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Desalination of Water: a Review

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Abstract

Purpose of Review In the face of rising water demands and dwindling freshwater supplies, alternative water sources are needed. Desalination of water has become a key to helping meet increasing water needs, especially in water-stressed countries where water obtained by desalination far exceeds supplies from the freshwater sources.

Recent Findings Recent technological advancements have enabled desalination to become more efficient and cost-competitive on a global scale. This has become possible due to the improvement in the materials used in membrane-based desalination, incorporation of energy-recovery devices to reduce electricity demands, and combining different desalination methods into hybrid designs. Further, there has been a gradual phasing-in of renewable energy sources to power desalination plants, which will help ensure the long-term sustainability of desalination. However, there are still challenges of reducing energy demands and managing waste products from the desalination to prevent adverse environmental effects.

Summary This article reviews the history, location, components, costs, and other facets of desalination and summarizes the new technologies that are set to improve the overall efficiency of the desalination process.

Keywords Desalination · Reverse osmosis · Membrane fouling · Brine management

Introduction

We live in a thirsty world. Despite the existence of ample amounts of water on the Earth (1.4×10^9 km³), 97.5% of this water is seawater with average salinity of 35,000 ppm or milligrams per liter [1, 2]. In other words, the Earth only has 2.5% freshwater, of which 80% is locked up in glaciers, leaving 20% (or 0.5% of freshwater) available in the world's rivers, lakes, and aquifers [1]. In many regions of the world, freshwater is being

extracted at rates exceeding the natural recharge rates [3]. With a rapidly growing and urbanizing population, increase in global water use is expected. 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, water recycling, water imports, and desalination [3]. Desalination is the process of removing excess salts and other dissolved chemicals from the seawater [5], which reduces salt concentrations 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 Aprosias described sailors boiling seawater and suspending

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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, which 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, however, it was not until 1960s when inventors in Canada patented an asymmetrical membrane that allowed for more cost-effective desalination, resulting in rapid expansion of the industry [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 80×10^6 m³/day water to 300 million people in 150 countries [9]. By 2015, the production capacity increased to nearly 97.5×10^6 m³/day [10]. The supply of desalinated water is expected to increase to 192×10^6 m³/day by 2050 [11]. Supplemental Table 1 shows the top 10 countries employing desalination (see supplemental material). Saudi Arabia is currently the largest producer of desalinated water worldwide and meets 60% of total water demand through desalination [4, 12]. In some countries like Kuwait and Qatar, 100% of the water used is obtained via desalination [13]. Despite the widespread use, desalination is still controversial as it is an expensive way to produce water [3]. Further, desalination has several environmental effects, including high greenhouse gas emissions and waste products that can affect the marine habitats [3, 5].

Types of Desalination Processes

Two main desalination processes are thermal-based and membrane-based [14]. 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 [15]. 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 [14]. Some examples of the most common thermal-based processes are multi-stage flash (MSF), multi-effect distillation (MED), and vapor compression distillation [14].

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 [16]. Some membrane technologies include ultrafiltration, electrodialysis, and reverse osmosis [14, 17]. Reverse osmosis

(RO) 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 supplemental Fig. 1).

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 to 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 [18]. Figure 1 shows a schematic diagram of the RO process. The five major components of an RO plant are as follows: (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]. After pumps intake feed water, it is necessary to pretreat this water to reduce the concentration of microorganisms and chemicals that may later foul the RO membranes [17]. This pretreatment process often consists of conventional treatment methods like a chemical feed followed by coagulation, filtration, and sedimentation [19]. After pretreatment, high pressure pumps supply substantial amounts of pressure (typically 69–80 bar for a conventional seawater RO 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 and other contaminants [14, 18, 19] (see supplemental Fig. 2). 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 quality and intended use of desalinated water, and may involve pH adjustment, disinfection, and remineralization [19].

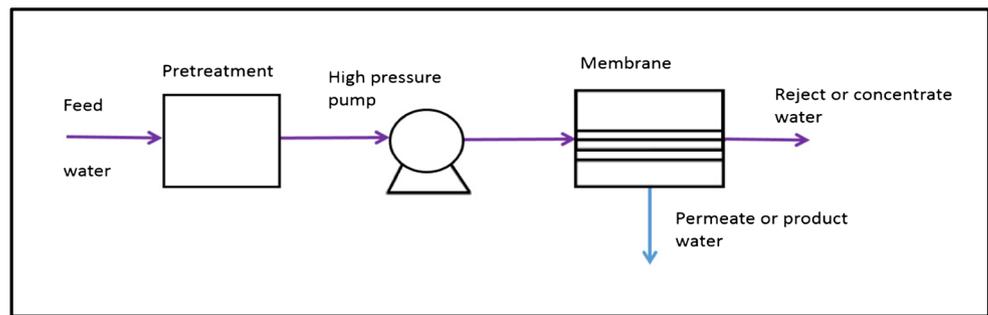
Factors Affecting Reverse Osmosis Desalination

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, recovery efficiency of the plant, level of membrane fouling, and the production and disposal of the waste product (i.e. brine). These factors are discussed in the below section.

Energy Use, Efficiency, and Water Recovery

Two of the most significant factors in RO desalination are the substantial electricity requirements and capital investment costs

Fig. 1 Schematic diagram of the reverse osmosis process. Adapted from Garud et al. [19]



[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 its 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]. For instance, the RO Adelaide Desalination Plant in Australia is being run entirely on energy from wind, solar, and geothermal sources [3, 18].

A significant issue with the RO process is the recovery efficiency, i.e. the ratio of the volume of desalinated water produced to feed water [2]. 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 [13]. While it is

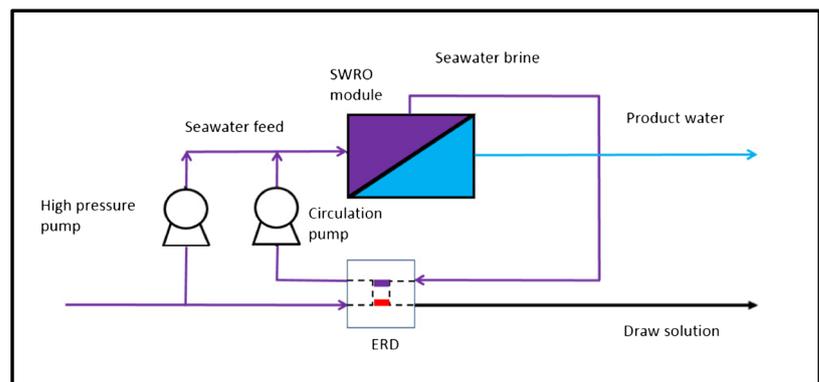
possible to achieve recoveries as high as 97% with thermal desalination, these processes are often too energy- and cost-intensive to be practical [13].

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 RO (SWRO) plants, energy recovery devices (ERDs) are a key component that have greatly helped reduce operation costs [24]. Figure 2 shows a SWRO process with an integrated ERD, where a part of the incoming seawater stream is sent to the ERD rather than through 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 from the brine to pressurize the stream of feed seawater [26, 27]. The now-pressurized seawater is 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 [25]. The ERDs can reduce the specific energy consumption from 8 to 2 kW-h per m^3 of water for desalination plants [27]. However, they have to operate at high pressure differences, which can lead to leakage and a subsequent reduction in efficiency [27]. In SWRO plants, ERDs are set up in parallel to attain a greater capacity, and this system need to be highly adaptable to flow changes [26].

Membrane Fouling

Another factor affecting RO desalination is membrane fouling [14], which reduces membrane efficiency and consequently

Fig. 2 Seawater reverse osmosis process with integrated energy recover device. Adapted from Sim et al. [25]. HP = high pressure, SWRO = Seawater Reverse Osmosis, ERD = energy recovery device, PRO = pressure-retarded osmosis



increases 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 of factors, including feed water characteristics and membrane materials and surface properties such as surface charge [14]. Proper pretreatment of the feed water is important because it can remove fouling agents such as dissolved organic compounds, 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 [14].

Besides pretreatment, there are other ways to control membrane fouling [14]. 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. In addition, acids, disinfectants, and scale inhibitors are added to the water to reduce scaling and fouling [14]. Also, modification of membrane surface characteristics or materials can be beneficial [17]. For instance, membranes with greater surface hydrophilicity and smoothness tend to have a lower fouling tendency [17]. 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 [17]. 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 [17]. However, more research is needed before these new materials can become widely available commercially.

Waste Products and Other Environmental Concerns

Brine Pollution Issues

Aside from the energy and maintenance costs, another common concern with desalination plants is the management and disposal of its main waste product, brine. The quantity and quality of brine depend on the feed water quality, pretreatment processes, type of desalination process employed, and percent water recovery [14]. The most common disposal method for brine worldwide is to discharge it directly into the ambient water through injection points [18]. The concern with this practice is that the higher salinity of brine causes it to be denser than the ambient water, so when it is discharged into oceans it can form “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 products added for pretreatment of feed water (e.g., antiscalants and coagulants) may contain toxic chemicals that are not always adequately removed during subsequent steps, and the concentration of contaminants such as nitrate, phosphate, and naturally occurring radioactive materials can be 4–10 times higher in the brine than the source water [2, 11, 14]. The concentrated nutrient content in the brine can cause coastal eutrophication, leading to algae blooms and hypoxia [28].

Further, brine water can contain high concentrations of heavy metals resulting from corrosion of the metallic materials used in the desalination plants [29]. Water flow, dissolved gases, and treatment chemicals (i.e. acids) all contribute to this effect on metallic equipment. For instance, copper can enter the brine stream when the copper-nickel alloys used as heat exchangers in the desalination process begin to corrode [30]. A study of coastal sediments of the Al-Khafji area in the Saudi Arabian Gulf found that the highest copper levels in the northern coastline might have been due to discharge of the brine from the desalination plant located along that coastline [31]. In addition, the hypersaline water resulting from the desalination also contributed to higher strontium levels in the coastal sediments. A study by Alshahri (2016) found higher than background concentrations of copper, chromium, manganese, arsenic, and zirconium in the sand and sediments near the brine discharge site of Saudi Arabia’s Alkhobar desalination plant [30]. Long-term exposure to these metals can have severe effects on marine organisms, including reduced growth, cancer, nervous system damage, and even death [30]. This effect is further exacerbated by the low dilution speeds of brine underflows, causing prolonged exposure to metals and their buildup in marine sediments near the discharge locations [32]. Thus, the release of brine directly into coastal and marine waters can reduce water quality and endanger fragile ecosystems [5]. For instance, marine organisms in the Arabian Gulf live close to their limits of environmental tolerance due to the naturally harsh marine environment caused by high salinities, elevated temperatures, and low pH, where the release of hypersaline, contaminated brine can push organisms past these limits [32]. In addition, the highly saline feed water in this area requires higher concentrations of pretreatment chemicals (which then remain in brine) and has lower recovery efficiencies, further compounding environmental risks associated with the brine discharge [2].

The quality of the intake water also affects the quality of brine. Discharge of municipal sewage near the intake points of

desalination plants can contaminate the intake seawater with fecal coliform and organic pollutants [29]. Even after treatment, organic pollutants may still be present in trace amounts in brine. A study in Cape Town, South Africa, found that 14 indicator organic compounds consisting of perfluorinated compounds, pharmaceuticals, personal care products, and industrial chemicals were present in seawater samples and marine organisms [29]. If the brine is left untreated before discharge into the ocean, these compounds are returned in potentially greater concentrations and could continue to bioaccumulate and cause harm to the marine life [29]. It is therefore important to include tertiary treatment of the intake seawater in order to remove contaminants such as pharmaceuticals and prevent their cycling in the marine environment.

Worldwide, many desalination plants must meet brine salinity limits and/or seawater-brine discharge dilution ratios prior to open-ocean discharge of the brine [33]. For example, the Environmental Impact Statement of the Adelaide Desalination Plant in Australia states a minimum seawater-brine dilution ratio of 50:1, but a study found that the actual operating license only sets a maximum limit of 1.3 parts per thousand above the ambient salinity at 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 [18]. 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 [18].

Apart from the surface water discharge, there are other common disposal options for brine, such as blending the brine with industrial or municipal wastewater prior to transport to publicly owned treatment works [34]. Other options include deep well injection, land application, and evaporation ponds [34]. These can be more favorable choices for desalination plants located inland. The most desirable option depends on the brine quantity and quality, available technologies, land availability, cost of disposal, and permitting requirements, among other factors [14, 21]. For instance, the evaporation ponds are most suited for small volumes of brine and for level, warm, dry areas with high evaporation rates [34]. However, the land-based disposal options can be risky due to the potential leaching into groundwater and build-up of salts, ions, and heavy metals in the soil [35]. For instance, in the United Arab Emirates, brine surface impoundments were built in sandy soils with low organic matter and clay content, which led to adverse impacts on the soil and groundwater due to the lower contaminant adsorption in the soil [34].

Much research has also focused on developing technologies for recovery enhancement and brine volume reduction [14]. Options to reduce the volume of brine generated and its disposal costs are zero liquid discharge (ZLD) and near-ZLD technologies [34]. 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 [14]. However, these are costly due to the high capital and energy requirements and the disposal of the final brine [14]. 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 [14]. In Japan, electro dialysis based technologies are employed to recover table salt, acids, and bases from the brine [14].

The effects of brine on an ecosystem depend on the sensitivity of the ecosystem and the volume, salinity, and speed of dilution of the brine plume, among other factors [36]. Some mitigation strategies, such as selecting more suitable disposal sites, diluting the brine discharge, or mixing it more rapidly, have been successful. After brine discharges were shown to affect the benthic communities near SWRO desalination plants in San Pedro del Pinatar, Spain, a diffuser was added to the pipeline end in 2010 [36]. The diffuser caused the effluent to emerge at 60° to the horizontal, thus, allowing it to be more effectively mixed with the seawater. As a result, salinity levels in the seawater dropped and eventually the richness and diversity of polychaete assemblages (serving as bioindicators) increased.

Another option to minimize brine's impact on the environment is to incorporate it into production processes. Communities in the semi-arid region of Brazil have developed an integrated production scheme that uses the reject brine from inland desalination plants for tilapia farming and subsequently for irrigation of halophytic forage crops [35]. This has managed to turn a severe pollution issue associated with desalination into a new economic opportunity. However, irrigation of other commercial crops with the brine has been less effective. As salts accumulate in the soil, they reduce plants ability to absorb soil moisture, and this necessitates use of additional amount of freshwater to flush salts from the soil [35].

Other Environmental and Public Health Concerns Associated with Desalination

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 [12]. This effect was particularly controversial for the Carlsbad Desalination Plant in the USA [28]. The plant was built in close proximity to the Marine Protected Area (MPA) network along the California coast. Entrainment and impingement in the intake pipes could reduce larval connectivity among MPAs and compromise the effectiveness of the MPA network as a whole in safeguarding marine life [28].

Air pollution is another significant effect of the desalination processes. The formidable quantity of energy required to power desalination plants—energy that is most often sourced from fossil fuels—releases significant amount of air pollutants such as greenhouse gases, which can degrade air quality and exacerbate climate change [12]. For instance, in the United Arab Emirates, desalination plants are responsible for nearly a third of the greenhouse gas emissions [16]. The Intergovernmental Panel on Climate Change estimated that 130 million tons/year of oil is used to produce 13 million cubic meters/day of potable water, thus, contributing to widespread environmental pollution [37]. Increasing greenhouse gas emissions can lead to indirect impacts such as ocean acidification and sea level rise [28].

Desalinated water also raises public health concerns as it is intimately linked to water quality and quantity, which can affect a country's natural, food, and financial resources [12]. The livelihoods of people in many areas where desalination plants are located are highly dependent on the 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 this will affect the public health and economic wellbeing of the coastal communities. 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 although the causal relationship 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 may not provide a significant source of plant nutrients if this water is used for irrigation [38]. However, it can be extremely beneficial to use desalinated water for growing high value crops (e.g., grapes), which 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 [38].

The Future of Desalination

Recent research and technological advancements have helped improve the efficiency and lower the costs of running desalination plants. For instance, a process that could decrease the specific energy consumption is brine recycling, via a semi-batch process known as closed-circuit RO (CCRO), as shown in Fig. 3. In this system, feed water is continuously pumped into the RO membrane module [39]. 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. Then, the resulting mixture is circulated through the RO

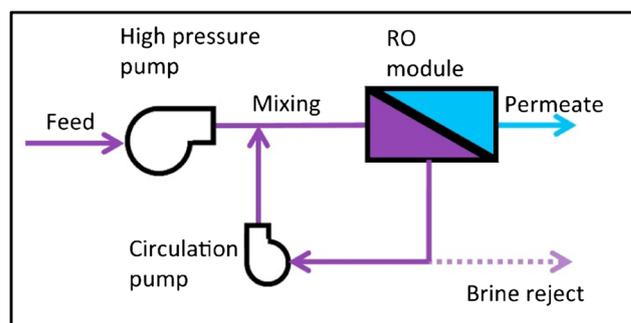


Fig. 3 Schematic diagram of a closed-circuit reverse osmosis system. Adapted from Warsinger et al. [39]. RO = reverse osmosis

module and is further concentrated, which increases osmotic pressure and thus liquid pressure to overcome the osmotic pressure [39]. This variance in pressure allows for significant energy reduction (~37%) 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 involves the recirculation of brine through the RO membrane module without incorporating new feed water can result in 64% energy savings [39]. These technologies are especially beneficial at high recovery ratios (> 75%) and high salinities. However, these processes have not yet been commercialized or modeled in detailed; therefore, further research is needed to expand the use of these technologies.

Another example of a promising development is the recovery of energy from the brine by taking advantage of the chemical energy difference between the brine and lower-salinity waters, i.e. the salinity gradient [14]. An example of this technology is pressure-retarded osmosis (PRO) [40], 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, 40]. 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 [40]. 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 [18]. 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, 40]. Husnil et al. (2017) conducted a preliminary analysis of conceptual designs that would integrate RO, PRO, and electrodialysis to produce drinking water, electricity, and salt, respectively [41].

Another system that can enhance desalination efficiency is two-stage or dual RO (see supplemental Fig. 3) [42]. In this system, 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, 42]. The brine streams from both stages have different osmotic pressures and therefore different applied pressure requirements [42]. Since the applied pressurization can be tailored to each stage, this lowers the overall specific energy consumption of the process compared to the conventional, single-stage RO [42]. However, the membranes of this stage are more vulnerable to fouling and scaling because concentrated brine is used as the feed for the second stage [43]. 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, Ca, Ba, and SiO₂ [14]. When using brackish source water, this type of system can lead to overall water recovery of 95% or greater. However, two-stage systems must be carefully designed and operated to ensure that the energy savings are comparable to single-stage systems [21].

As mentioned 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 [44], 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. Also, stand-alone solar desalination systems are sustainable, lower-cost options for many localities [44]. One example of these systems are solar stills, which consist of a shallow basin with a clear glass cover (see supplemental Fig. 4). As solar radiation reaches the water contained in the basin, the water begins to evaporate and dissolved salts and other contaminants are left behind [45]. The rising moisture then condenses on the glass and flows down into a rack where the desalinated water is collected. The solar stills cannot be used for high volume production because they require a larger surface area, however, they can be a beneficial option for remote communities that otherwise might not have easy access to freshwater or desalinated water [1, 44]. New research has found that effective latent heat storage systems (consisting of solid-liquid phase change materials, PCMs) can help collect solar energy during times of high solar incidence and store it for later use, thus, increasing the potential industrial applications of solar stills [45, 46].

Conclusions

Desalination is an 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 their 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 such as desalination plants, which can have significant ramifications. In conclusion, desalination technology has great benefits for the global 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 tensions 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 desalination. 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 freshwater demands around the world.

Author Contributions N.D. wrote the first draft, and G.S.T. contributed to the revision.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

References

1. Ibrahim AGM, Rashad AM, Dincer I. Exergoeconomic analysis for cost optimization of a solar distillation system. *Solar Energy*. 2017;151:22–32.
2. Shahzad MW, Burhan M, Ng KC. Pushing desalination recovery to the maximum limit: membrane and thermal processes integration. *Desalination*. 2017;416:54–64.
3. Richter BD, Abell D, Bacha A, et al. Tapped out: how can cities secure their water future? *Water Policy*. 2013;15(3):335–63.
4. Rabinowitz O. Nuclear energy and desalination in Israel. *Bull At Sci*. 2017;72(1):32–8.
5. Sepehr M, Fatemi SMR, Daneshkar M, Moradi AM. Application of Delphi method in site selection of desalination plants. *Glob J Environ Sci Manag*. 2017;3(1):89–102.

6. Esfahani IJ, Rashidi J, Ifaei P, Yoo C. Efficient thermal desalination technologies with renewable energy systems: a state-of-the-art review. *Korean J Chem Eng*. 2016;33(2):351–87.
7. Nair M, Kumar D. Water desalination and challenges: the Middle East perspective: a review. *Desalin Water Treat*. 2012;51:10–2.
8. Judd SJ. Membrane technology costs and me. *Water Res*. 2017;122:1–9.
9. Nriagu J, Darroudi F, Shomar B. Health effects of desalinated water: role of electrolyte disturbance in cancer development. *Environ Res*. 2016;150:191–204.
10. He W, Wang J. Feasibility study of energy storage by concentrating/desalinating water: concentrated water energy storage. *Appl Energy*. 2017;185(Pt. 1):872–84.
11. Frank H, Rahav E, Bar-Zeev E. Short-term effects of SWRO desalination brine on benthic heterotrophic microbial communities. *Desalination*. 2017;417:52–9.
12. DeNicola E, Aburizaiza OS, Siddique A, Khwaja H, Carpenter DO. Climate change and water scarcity: the case of Saudi Arabia. *Ann Globe Health*. 2015;81(3):342–53.
13. Blanco-Marigota AM, Lozano-Medina A, Marcos JD. The exergetic efficiency as a performance evaluation tool in reverse osmosis desalination plants in operation. *Desalination*. 2017;413:19–28.
14. Xu P, Cath TY, Robertson AP, Reinhard M, Leckie JO, Drewes JE. Critical review of desalination concentrate management, treatment and beneficial use. *Environ Eng Sci*. 2013;30(8):502–14.
15. Harandi HB, Rahnema M, Javaran EJ, Asadi A. Performance optimization of a multi stage flash desalination unit with thermal vapor compression using genetic algorithm. *Appl Therm Eng*. 2017;123:1106–19.
16. Eveloy V, Rodgers P, Qui L. Hybrid gas turbine–organic Rankine cycle for seawater desalination by reverse osmosis in a hydrocarbon production facility. *Energy Convers Manag*. 2015;106:1134–48.
17. Jiang SX, Li YN, Ladewig BP. A review of reverse osmosis membrane fouling and control strategies. *Sci Total Environ*. 2017;595:567–83.
18. Kämpf J, Clarke B. How robust is the environmental impact assessment process in South Australia? Behind the scenes of the Adelaide seawater desalination project. *Mar Policy*. 2013;38:500–6.
19. Garud RM, Kore SV, Kore VS, Kulkarni GS. A short review on process and applications of reverse osmosis. *Univers J Environ Res Technol*. 2011;1(3):233–8.
20. Chong TH, Loo S, Fane AG, Krantz WB. Energy-efficient reverse osmosis desalination: effect of retentate recycle and pump and energy recovery device efficiencies. *Desalination*. 2015;366:15–31.
21. Wei QJ, McGovern RK, Lienhard VJH. Saving energy with an optimized two-stage reverse osmosis system. *Environ Sci Water Resour Technol*. 2017;3:659–70.
22. Aliewi A, El-Sayed E, Akbar A, Hadi K, Al-Rashed M. Evaluation of desalination and other strategic management options using multi-criteria decision analysis in Kuwait. *Desalination*. 2017;413:40–51.
23. Chen X, Zhang Z, Liu L, Cheng R, Shi L, Zheng X. RO applications in China: history, current status, and driving forces. *Desalination*. 2016;39:185–93.
24. Wu JN, Jin Q, Wang Y, Tandon P. Theoretical analysis and auxiliary experiment of the optimization of energy recovery efficiency of a rotary energy recovery device. *Desalination*. 2017;415:1–7.
25. Sim VST, She Q, Chon TH, Tang CY, Fane AG, Krantz WB. Strategic co-location in a hybrid process involving desalination and pressure retarded osmosis (PRO). *Membranes*. 2013;3(3):98–125.
26. Zhou J, Wang Y, Duan YW, Tian JJ, Xu SC. Capacity flexibility evaluation of a reciprocating-switcher energy recovery device for SWRO desalination system. *Desalination*. 2017;416:45–53.
27. Ning L, Zhongliang L, Li Y, Lixia S. Studies on leakage characteristics and efficiency of a fully-rotary valve energy recovery device by CFD simulation. *Desalination*. 2017;415:40–8.
28. Heck N, Adina P, Potts D, et al. Predictors of local support for a seawater desalination plant in a small coastal community. *Environ Sci Pol*. 2016;66:101–11.
29. Petrik L, Green L, Abegunde AP, Zackon M, Sanusi CY, Barnes J. Desalination and seawater quality at green point, cape town: a study on the effects of marine sewage outfalls. *S Afr J Sci*. 2017;113(11/12):1–10.
30. Alshahri F. Heavy metal contamination in sand and sediments near to disposal site of reject brine from desalination plant, Arabian Gulf: assessment of environmental pollution. *Environ Sci Pollut Res*. 2017;24:1821–34.
31. Alharbi T, Alfaifi H, Almadani SA, El-Sorogy A. Spatial distribution and metal contamination in the coastal sediments of Al-Khaffi area, Arabian Gulf, Saudi Arabia. *Environ Monit Assess*. 2017;189:634–48.
32. Naser HA. Assessment and management of heavy metal pollution in the marine environment of the Arabian Gulf: a review. *Mar Pollut Bull*. 2013;72:6–13.
33. Jenkins S, Paduan J, Robets P, Schlenk D, Weis J. Management of brine discharges to coastal waters: recommendations of a Science Advisory Panel (Tech. Report No.694). Southern California Coastal Water Research Project. 2012.
34. Subramani A, Jacangelo JG. Treatment technologies for reverse osmosis concentrate volume minimization: a review. *Sep Purif Technol*. 2014;122:472–89.
35. Sanchez AS, Nogueira ABR, Kalid RA. Uses of the reject brine from inland desalination for fish farming, *Spirulina* cultivation, and irrigation of forage shrub and crops. *Desalin*. 2015;364:96–107.
36. Del-Pilar-Ruso Y, Martinez-Garcia E, Gimenez-Casaldueiro F, Loya-Fernandez A, et al. Benthic community recovery from brine impact after the implementation of mitigation measures. *Water Res*. 2015;70:325–36.
37. Ameri M, Eshaghi MS. A novel configuration of reverse osmosis, humidification–dehumidification and flat plate collector: modeling and energy analysis. *Appl Therm Eng*. 2016;103:855–73.
38. Kaner A, Tripler E, Hadas E, Ben-Gal A. Feasibility of desalination as an alternative to irrigation with water high in salts. *Desalination*. 2017;416:122–8.
39. Warsinger DM, Tow EW, Nayar KG, Maswadeh LA, Lienhard JH. Energy efficiency of batch and semi-batch (CCRO) reverse osmosis desalination. *Water Res*. 2016;106(1):272–82.
40. Zhang S, Chung T. Osmotic power production from seawater brine by hollow fiber membrane modules: net power output and optimum operating conditions. *AIChE J*. 2016;62(4):1216–25.
41. Husnil YA, Gregorius RH, Riezqa A, Yus DC, Moonyong L. Conceptual designs of integrated process for simultaneous production of potable water, electricity, and salt. *Desalination*. 2017;409:96–107.
42. Lin S, Elimelech M. Kinetics and energetics trade-off in reverse osmosis desalination with different configurations. *Desalination*. 2012;401:42–52.
43. Blair D, Alexander DT, Couperthwaite SJ, Darestani M, Millar GJ. Enhanced water recovery in the coal seam gas industry using a dual reverse osmosis system. *Environ Sci Water Res Technol*. 2017;3:278–92.
44. Shalaby SM. Reverse osmosis desalination powered by photovoltaic and solar Rankine cycle power systems: a review. *Renew Sust Energy Rev*. 2017;73:789–97.
45. Shukla A, Kant K, Sharma A. Solar still with latent heat energy storage: a review. *Innovative Food Sci Emerg Technol*. 2017;41:34–46.
46. Sawar J, Mansoor B. Characterization of thermophysical properties of phase change materials for non-membrane based indirect solar desalination application. *Energy Convers Manag*. 2016;120:247–56.