmental impacts, the technology is rapidly changing, which will likely lead to improvements in its sustainability.

REVERSE OSMOSIS VS. MULTI-STAGE FLASH DESALINATION

While the process of RO has already been discussed, there is another method for the desalination of water, multi-stage flash distillation (MSF). Multi-stage flash desalination uses reduced pressure instead of extremely high temperatures to create steam. MSF plants also use regenerative heating systems to reduce their overall heat input [7]. On the other hand, RO applies the principles of osmosis to get potable water.

Multi-Stage Flash Distillation

MSF begins with the uptake of ocean water. The entire uptake system contains, "An open intake channel or submarine pipe, a pumphouse, sodium hypochlorite generators, and distribution and return piping or channel," according to Akili D.Khawaji, a published engineer [7]. The uptake stream is then taken to the main plant. The seawater is heated by the brine heater and by a low-pressure vapor that is supplied by cogeneration power plant, such as a gas turbine with a heat recovery steam generator [7]. Then the heated seawater flows into the evaporator flash chambers. The evaporator is made of multiple stages; typically a modern large-scale MSF plant will have 19-28 stages [7]. The plant will typically run from 90-120℃. Operating the plant at a higher temperature will increase the efficiency of the plant but has the potential to damage the plant [7]. At temperatures above 120℃, the potential for scale formation and accelerated corrosion of the metal surfaces in contact with seawater increases [7]. The boiling continues until the seawater reaches the minimum vapor pressure required in that flash chamber for vaporization. As the water travels through each chamber, it is sequentially increasing the concentration of salt and other dissolved particulates. This allows the sea water to dissolve without adding in more heat [7].

The water vapor is then cooled and condensed by the colder seawater that flows in the tubes of the condenser to produce liquid water. The heat absorbed in the condenser is then recycled to heat the incoming brine water. The water is also collected sequentially and then collected in large storage tanks. MSF typically yields water with a 2-10 ppm of dissolved solids [7]. The water will then go through remineralization in the post-treatment process [7]. The quantity of water produced from an MSF plant varies depending on many factors. With higher temperatures, the amount of water produced increases, but it also puts the plant at risk for corrosion [7]. The more evaporation stages that a plant has, the more water it can produce, but the more stages a plant has, the more expensive it is to heat all of the chambers. This decreases the economic feasibility of the plant [7]. The figure below depicts the different stages of a typical MSF plant. As the water moves from one chamber to the next, it continuously increases in salinity until it is discharged as brine.

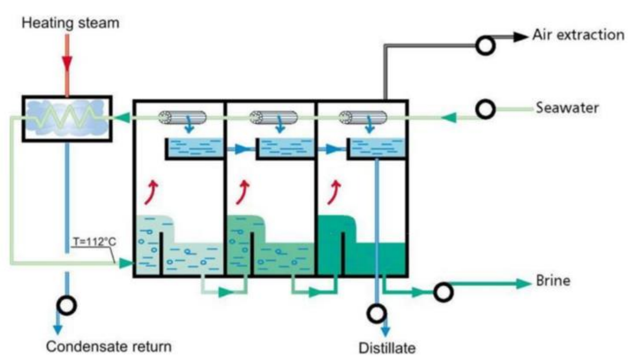

Figure 4 [17]
The layout of MSF process

Comparison

The cost of water production varies from each plant and depends on several factors. According to Fazil T. Najafi, these factors include: "Energy requirements, source, water characteristics, geographical and location constraints, product water requirements, waste disposal options, operational and maintenance issues and utilization rates" [17]. High capital, operational and maintenance costs, high energy costs, and environmental impacts are the main challenges that desalination plants have to overcome today [17]. The production of RO plants has increased due to notable developments in new technology, while other types of desalination plants have remained stagnant. In the next section of this paper, the developments in RO will be described in depth.

Currently, MSF represents 36.5% of the worlds desalination, second to only RO at 47.2% [17]. The MSF process is composed of simple mechanics which helps to keep it in the top two despite the high costs associated with it. RO is considered the most cost-effective form of desalination when compared to other methods, which is why it is the most widely used method. The recovery percentage, which is the percentage of usable permeate water, also favors RO over MSF. RO has a recovery percentage range of 30-50% while MSF is a mere 10-20% [17]. Per m^3/day of water, it costs MSF from \$1,000-\$1,500, in comparison to RO, which has a range of \$700-\$1,500 [17]. RO additionally prevails over MSF with energy consumption; its usage of (3-4 kWh/m^3) trumps the (5.5-16 kWh/m^3) energy usage of MSF [15]. The greater energy efficiency of RO demonstrates its sustainability. As the process of RO incorporates new technologies, the energy input will continue to decrease, leading to a decrease in the price of water [18]. The economic sustainability of RO will then improve because of the lower costs associated with it.

RO plants are also very effective on a large scale, making them an exceptional option for governments or private water industries to provide water to a significant number of people such as cities or even countries. One criticism of RO is that it is not effective in small populations. However, small RO plants have been constructed in rural areas where desalination is the only way to secure potable water [8]. A small-scale RO plant has been presented by a Loughborough University professor, with excellent energy efficiency [19]. It promises to deliver 120 gal/hr of water while consuming less than 1600 W of power. Also, the flow may be controlled to reduce energy spent during non-peak hours [19]. The major factors implemented in this small-scale design are the use of renewable energy resources. The plant will use wind and solar power without the need for batteries to power a significant amount of the system [19]. If the plant is monitored daily and is given proper maintenance, there are essentially no long-term operational problems [8].

IMPROVEMENTS

The process of RO is relatively new; therefore, there has been a steady increase in its use in seawater desalination plants over the past few decades. This increase in the application of RO and desalination plants, in general, illustrates the recent improvements in efficiency and cost. A large amount of research and development has been conducted in recent years to allow such an increase in efficiency. The advancement of RO, in particular, has led to a gradual increase in RO desalination plants mainly because of its lower cost and simplicity [7]. Much of the progress made in the field of RO has been in the membranes used.

Improvements in Efficiency

Improvements in the membranes have bettered the resistance compression, improved flux, increased length of life, and improved salt passage [7]. There have also been significant increases in recovery rate; in the Middle East, a region responsible for producing nearly two-thirds of the world's desalinated water, the recovery rate was 35%. However, more recently an improved recovery rate of 60% in the Pacific Ocean has been reported [7]. A significant improvement in recovery rate will allow for an overall increase in efficiency of the RO process and a decrease in operating costs. More improvements in efficiency have been made in energy recovery. Similar to water recovery, any increase in its rate will allow the plant to lower its operating costs. Previously, energy recovery devices were not used in plants, but their implementation has allowed for the energy consumption to change from approximately 6-8 kWh/m3 to 4-5 kWh/m3 [7]. This decrease in energy consumption due to energy recovery devices is critical for making the plants more economically feasible. The environmental sustainability of the plants is also significantly impacted by a reduction in energy use, which boosts the impact of these improvements.

Improvements in Nanofiltration

A rather large problem with RO plants in specific regions, such as the Middle East, is the pre-treatment area because standard filtration methods are inadequate. This is due to seasonal organic blooms, high biological activity, and turbidity, which cause problems with the desalination plant [7]. However, recently designed nanofiltration membrane pretreatment, paired with the conventional filtration system has been successfully applied in an operating plant with outstanding results. The procedure averted fouling, which causes loss of production, by the removal of turbidity and bacteria. A 40% production increase was found the operating plant which implemented this process [7]. The impressive results from this process show the practicality of implementing nano filter technology with RO to significantly increase the efficiency of plants. Further improvements in the field of RO are likely to continue, as the amount of research in the field remains high.

Future Improvements

There has been more research conducted in the field of RO that may be implemented in the future. One such study conducted by Abdel-Hameed Mostafa El-Assar, a hydrogeochemist, investigates the role of titanium dioxide nanoparticles in the improvement of performance of polyamide thin-film composite RO membranes [20]. Thin film composite membranes have three layers bonded together, with a third, thin layer of polyamide in the case of this study. To test the RO performance of the polyamide thin-film composite membranes, the permeate flux (L/m2h) and salt rejection (%) were measured using crossflow filtration. The aqueous feed solution contained 2,000 ppm NaCl with pH range 7 ± 0.3, the flow rate was 1 gallon per minute and applied pressure 225 psi [20]. The study found that the use of titanium dioxide nanoparticles increased the permeate flux from 33.6 to 40 L/m2h with a small increase of salt rejection from 99.75 to 99.82 % [20]. This may not seem like a substantial increase in the salt reject rate, but it is certainly an improvement. As more research is conducted with nanoparticles, the salt rejection is likely to continue to increase, which means the overall efficiency of RO will also improve.

Hybrid Systems

Another way to decrease the cost of water production in desalination plants is combining multiple desalination processes. Employing a hybrid system that consists of two or more desalination processes can enable an increase in overall water production. The world's largest hybrid desalination plant can produce 280,000 m^3 per day by MSF and 170,000 m^3 per day by RO [7]. The massive amount of water produced is due to the mix of MSF and RO. By implementing a combination of both desalination techniques, a plant can see the benefits from each, while also increasing the overall production of water. Figure 5 provides the layout of a simple hybrid desalination plant. The figure shows how the two different processes come together using the same inlet stream, power plant, and product stream. The significant advancements that have been made in recent years in RO have increased the practicality of desalination plants. Khawaji continues to explain that as efficiency increases over time, so will the number of plants in use [7]. This may be able to drastically change the water supply and aid in the increasing issue of water scarcity.

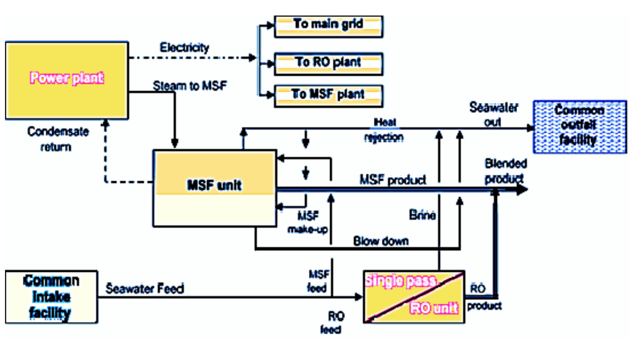

Figure 5 [21]
Diagram of Simple Hybrid Desalination Plant

REAL WORLD EXAMPLES

Two of the most modern and powerful desalination plants are the Carlsbad desalination plant in San Diego, California and the Sorek plant in Tel Aviv, Israel. The Carlsbad plant is located in Carlsbad, California, about an hour north of the center of San Diego, and produces an astonishing 56,000 acre-feet of water per day which is roughly 50 million gallons per day [22]. It produces enough water per day to support 400,000 people and has won numerous awards for design, implementation, and energy efficiency [22]. While Carlsbad has a very impressive plant and produces a staggering amount of water, it does not even compare to the Sorek plant located in Tel Aviv, Israel. The Sorek plant produces over three times as much water as Carlsbad and produces 164,000,000 gallons per day [23].

Carlsbad

Winner of the Desalination Plant of the Year for 2016 by Global Water Intelligence and publisher of periodicals for the international water industry, the Carlsbad desalination plant is the face of RO plants in the United States [24]. The Carlsbad plant is the largest one in the western hemisphere and cost a total of $922 million to construct. This not only includes the plant itself, but also the water storage facility, and a ten-mile pipeline that moves the water from the plant to nearby areas [24]. While the plant was in the build process, there was a drought in California which cause the completion date to be advanced. The plant was originally scheduled to be completed in 2016, but the drought forced an early completion date in 2015 [25]. By advancing the timeline, the cost of the project increased. Carlsbad produces roughly 50 million gallons of water per day. This is enough to support 10% of the total population of San Diego and surrounding suburbs [26]. According to the San Diego County Water Authority, the price of water per home per month can be as low as $5. The price of water from Carlsbad has an estimated inflation of 2.5% per year. This compares favorably to the average 8% inflation rate of imported treated water rates imposed by the Metropolitan Water District of Southern California from 2008 through 2018 [27]. The plant also has built-in room for inflation due to new policies and environmental laws. This is capped at 30% over the 30-year term of the agreement [27].

The Carlsbad plant implements a RO system developed by IDE Technologies. The process begins with ocean water uptake into the plant. Once in the plant, suspended particles are removed from the water by sand-anthracite filtration process. The water is forced through the semipermeable RO membranes that remove salts and other dissolved particles. Essential minerals are then added back to the water before it is piped to the Water Authority's aqueduct as drinking water [27]. The plant also incorporates a 50,000 ft^2 rooftop solar panel power generator. For every gallon of drinkable water that the process produces, it also produces one gallon of concentrate which is 67,000 ppm of salt. The concentrate is then blended with the cooling water of the adjacent power plant and discharged into the Pacific Ocean via the power plant's discharge canal [26].

According to the California Drought: Hydrological and Regulatory Water Supply Issues, "At the beginning of the 2015 water year- as of October 1, 2014- nearly 60% of California was experiencing exceptional drought, the most severe U.S. federal drought classification" [28]. In 2014, California experience the third driest year on record regarding precipitation. The low rainfall has had a lasting impact on the California landscape including topsoil moisture, unregulated streamflow, and wildfires [28]. Desalination will reduce the stress on natural water resources that are dependent on rainfall.

Sorek

The Sorek desalination plant located approximately 10 miles south of Tel Aviv, Israel is the largest modern RO plant in the world [29]. Advances in RO technology has allowed the water produced by Sorek to be unbelievably cheap. Sorek sells one m^3 of potable water for 58 US cents compared to Carlsbad's price of $1.18 per m^3 [30]. The plant was constructed by Israel Desalination Enterprises and cost around $500 million to construct for the government. Although the initial cost of construction was very high, it appears to be a very worthwhile investment. Not only does the plant sell water at lower prices than most, but it also provides 20% of all water consumed by households [29]. Even with such low prices, the plant can make a profit from selling water. This is because the plant's energy consumption is one of the lowest of any large-scale desalination plant [29].

Although construction was finished in 2013, the plant has just recently reached its maximum water output of 627,000 m^3 or 165 million gallons of potable water [29]. This level of production is advantageous for the water community, proving that desalination by RO can be constructed on a large-scale while being profitable. Since 2004, most of the Israeli water supply originated from rainfall or groundwater. Since the arrival of large-scale desalination plants, the reliance on natural water has decreased dramatically. Approximately 40% of Israel's water supply is now coming from four desalination plants [29]. It was expected that the number could increase to 50% by the year 2016 [29]. This steady supply of water is crucial in the continuing expansion in the region [29].

Water first enters pre-treatment where it undergoes flocculation, after its initial uptake from the ocean [31]. The process of flocculation involves particles becoming neutral so that they can stick together to form larger particles, and can be removed by filtration [32]. Sorek has been a guinea pig for many new technologies which have helped increase production and lower costs. They introduced a pressure center concept which allows the plant to continue to run all of the desalination trains even when the plant is not running at full speed. Also, the plant uses large diameter membrane elements which reduces the amount of time spent on maintenance. The Sorek plant implements two redundant energy sources to reduce the amount of electrical power needed for the RO process, without compromising reliability [33]. This, in turn, allows the plant to dedicate less money to the energy required to run the plant and sell water at a lower cost.

Applications of Reverse Osmosis in Other Industries

RO is being used in industries other than the production of potable water. Currently, it is being used in the steel industry to treat wastewater and reduce the overall water usage [34]. The steel sector is one of the most energy and water intensive process industries [34]. Water is mainly used in cooling facilities and process and environmental-technical applications. These applications include but are not limited to; wet gas cleaning, sanitary applications, and the process of producing steel from iron ore and fossils [34]. As water is used in different processes, it becomes contaminated, and it is important that the plant can recycle this water to reduce the plant's overall water use, thus improving its sustainability [34]. RO has been shown to be particularly effective when used on water with high conductivity, such as iron and steel wastewater [34]. RO showed to have a 100% efficiency rate in removing monovalent and divalent ions that cannot be removed via conventional physicochemical treatment [34]. The process yielded very high rejection rates for a variety of different compounds, 98% for chlorides, 92% for sulphates and 98% for fluorides [34]. According to a study that applies RO to the steel industry, "Although RO is an energy intensive process, its energy demand is lower if compared to thermal technologies" [34]. Due to the comparatively low energy requirements of RO versus other methods, it is the preferred method of wastewater treatment [34].

OUR VIEW

Today, more than 4 billion people from developed and underdeveloped countries are being affected by water scarcity [1]. For example, in San Diego when water ran low in 1991, more than 2.5 million Americans felt the effects of the drought [35]. RO has proven to be the most reliable and promising solution to the current water crisis. Partly because of the sustainable practices followed by desalination plants for water reuse and energy, which can reduce stress on the limited existing water and energy sources, with minimal impact on the environment [6]. Several new and improved desalination plants have been successfully implemented around the globe in the past few decades. With the evolution and emergence of RO desalination, the impact of water scarcity will be greatly reduced and effect fewer nations worldwide. A current constraint for RO is the high costs associated with it, but the positive outcomes of current plants indicate the future potential of the process. Modern technology and engineering aim to reduce the overall costs while increasing the efficiency of the RO process. Improvements will make plants viable not only for developed countries but also third world countries with no other options for potable water. New technology is being implemented in plants around the world, such as energy recovery devices, new membranes, and larger diameter tubes. The process will need some fine tuning, but its promise is unlimited. It has the potential to end water scarcity once and for all.

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