Desalination of Water:

A Review

M.S. Professional Student:

Natasha C. Darre

Soil and Water Science Department

Major Paper

Committee Members and Reviewers:

Gurpal Toor, Ph.D. (Advisor)

Lena Ma, Ph.D.

Kanika Inglett, Ph.D.

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Abstract

Purpose of Review: In the face of rising water demands and dwindling freshwater supplies, it is becoming necessary to search for alternative water sources. Desalination of water has become a key to helping meet increasing water needs. In many water stressed countries, water obtained by desalination far exceeds supplies from freshwater sources.

Recent Findings: Recent technological advancements have enabled desalination to become more efficient and cost-competitive on a global scale. Some ways this has been accomplished is by improving materials used in membrane-based desalination, incorporating energy-recovery devices to reduce electricity demands, and combining different desalination methods into hybrid designs. Additionally, there has been a gradual phasing-in of renewable energy sources to power desalination plants, which will help ensure desalination’s long-term sustainability. However, there are still challenges with reducing even further desalination’s energy demands and managing its waste products in order to prevent adverse environmental effects.

Summary: This review article provides a comprehensive review of desalination, including the history, location, components, costs, and other facets of desalination. The article also explores two case studies of desalination plants and provides a review of new technologies that are set to improve the overall efficiency of the desalination process.

Keywords: Desalination; Reverse Osmosis; Membrane Fouling; Brine Management

1.0 Introduction

We live in a thirsty world. Despite the existence of ample amount of water on Earth ($1.4x10^9$ km^3), 97.5% of this water is seawater with average salinity of 35,000 parts per million (ppm) or milligrams per liter [1, 2]. This means that only 2.5% of the Earth's water is freshwater [1], of which 80% is locked up in glaciers, leaving 20% (or 0.5% of freshwater) available in rivers, lakes, and aquifers in the world [1]. In many regions around the world, freshwater is being extracted at rates exceeding the natural recharge rates [3]. With a rapidly growing and urbanizing population, global water use is expected to increase. As demand for water is growing, water scarcity is expanding and intensifying around the globe. It is estimated that around 40% of the global population suffers from serious water shortages, and this number is expected to rise to 60% by 2025 [1]. This is largely due to the increase in global population, contamination and overexploitation of freshwater sources, and economic activities [1, 3]. The water shortages could increase conflicts within and among governments over the allocation of shared water resources, as seen in the 1950s-1960s conflicts in the Middle East over water from the Jordan River [4].

In several regions across the world with local water basins depletions, communities have turned to alternative water sources, including water recycling, water import, and desalination [3]. Desalination is the process of removing excess salts and other dissolved chemicals from the seawater [5]. This process reduces salt concentrations to at or below the World Health Organization's drinking water limit of 500 ppm [6]. Desalination has been around for centuries, but has gained prominence in the last few decades. The first references to desalination practices are found from 300 BC to 200 AD [7]. In 320 BC, Alexander of Aphrodisiacs described sailors boiling seawater and suspending sponges from vessels to absorb the vapor, then collecting this "sweet water" for drinking. In 1565, the French explorer Jean de Lery was successful in desalinating water during a journey to Brazil, and in 1627 Sir Francis Bacon proposed the use of sand filters to desalinate water [7]. During the mid-1700s, advances in steam processes allowed for the wide use of evaporation and condensation methods for desalination, and these continued to be the most common methods throughout the early 1900s [7]. In the mid-1900s, the development of membrane technology to aid in desalination began, but it was not until in the 1960s, when inventors in Canada patented an asymmetrical membrane that allowed for more cost-effective desalination, that the industry rapidly expanded [8].

Desalination of brackish water and seawater has since grown rapidly around the globe [9]. In 2013, there were over 17,000 active desalination plants, providing about $80x10^6$ m^3/d to 300 million people in 150 countries [9]. By 2015, the production capacity increased to nearly $97.5x10^6$ m^3/d [10] and the supply of desalinated water is expected to increase to $192x10^6$ m^3/d by 2050 [11]. Table 1 shows the top 10 countries employing desalination.

No.	Country	Total capacity (million M^3/d)	Market share (%)
1	Saudi Arabia	9.9	16.5
2	USA	8.4	14.0
3	UAE	7.5	12.5
4	Spain	5.3	8.9
5	Kuwait	2.5	4.2
6	China	2.4	4.0
7	Japan	1.6	2.6
8	Qatar	1.4	2.4
9	Algeria	1.4	2.3
10	Australia	1.2	2.0

Table 1. Top 10 countries employing desalination. Adapted from Nair & Kumar [7].

Saudi Arabia is currently the largest producer of desalinated water worldwide, and meets 60% of total water demand through desalination [4, 13]. In some countries like Kuwait and Qatar, 100% of the water used is obtained via desalination [14]. However, despite the widespread use, desalination is still controversial as it is expensive for governments, industries, and consumers [3]. Additionally, desalination has several environmental effects, including high CO2 emissions and waste products that affect the marine habitats into which they are discharged [3, 5].

2.0 Types of Desalination Processes

Two main desalination processes are thermal-based and membrane-based [15]. Thermal-based technologies operate on the basis of supplying thermal energy to seawater to evaporate water vapor and then condense this vapor to obtain potable water [16]. Thermal technologies tend to be used in regions where water salinity levels are high and energy costs are low, such as in the Caribbean and the Middle East [15]. Some examples of the most common thermal-based processes are multi-stage flash (MSF), multi-effect distillation (MED), and vapor compression distillation [15].

Despite the wide-use of thermal technologies, membrane-based technologies are becoming more popular in areas like the Middle East due to their lower specific energy consumption, lower environmental footprint, and more flexible capacity than their thermal counterparts [17]. Some membrane technologies include ultrafiltration, electrodialysis, and reverse osmosis (RO) [15, 18]. Reverse osmosis is now the most commonly used desalination process worldwide, comprising 61% of the global share, followed by MSF at 26%, and MED at 8% [7] (See Figure 1).

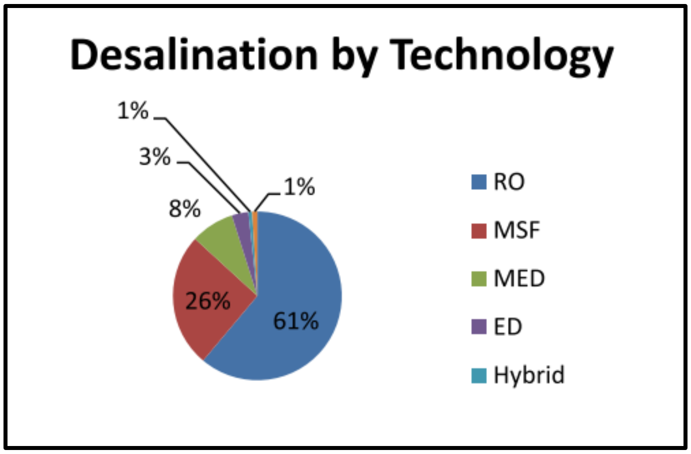

Fig. 1. Desalination worldwide by technology. Adapted from Nair & Kumar [7]. RO = Reverse Osmosis; MSF = Multi-stage Flash; MED = Multi-effect Distillation; ED = Electrodialysis.

Reverse osmosis is based on applying excess pressure to reverse the spontaneous process of osmosis, where water in solution moves across a semi-permeable membrane from lower solute concentration to the higher solute concentration. In RO plants, this excess pressure is applied by high pressure pumps, which push seawater through semi-permeable membranes to obtain desalinated water [12]. Figure 2 shows a schematic diagram of the RO process. The five major components of an RO plant are: (i) the seawater intake system, (ii) feed pretreatment facility, (iii) high pressure pumps, (iv) RO membranes, and (v) brine disposal and post-treatment facility [2].

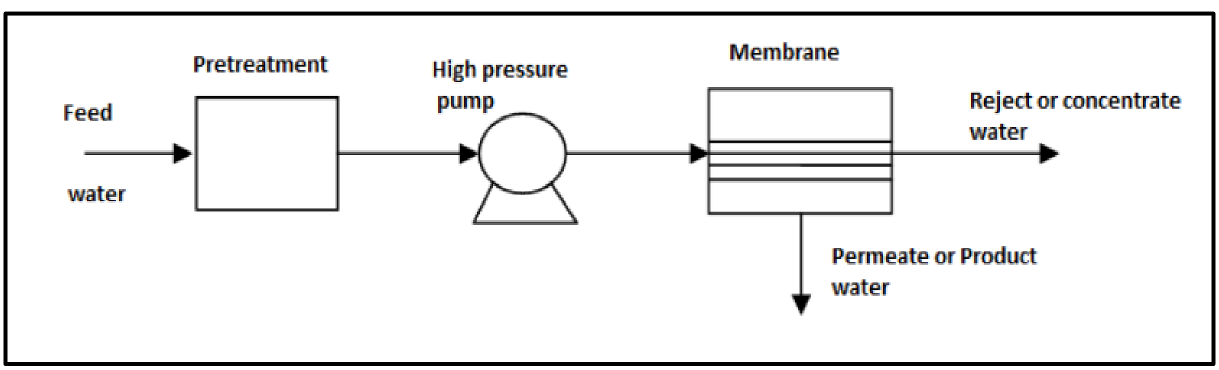

Fig. 2. Schematic Diagram of the Reverse Osmosis Process. Adapted from Garud et al. [19].

After pumps intake feed water, it is necessary to pretreat this water because it reduces the concentration of microorganisms and chemicals that may later foul the RO membranes [18]. This pretreatment process often consists of conventional treatment methods like a chemical feed followed by coagulation, filtration, and sedimentation [19]. Directly after pretreatment, high pressure pumps supply substantial amounts of pressure (typically 69-80 bar for a conventional seawater reverse osmosis pump) to push water through membrane systems while overcoming osmotic pressure, membrane resistance, and flow through the channels [20]. These membrane systems are composed of a pressure vessel with an interior semi-permeable membrane, which is typically made of polyamide thin-film composite and has openings small enough to allow water molecules to pass through while preventing the passage of salt molecules and other contaminants [12, 15, 19]. Figure 3 shows a simplified cross section of an RO membrane. After passing through the RO system, two streams are produced: desalinated water and brine [19]. The desalinated water is sent to post-treatment, which depends on the desalinated water's quality and intended use and may involve pH adjustment, disinfection, and remineralization [19].

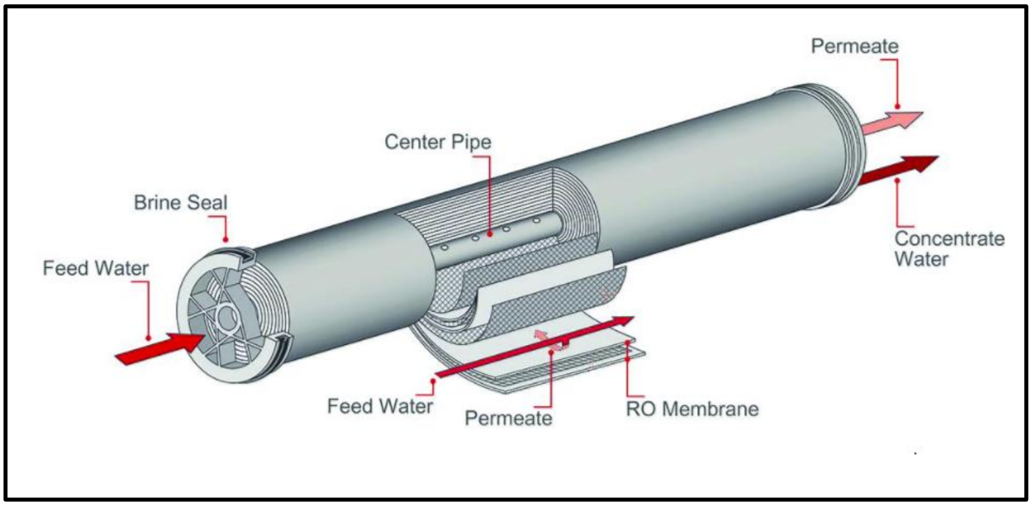

Fig. 3. A reverse osmosis membrane in a pressure vessel. Adapted from https://www.watertechonline.com.

3.0 Factors Affecting Reverse Osmosis Desalination

Desalination plants are beneficial because they provide a significant, dependable source of drinking water, particularly in areas that do not readily have access to sufficient natural freshwater. However, there are many factors that affect the success of a desalination plant in a particular location, including the substantial costs to run, the recovery efficiencies of the plant, the level of membrane fouling, and the production and disposal of the waste product (i.e. brine). These factors are discussed below.

3.1 Energy use, Efficiency, and Water Recovery

One of the most significant factors in RO desalination are the substantial electricity requirements and capital investment costs [1]. For example, large scale RO plants can consume 3.5 to 4.2 kW-h of energy per m^3 of water, of which 2.9 to 3.5 kW-h is used by the RO system directly and the remainder is used for the intake of feed water, pretreatment, and other auxiliary systems [21]. In addition, the energy required to remove salts from the feed water, transport treated water, and manage waste is typically obtained from fossil-fuel combustion [1], which is costly and unsustainable. For instance, it is estimated that approximately 50% of the oil produced domestically in Saudi Arabia is used to fuel desalination plants, and in Kuwait 70% of the fossil-fuel produced electricity is used to desalinate water [12, 22]. Many countries are looking to reduce costs by powering their desalination plants with renewable energy resources such as solar and wind power [6].

A significant issue with the RO process is the recovery efficiency [2] i.e. the ratio of the volume of desalinated water produced to feed water. RO technology has significantly improved in the last few decades, with recovery of freshwater from seawater increasing from 25% in the 1980s to 45% in 2016 [2]. Unfortunately, recovery efficiencies are still low in desalination plants obtaining their feed water from highly-saline water bodies such as the Red Sea, Mediterranean Sea, and Arabian Gulf, which can have salinities as high as 40,000 ppm and, consequently, recovery efficiency below 30% [2]. Brackish water RO plants can achieve 75 to 85% water recovery, but this may be lower due to the membrane/equipment scaling and energy-saving considerations [14]. While it is possible to achieve recoveries as high as 97% with thermal desalination, these processes are often too energy- and cost-intensive to be practical [14].

The good news is that the efficiency of RO technology has been improving, allowing it to become more widely applied around the world [23]. In seawater reverse osmosis (SWRO) plants, energy recovery devices (ERDs) are a key component that have greatly helped reduce operation costs [24]. Figure 4 shows a SWRO process with an integrated ERD, where a part of the incoming seawater stream is sent to the ERD rather than though the high pressure pump to be pressurized. The ERD is in turn connected to the stream of high pressure brine (the waste product from the RO system) and recovers the energy in this brine to pressurize the stream of feed seawater [25, 26]. The now-pressurized seawater in sent through a normal circulation pump to mix with the stream pressurized by the high pressure pump, and the entire stream is run through the RO membrane system [27].

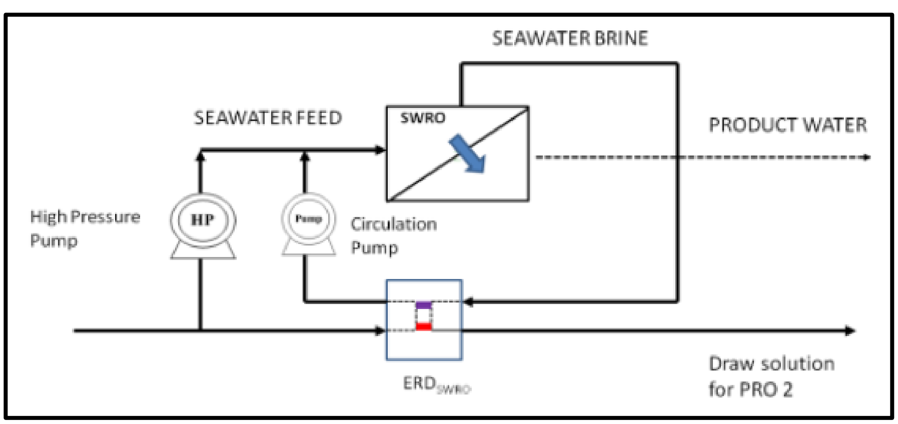

Fig. 4. Seawater reverse osmosis process with integrated energy recover device. Adapted from Sim et al. [27].

ERDs can reduce the specific energy consumption from 8 to 2 kW-h per m^3 of water for desalination plants [26]. However, they have to operate at high pressure differences, which can lead to leakage and a subsequent reduction in efficiency [26]. In SWRO plants, ERDs are set up in parallel to attain a greater capacity, and this system must be highly adaptable to flow changes [25].

3.2 Membrane Fouling

Another factor affecting RO desalination is membrane fouling [15], which reduces membrane efficiency and consequently increase costs because more pressure needs to be applied by the pumps to maintain a constant water production [20]. The level of fouling depends on a variety factors, including feed water characteristics and membrane materials and surface properties such as surface charge [15]. Proper pretreatment of the feed water is important because it can remove fouling agents such as dissolved organic compounds, inorganic salts, colloids, and bacteria. Effective removal of bacteria can be especially challenging because unless 100% of these microorganisms can be removed, they will continue to adhere and reproduce on the membrane, causing biofouling and thus making the membrane harder to clean and less efficient [15].

Besides pretreatment, there are other ways to control membrane fouling [15]. For instance, it is important to clean membranes periodically and to monitor the RO performance (e.g., monitoring for a flux drop over time) as an indicator of fouling levels. Additionally, acids, disinfectants, and scale inhibitors are added to the water to reduce scaling and fouling [15]. Also, modification of membrane surface characteristics or materials can be beneficial [18]. For instance, membranes with greater surface hydrophilicity and smoothness tend to have a lower fouling tendency [18]. Furthermore, researchers have found a variety of materials with excellent antifouling properties that can enhance conventional thin-film composite membranes, including carbon nanotubes (which can increase surface hydrophilicity), nanoporous graphene, and metal oxide nanoparticles [18]. Researchers have also been investigating materials that could substitute the polyamide in thin-film composite membranes. For instance, a study by Falath et al. (2017) found that a polyvinyl alcohol (PVA) and Gum Arabic membrane showed superior permeation, salt rejection, and biofouling resistance [18]. However, more research into new materials is needed before to make them commercially widely available.

3.3 Waste Product and Other Environmental Concerns

Aside from the energy and maintenance costs, another common concern with the desalination plants is the management and disposal of its main waste product, brine. The quantity and quality of brine depends on the feed water quality, pretreatment processes, type of desalination process employed, and percent water recovery [15]. The most common disposal method for brine worldwide is to discharge it directly into the ambient water through injection points [12]. The concern with this practice is that the higher salinity of brine causes it to be denser than the ambient water, so when brine is discharged directly into oceans it can form the so-called “brine underflows,” where layers of hypersaline solution spread across the seafloor. The brine concentrate is mixed to the extent possible at the point of discharge, but this mixed product often still tends to sink to the ocean floor [12]. With time, the brine underflows deplete dissolved oxygen (DO) in the ocean.

The high salinity and reduced DO levels cause habitat degradation, particularly for benthic (i.e. bottom-dwelling) organisms, which can in turn lead to a reduction in the numbers of benthic bacteria, phytoplankton, invertebrates, and fish communities [4, 11]. In addition, the chemicals added for pretreatment of feed water (e.g., antiscalants and coagulants) may contain toxic chemicals that are not always adequately removed during subsequent steps [2, 11]. For example, the concentration of contaminants such as nitrate, arsenic, and naturally-occurring radioactive materials can be 4 to 10 times higher in the brine than the source water [15]. Therefore, the release of brine directly into coastal and marine waters can reduce water quality and endanger the fragile ecosystem [5]. The environmental risks of brine discharge can be compounded in areas that have highly saline feed water as they require higher concentrations of pretreatment chemicals and have lower recovery efficiencies [2].

Apart from the surface water discharge, there are other common disposal options for brine, including deep well injection, land application, and evaporation ponds [28]. These can be more favorable options for desalination plants located inlands. Another option is blending the brine with industrial or municipal wastewater prior to transport to publicly-owned treatment works [28]. The most desirable option depends on brine quantity and quality, available technologies, land availability, cost of disposal, permitting requirements, and potential environmental impacts [15, 21]. For instance, evaporation ponds are most suited for small volumes of brine and for level, warm, dry areas with high evaporation rates [28].

Much research has also focused on developing technologies for recovery enhancement and brine volume reduction [15]. An option to reduce the volume of brine generated and its disposal costs are zero liquid discharge (ZLD) and near-ZLD technologies [28]. These allow feed water recoveries of 95 to 98% by chemical precipitation. These technologies are advantageous because they do not require permitting and have a smaller impact on the environment [15]. However, they are very costly due to the high capital and energy requirements and the disposal of the final brine [15]. Some technologies also focus on the extraction of salts from brine so that they can be used for other beneficial applications. For instance, the Mekorot Water Company in Israel operates a SWRO plant that produces both drinking water and food grade table salt [15]. In Japan, electrodialysis-based technologies are employed to recover table salt, and acids and bases from the brine [15].

Besides the production and disposal of brine, there are other environmental and ecological concerns surrounding desalination plants. For instance, marine organisms such as algae and plankton can become entrapped and entrained when the desalination plant's intake pumps are running [13]. Furthermore, the formidable quantity of energy required to power desalination plants, which is most often sourced from fossil fuels, releases significant air pollutants such as greenhouse gases, which degrade air quality and exacerbate climate change [13]. For instance, in the United Arab Emirates (UAE), desalination plants are responsible for nearly a third of the greenhouse gas emissions [17]. The Intergovernmental Panel on Climate Change estimated that 130 million tons/year of oil is used to produce 13 million m^3/day of potable water, thus contributing to widespread environmental pollution [29].

Desalination raises public health concerns as well. Public health is intimately linked to water quality and quantity, which can affect a country's other natural, food, and financial resources [13]. Livelihoods of people in many areas where desalination plants are located are highly dependent on marine food webs and healthy fisheries. If the marine food web is affected by the low DO and high salinity of brine underflows, then there will be less food available locally, and it will affect the public health and economic wellbeing of the coastal community. Another health concern is that desalinated water may be low in essential minerals such Na, K, Mg, and Ca [9]. Thus, the consumption of this water could lead to electrolyte disorders such as hyponatremia and hypokalemia, which have been linked with certain cancers, however, the causal relationships between ingestion of this water and the malignancies are still not well understood [9].

The lower levels of K, Mg, Ca, and other nutrients in desalinated water might also affect crops when this water is used for irrigation and may require additional fertilization [30]. However, it can be extremely beneficial to use desalinated water for growing high value crops (e.g., grapes) that are very sensitive to salinity levels in irrigation water. Further, this water can be a much better alternative in many water-scarce countries highly reliant on agriculture where crops are often irrigated with recycled wastewater, brackish groundwater, or other low quality water [30]. Proper planning is necessary to the key to place and maintain desalination plants to reduce the environmental risks [2].

4.0 Solar Desalination

Solar desalination systems are popular worldwide because they can significantly reduce or even eliminate energy costs, thus saving money and fossil-fuels [31]. The two categories of solar water desalination systems include (1) direct solar desalination, where thermal desalination occurs in the same device, and (2) indirect solar desalination, where the plant is divided into the solar collector and the desalination system [32]. One of the most popular technology is solar stills, a type of direct solar desalination [1], which function on the basis of solar distillation–similar to the natural evaporation of water by heat from the Sun–to purify water [31]. The basic solar still design, shown in Figure 5, consists of a shallow basin with a clear glass cover. As solar radiation heats water contained in the basin, this water begins to evaporate and dissolved salts, minerals, and other contaminants are left behind [31]. The rising moisture then condenses on the glass and flows down into a rack where the desalinated water is collected. Small-scale solar stills are especially suitable for remote communities that otherwise might not have easy access to freshwater or desalinated water [1].

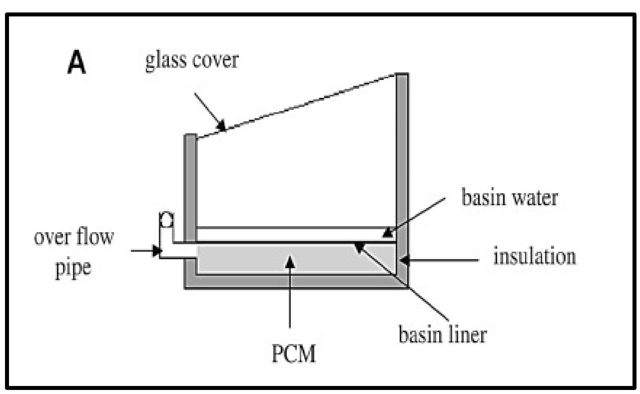

Fig. 5. Single slope-single basin solar still. The acronym PCM refers to solid–liquid phase change material. Adapted from Shukla et al. [29].

Despite the benefits of solar stills, there are still challenges, such as low efficiency of ~25% [31]. It has been found that efficiency increases with thinner water layers, but this decreases the overnight still productivity. Additionally, solar stills cannot be used for high volume production because they require a larger surface area as compared to other solar desalination technologies [32]. Another challenge is finding effective storage technologies that will help collect solar energy during times of high solar incidence for later use [31]. Studies have found that solid–liquid phase change materials (PCMs) such as organic paraffin waxes can dramatically improve the efficiency of solar stills, other direct solar desalination systems, and even some indirect systems [31, 33]. The PCMs act as a natural temperature buffer due to their latent heat storage during phase changes, resulting in no temperature change during that period, and subsequently can release large amounts of energy with little temperature change [31, 33]. These latent heat storage systems can reduce costs and increase output, thus increasing the potential industrial applications of solar stills [33].

5.0 Example Case Studies of Desalination Plants

5.1 Desalination Plant in Carlsbad, California, United States of America

In the United States, the freshwater supplies in many coastal areas have been dwindling due to the droughts, altering weather patterns, and saltwater intrusion into groundwater supplies [34]. Water authorities in these areas have been increasingly supporting desalination projects to meet growing demands while reducing dependence on imported water and groundwater [34]. An example of this can be seen in Carlsbad, a city located in Southern California, within the purview of the San Diego Water Authority district. This district obtains 16% of water supply from local sources, and remainder (~84%) from the Colorado River and northern California [34]. To diversify the water portfolio, the district entered into a 30-year agreement with Poseidon Water to purchase 69,075,000 m^3 of water per year from the proposed desalination plant [35] (See Fig. 6).

Fig. 6. Location of the Carlsbad desalination plant [35].

Plans for this Carlsbad desalination plant began in 1998, but the project encountered many permitting delays and did not begin operation until late 2015, after a whopping USD $1 billion investment [34]. The plant is located on the Agua Hedionda Lagoon alongside the Encina power plant, with which it shares the intake and outfall structures. At full capacity, this RO plant uses $1.1x10^6$ m^3 of seawater, of which $3.8x10^5$ m^3 is pumped through the RO system to produce $1.9x10^5$ m^3 of potable water and $1.9x10^5$ m^3 of brine, and the remaining $7.6x10^6$ m^3 of saltwater is used to dilute the brine prior to discharge [35]. The plant has increased local water supplies to 26%, but has also increased water prices for homeowners by $5 per month [34]. Additionally, concerns have been raised about the negative impacts on the marine environment due to water intake, brine discharge, and CO_2 emissions [34]. A study by Heck et al. in 2016 found that a majority of local residents supported the plant, particularly in view of California's prolonged drought, but suggested that it will be necessary to reduce or mitigate the CO_2 emissions and detrimental effects on marine ecosystems in order to garner long-term community support and ensure sustainability [34].

5.2 Desalination Plant in Adelaide, Australia

The city of Adelaide, located on River Torrens, began seeing an increase in water demand in the 1940s to 50s, driving a search for new water supplies [3]. In the 1950s and 1970s, two inter-basin pipelines were built to deliver water to the city [3]. But heavy agricultural diversions–coupled with Australia's prolonged drought from 2003 to 2009– forced Adelaide to reduce its water use and search for alternative supplies, including water recycling and desalination [3, 12]. Costing AUD $1.8 billion, the Adelaide Desalination Plant was single most expensive infrastructure venture in South Australia's history [12]. This desalination plant began operation in 2011. It was originally planned to provide $1.4x10^5$ m^3 of water, it was soon re-designed to output $2.7x10^5$ m^3 of potable water by the end of 2012, and was projected to supply 25% of the water demand by 2013, thus reducing inter-basin imports [3].

The desalination plant uses RO technology and is being run entirely on energy from wind, solar, and geothermal sources [3, 12]. However, the cost has been substantial, and have contributed to a 400% increase in water prices since 2007 [3]. Despite the benefit of having an additional freshwater source, the plant has been controversial, and investigations have revealed that the conditions included in the Environmental Impact Statement (EIS) have not been appropriately met in the actual operating license [12]. For instance, the EIS states a minimum seawater-brine dilution ratio of 50:1, but a study found that the actual license only sets a maximum limit of 1.3 parts per thousand (ppt) above the ambient salinity a distance of 100 m from the diffuser, which corresponds to dilution ratios of only 8:1 to 27:1, depending on the recovery efficiency of the plant [12]. These lower dilution ratios could affect the ecologically and economically important environment of the South Australia gulf, which has a species endemism of over 85% and support a viable commercial fishing industry [12]. Groups have called for more stringent legislative requirements and regulations as well as independent review of monitoring and study results in order to ensure the plant is being run in an environmentally-sound manner [12].

6.0 The Future of Desalination

Recent research and technological advancements have helped improve the efficiency and lower the costs of running desalination plants. One example is batch process configuration that vary the salinity over time through brine recycling. For instance, a process that could decrease the specific energy consumption is closed-circuit RO (CCRO), a semi-batch process [36], as shown in Figure 7. In this system, feed water is continuously pumped over time into the RO membrane module. This produces two streams: (1) desalinated water or permeate and (2) brine, the latter of which is recirculated and mixed with feed water that has been pressurized [36]. Then, the resulting mixture is circulated through the RO module and is further concentrated, which increases osmotic pressure and thus liquid pressure to overcome this osmotic pressure [36].

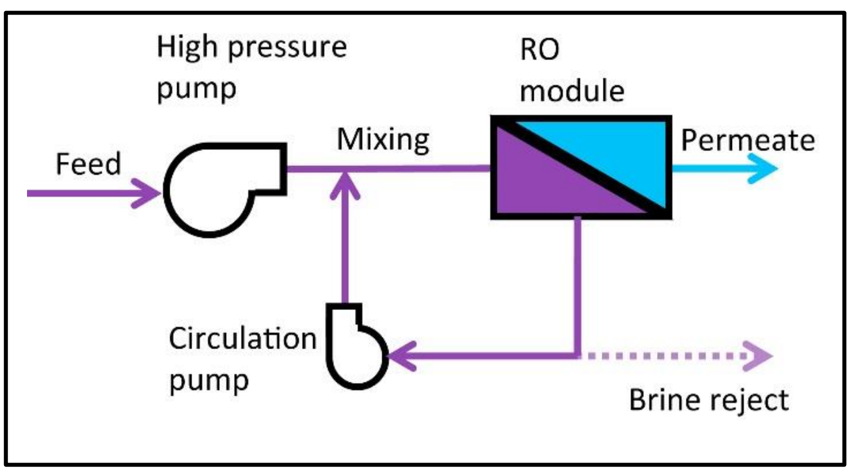

Fig. 7. Schematic diagram of a closed-circuit reverse osmosis system. Adapted from Zhang & Chung [37].

This variance in pressure allows for significant (37%) energy reduction in CCRO compared to conventional RO, where pressure along the entire flow path must be kept above the maximum osmotic pressure of the brine. Further, the full batch RO process, which involve the recirculation of brine through the RO membrane module without incorporating new feed water can result in 64% energy savings [36]. These technologies are especially beneficial at high recovery ratios (>75%) and high salinities, but they have not yet been commercialized or modeled in detailed, therefore further research is needed.

Another example of promising development is the recovery of energy from brine by taking advantage of the chemical energy difference between the brine and lower-salinity waters, i.e. the salinity gradient [15]. An example of this technology is pressure retarded osmosis (PRO) [37], which employs the natural process of osmosis to transfer water across a semipermeable membrane from an unpressurized low solute concentration to a pressurized high concentration due to the osmotic pressure difference [10]. The pressurized permeate then flows into energy transformation devices (e.g., a hydro-turbine) that transform this energy into electricity [10, 37]. Electricity obtained this way has the advantage of being from a renewable source and being gas-emission free [6]. Hybrid RO-PRO systems could be advantageous since the RO concentrate is already pretreated, highly saline, and under high pressure [37]. In these systems, a portion of the pretreated seawater is sent to the PRO as draw solution and a portion is passed through the RO membrane [12]. The brine of the RO is then transported to the PRO to be used as feed solution. Small scale pilot projects have successfully run these RO-PRO systems, which could be integrated so that the electricity produced by the PRO subsystem can be used to run the RO subsystem, thus allowing for co-generation of energy and freshwater [10, 37]. Additionally, Husnil et al. in 2017 conducted a preliminary analysis of conceptual designs that would integrate

RO, PRO, and electrodialysis to produce drinking water, electricity, and salt, respectively [38].

Another system that can enhance desalination efficiency is two-stage or dual RO, shown in Figure 8 [39]. In this method, the feed water is first pressurized and directed to an RO subsystem, and then the brine stream that is produced is re-pressurized and directed to a second RO subsystem [21, 39]. The brine streams from both stages have different osmotic pressures and therefore different applied pressure requirements [39].

Fig. 8. Schematic diagram of a two-stage reverse osmosis system. Adapted from Lin & Elimelech [39].

Since the applied pressurization can be tailored to each stage, this lowers the overall specific energy consumption of the process compared to conventional, single-stage RO [39]. However, because concentrated brine is used as the feed for the second stage, the membranes of this stage are more vulnerable to fouling and scaling [40]. Therefore, it is common to have an intermediate softening stage, where the brine exiting the first stage is treated with softening agents and then filtered to remove sparingly soluble salts of Mg^{2+}, Ca^{2+}, Ba^{2+}, and SiO_2 [15]. When using brackish source water, this type of system can lead to overall water recoveries of 95% or greater. However, two-stage systems must be carefully designed and operated to ensure energy savings compared to single-stage systems [21].

As discussed earlier, many countries are looking to integrate renewable energy sources, particularly solar energy, to cut costs and reduce reliance on fossil fuels. As proposed by Shalaby [32], a hybrid system combining solar and fossil fuel powers can be the most economical and reliable option, since it can function even when solar radiation is not present. But in order to improve desalination processes as a whole, it will be necessary to continue research to reduce energy consumption, improve membrane efficiency while reducing fouling, improving EDRs and brine minimization strategies, and find creative ways to integrate renewable energy sources, and energy recovery and transformation devices.

7.0 Conclusions

Desalination is a tremendously advantageous technology, with the potential to convert what is seen as the virtually limitless water supplies in oceans into potable water. However, the same water-conserving strategies that are advocated nowadays must continue to be practiced, especially since desalination plants are still limited by their production capacity. Additionally, it is important to find potable water sources that are more affordable than conventional desalination plants, particularly in low-income countries that will be severely affected by the effects of climate change and water scarcity. For instance, water reuse and recycling, especially in agriculture, can help meet water demands while improving food and water security.

Importantly, the problem of brine generation in desalination plants must be addressed. While the brine is often adequately diluted before being returned to the ocean, it is still possible that even a slight change in normal salinity levels will have an effect on marine organisms and habitats. It was once thought that the ocean was too large to be significantly affected by anthropogenic activities, but issues like ocean acidification prove that this is far from true, and that cumulative small inputs of contaminants can result in global impacts. Therefore, we must exercise caution when developing and running large-scale activities as desalination plants, which can have such significant ramifications.

In conclusion, desalination technology has great potential to provide water for a growing world population. It will help meet freshwater demands, increase water security, reduce groundwater mining, and alleviate public health problems arising from drinking contaminated surface water. It may even help reduce tension within and among nations over water allocation rights. Therefore, the technology must continue to be improved, but we must also seek to minimize the unique environmental and health effects associated with it. Better management of brine discharges together with improvements in the efficiency of desalination plants will help make desalination a cost-effective and sustainable option for meeting water demands around the world for increasing global population.

Compliance with Ethical Standards

Conflicts of Interest: The authors declare no conflict of interest.

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