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The Future of Seawater Desalination: Energy, Technology, and the Environment

Menachem Elimelech* and William A. Phillip†

In recent years, numerous large-scale seawater desalination plants have been built in water-stressed countries to augment available water resources, and construction of new desalination plants is expected to increase in the near future. Despite major advancements in desalination technologies, seawater desalination is still more energy intensive compared to conventional technologies for the treatment of fresh water. There are also concerns about the potential environmental impacts of large-scale seawater desalination plants. Here, we review the possible reductions in energy demand by state-of-the-art seawater desalination technologies, the potential role of advanced materials and innovative technologies in improving performance, and the sustainability of desalination as a technological solution to global water shortages.

Water scarcity is one of the most serious global challenges of our time. Presently, over one-third of the world's population lives in water-stressed countries and by 2025, this figure is predicted to rise to nearly two-thirds (1). The challenge of providing ample and safe drinking water is further complicated by population growth, industrialization, contamination of available freshwater resources, and climate change. At the same time, greater recognition of the broad societal and ecological benefits that stem from adequate water resources—economic vitality, public health, national security, and ecosystem health—is motivating the search for technological solutions to water shortages.

Several measures to alleviate the stresses on water supply should be implemented, including water conservation, repair of infrastructure, and improved catchment and distribution systems. However, while these measures are important, they can only improve the use of existing water resources, not increase them. The only methods to increase water supply beyond what is available from the hydrological cycle are desalination and water reuse (2). Of these, seawater desalination offers a seemingly unlimited, steady supply of high-quality water, without impairing natural freshwater ecosystems. Desalination of brackish groundwaters is also an option to augment water supply for inland regions; however, the management of brines from inland desalination plants is a major challenge because these plants are placed far from the coast.

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There has been rapid growth in the installation of seawater desalination facilities in the past decade as a means to augment water supply in water-stressed countries (1, 3, 4). Notable examples are the large-scale seawater reverse osmosis (SWRO) desalination plants recently constructed in Spain (5) and Israel (6, 7). In 2016, the global water production by desalination is projected to exceed 38 billion m³ per year, twice the rate of global water production by desalination in 2008 (3).

Early large-scale desalination plants, mostly in the arid Gulf countries, were based on thermal desalination, where the seawater is heated and

the evaporated water is condensed to produce fresh water (8). Such plants, still in operation in the Gulf countries, consume substantial amounts of thermal and electric energy, which result in a large emission of greenhouse gases (9). Excluding those in the Gulf countries, the vast majority of desalination plants constructed in the past two decades, as well as future planned facilities, are based on reverse osmosis technology (Fig. 1), where seawater is pressurized against a semi-permeable membrane that lets water pass through but retains salt (4). Reverse osmosis technology has improved considerably in the past two decades, and current desalination plants can desalinate seawater with much less energy than thermal desalination (4, 9). At present, reverse osmosis is the most energy-efficient technology for seawater desalination and is the benchmark for comparison for any new desalination technology.

In this review, we assess the energy efficiency, the state of the technology, and the environmental challenges of seawater desalination. We highlight the main open questions, how future studies might address them, and what new approaches are needed to advance the science and technology of seawater desalination.

What Is the Current Energy Efficiency of Desalination and Can It Be Improved?

The amount of power needed to drive desalination in SWRO plants has declined dramatically in the past 40 years (Fig. 2A) (4, 8, 10, 11). This decrease in energy consumption is attributed to continual technological improvements, including higher-permeability membranes, installation of energy recovery devices, and the use of more efficient pumps (4). The potential to operate the

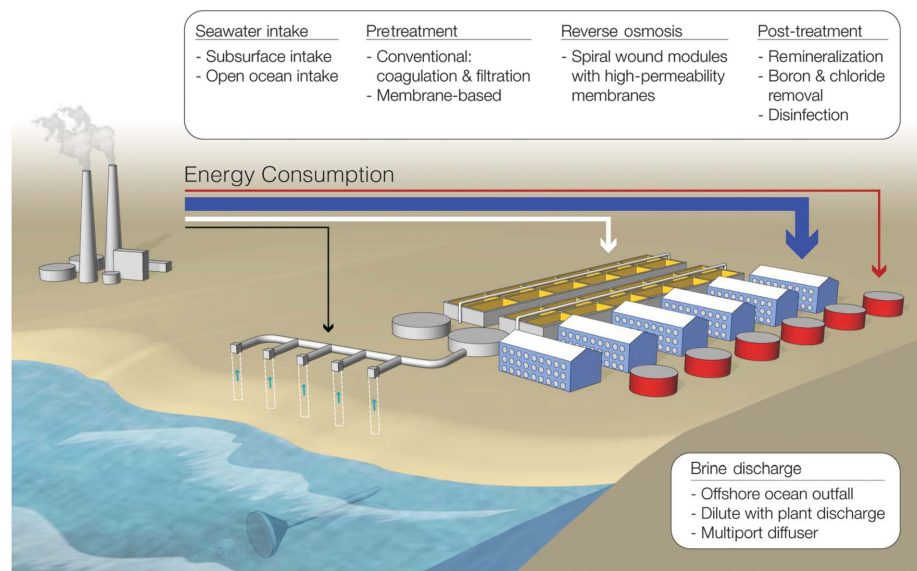


Fig. 1. Conceptual drawing of an SWRO desalination plant showing the various stages—seawater intake, pretreatment, reverse osmosis, posttreatment, and brine discharge—and their interactions with the environment. The thickness of the arrows for the energy consumption represents the relative amount of energy consumed at the various stages.

desalination step at an energy consumption rate of 1.8 kWh/m^3 using new, high-permeability SWRO membrane elements has recently been demonstrated on a controlled pilot-scale system at 50% recovery (11).

Understanding the minimum amount of energy required to separate pure water from seawater provides a benchmark for comparison and can help to guide future efforts to further reduce energy demand. This theoretical minimum energy, which is independent of the desalination method, is realized when the separation occurs as a reversible thermodynamic process (12). Thus, the energy for the separation will be equal in magnitude but opposite in sign to the free energy of mixing (13). There is a close relationship between the free energy of mixing and the osmotic pressure:

$$-d(\Delta G_{\text{mix}}) = -RT \ln a_w dn_w = \Pi_s \bar{V}_w dn_w \quad (1)$$

where ΔG_{mix} is the free energy of mixing, R is the ideal gas constant, T is the absolute temperature, a_w is the activity of water, n_w is the number of moles of water, Π_s is the osmotic pressure of the seawater, and \bar{V}_w is the molar volume of water. This connection between the minimum energy and the osmotic pressure is consistent with our physical understanding of reverse osmosis. In order to drive an infinitesimally small volume of water across a semipermeable membrane, $\bar{V}_w dn_w$, the applied pressure must be equal to the osmotic pressure of seawater.

The theoretical minimum energy of desalination as a function of percent recovery (i.e., the percent of seawater converted to fresh water) can be obtained from integration of Eq. 1 (12, 13) (Fig. 2B). As the salinity of seawater or desired water recovery increases, so does the minimum energy required for desalination. For example, the theoretical minimum energy of desalination for seawater at 35,000 parts per million (ppm) salt and at a typical recovery of 50% is 1.06 kWh/m^3 . The actual energy consumption, however, is larger because desalination plants are finite in size and do not operate as a reversible thermodynamic process.

In a SWRO desalination unit, pressurized seawater, V_F , is fed to a membrane module, where a pure water permeate, V_P , and a concentrate, V_C , containing the retained salts are produced (Fig. 2C). The energy to drive this separation enters the system through a pump that brings the feed volume to a high pressure, P_H . This requires an amount of energy equal to $V_F P_H$. The concentrate that exits the membrane module still contains energy equal to $V_C P_H$, which can be recovered and transferred to the feed through the use of energy recovery devices. The invention of more effective energy recovery devices was crucial in reducing the power consumption of desalination to its current level (4, 8, 14). The energy to drive the permeation of water $V_P P_H$ is split between the need to bring the seawater to a pressure equal to its osmotic pressure (i.e., $V_P \Pi_s$, the theoretical

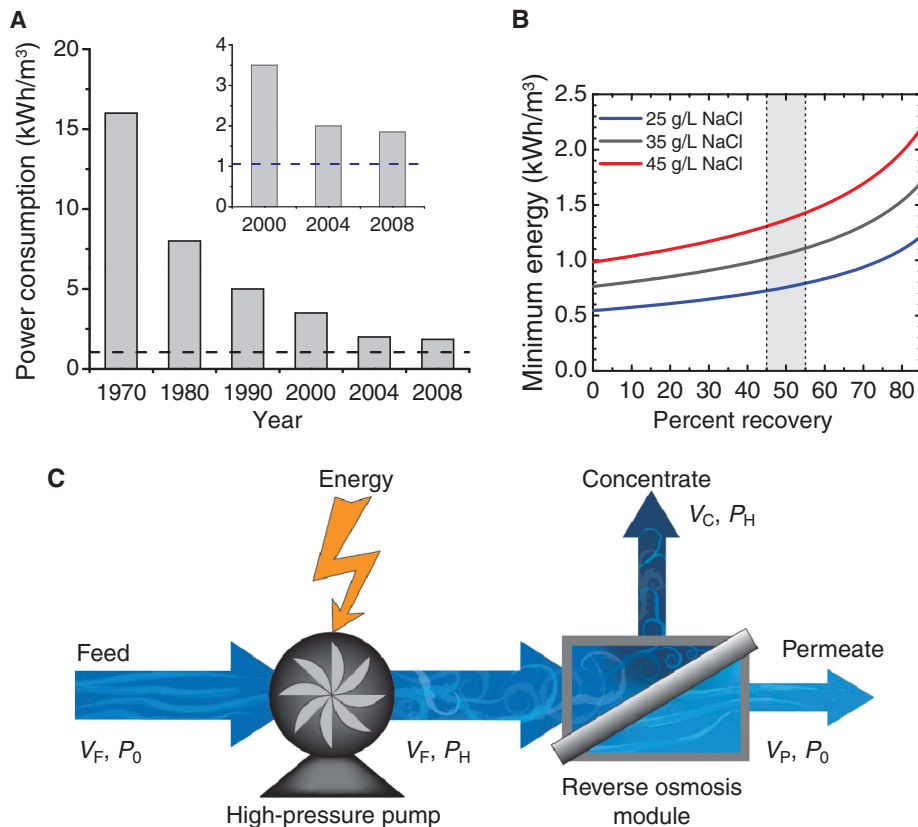


Fig. 2. (A) The change in power consumption for the reverse osmosis stage in SWRO plants from the 1970s to 2008 (SOM text). The horizontal dashed line corresponds to the theoretical minimum energy required for desalination of 35 g/liter seawater at 50% recovery (1.06 kWh/m^3). The energy data presented exclude the energy required for intake, pretreatment, posttreatment, and brine discharge. **(B)** Theoretical minimum energy for desalination as a function of percent recovery for common seawaters: 25 g/liter is typical of the less saline seawater drawn from the Tampa Bay estuary, 35 g/liter is an average value for seawater, and 45 g/liter is characteristic of water from the Arabian Gulf. Minimum energies for recoveries between 45 and 55%, the range in which most SWRO plants operate, are highlighted. **(C)** A schematic of flows and pressures in a reverse osmosis desalination system. The pressurized feed volume, V_F , is fed to a membrane module containing a semipermeable membrane where it is separated into a pure water permeate, V_P , and a concentrate containing the retained salts, V_C . The energy put into the system through a high-pressure pump is consumed at several points throughout the process.

minimum energy) and the need to generate reasonable water fluxes, which requires an amount of energy equal to $(P_H - \Pi_s)V_P$.

The membrane permeability will determine the magnitude of the overpressure ($P_H - \Pi_s$) necessary to generate reasonable water fluxes. However, regardless of how permeable a membrane is, the applied pressure cannot be reduced below the osmotic pressure of the concentrate (15–17). The implications of this restriction are critical to examining the energy use of reverse osmosis. Reverse osmosis modules use several membrane elements in series, with the concentrate from the first element being the feed to the second element, and so on. Therefore, the pressure applied to the feed of the first element must be at least equal to the osmotic pressure of the concentrate leaving the last element (i.e., $P_H \geq \Pi_c$) (15–17). When the applied pressure is equal to the osmotic pressure of the concentrate, the system is said to be operating at the thermo-

dynamic limit. At this limit, kinetic considerations no longer influence the energy consumption of the process. For a system at the thermodynamic limit, highly permeable membranes may help reduce capital costs by reducing the membrane area needed, but they will not reduce energy consumption. The energy consumption is set by the need to bring the feed volume to a pressure equal to the osmotic pressure of the concentrate.

Additional energy, $>1 \text{ kWh/m}^3$, is consumed by the intake, pretreatment, posttreatment, and brine discharge stages of the desalination plant (4). Of these stages, pretreatment of the raw seawater before it is fed into the reverse osmosis stage accounts for most of this energy use. Another source of energy consumption is the posttreatment for the removal of boron and chlorides to meet the requirements of irrigation water (6). To reduce boron and chloride to acceptable levels, part or all of the product water goes through

one or more reverse osmosis passes, adding to the total energy consumption and capital cost (4, 6).

Can Novel Materials Reduce Energy Consumption?

At the core of the reverse osmosis desalination process is a semipermeable membrane capable of separating pure water from seawater (18). The first commercially viable membrane with the ability to effect such a separation was an asymmetric cellulose acetate membrane developed in the early 1960s (19). Membranes of this type were the best available technology until the 1980s when robust thin-film composite membranes were developed (20). Along with the ability to remain stable over a greater pH range than cellulose-based membranes, thin-film composite membranes exhibit much higher intrinsic water permeabilities because of their extremely thin (~100 nm) polyamide-selective layers (Fig. 3). Water and salt transport across such membranes is governed by a solution-diffusion mechanism, where species first partition into the polyamide phase and then diffuse down a concentration gradient (21).

The fabrication and performance of thin-film composite membranes have been greatly improved in the past few decades and today, nearly all reverse osmosis desalination operations use such membranes (18). Thin-film composite membranes exhibit water permeabilities around $3.5 \times 10^{-12} \text{ m}^3 \text{ m}^{-2} \text{ Pa}^{-1} \text{ s}^{-1}$ and can reject 99.6 to 99.8% of the salts dissolved in the seawater feed (10). Empirical evidence suggests that it is difficult to further increase the water permeability of these membranes without sacrificing selectivity (22).

Despite the great improvements in thin-film composite membranes, there are still shortcomings that hinder their application. The fabrication technique has not been successfully extended to hollow fiber configurations that offer higher packing densities. In addition, the surface properties of thin-film composite membranes (Fig. 3, B and C) make them prone to fouling, which diminishes process performance. Biofouling—the growth of microbes on the membrane surface—could potentially be reduced or even prevented if chlorine or other oxidants were added to the feed. However, the amide linkage in polyamide composite membranes (Fig. 3A) is susceptible to attack by chlorine, and great care must be taken to prevent the membrane from being exposed to oxidizing agents (23). Given the limitations of thin-film composite membranes, along with recent developments in the fabrication of advanced materials, it is natural to question whether these advanced materials can be leveraged to improve the energy usage, reliability, and environmental impact of SWRO.

Ultrahigh-permeability membranes have recently received a lot of attention as potential alternatives to thin-film composite membranes. It is argued that increasing the membrane permeability will reduce the pressure needed to drive per-

meation, thereby reducing the energy demand of reverse osmosis desalination. Two such ideas for ultrahigh-permeability membranes are based on incorporating aligned nanotubes (24, 25) or aquaporins (26) into a barrier matrix. Of these, aligned carbon nanotube membranes have demonstrated the most potential so far.

Experiments with aligned carbon nanotubes have shown water fluxes that are three to four orders of magnitude higher than those expected from conventional hydrodynamic theories (24, 25). These extremely high water fluxes may be due to the molecular smoothness of nanotube walls, the structure that water takes within nanotubes (27), and the smooth energetic landscape inside nanotubes (28). Notably, none of these mechanisms provide a means for selectively rejecting the dissolved salts. Therefore, chemical functionalities that reject ions must be added to the mouth of the nanotube pores or the nanotube diameter must be small enough to sieve ions from solution based on size. A nanotube inner diameter of 0.5

to 0.6 nm can theoretically produce a separation comparable to that of thin-film composite membranes (i.e., 99% rejection) (27). To date, however, no experimental studies have demonstrated salt rejection adequate for desalination. If such nanotubes were incorporated into membranes at a pore density of 2.5×10^{11} pores per cm^2 (24), the membranes would have water permeabilities that are four to six times higher than current thin-film composite membranes (27).

The amount of energy that can be saved by using nanotube- or aquaporin-based membranes is likely to be very small. Current SWRO plants are already operating near the thermodynamic limit, with the applied pressure being only 10 to 20% higher than the osmotic pressure of the concentrate, Π_c (10, 17). This additional pressure ($P_H - \Pi_c$) compensates for frictional losses along the membrane channel and ensures a positive net driving pressure just before the channel outlet. Although these membranes might make it possible to use a smaller membrane area, this

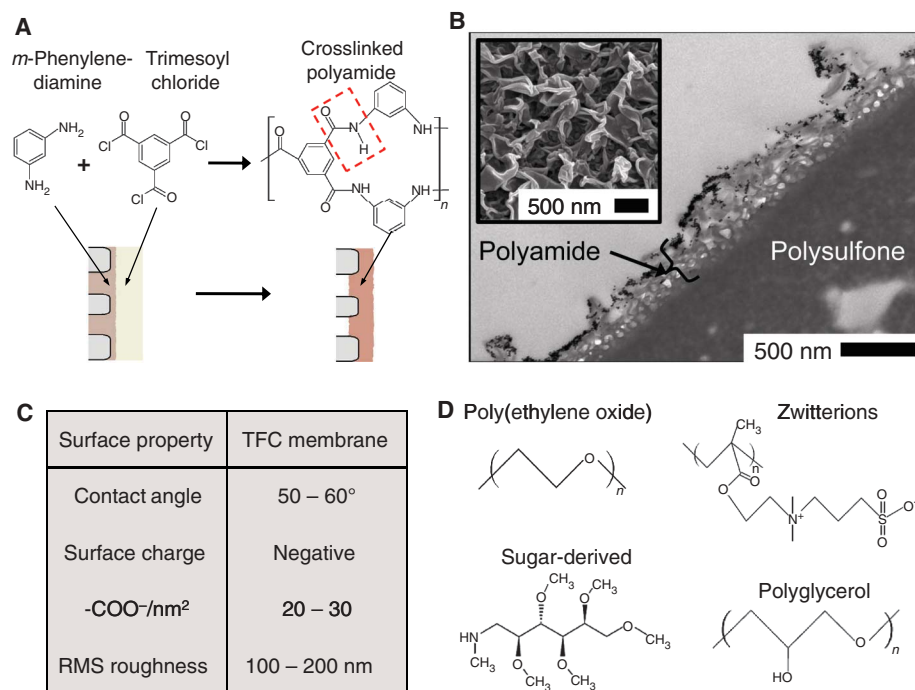


Fig. 3. (A) A schematic of the interfacial polymerization used to form thin-film composite (TFC) membranes. The monomers *m*-phenylenediamine and trimesoyl chloride react to form a highly cross-linked polyamide layer, which allows for the selective transport of water over salt. Ultrathin films are fabricated by dissolving the *m*-phenylenediamine in water and trimesoyl chloride in a water-immiscible organic solvent, such as hexane. A porous support is soaked in the aqueous solution and then contacted with the organic solution. The resulting polyamide formation is confined to the region near the interface of the two solutions. One drawback of the polyamide chemistry is the amide linkage (highlighted in dashed box), which is susceptible to attack by chlorine and other oxidizing agents. (B) Micrographs displaying the structure of the TFC membranes (48). A transmission electron micrograph of the membrane cross-section shows the extremely thin polyamide layer on top of a porous polysulfone support. The dark regions on top of the polyamide layer are gold nanoparticles used to obtain sufficient contrast between the polyamide and polysulfone layers during imaging. (Inset) A scanning electron micrograph of the polyamide top surface showing the rough ridge and valley structure typical of these films. (C) Surface properties of TFC membranes (49, 50). Fouling-resistant membranes would be smooth and possess surface chemical properties postulated by (30); TFC membranes do not meet all of these constraints, consistent with their high fouling propensity. (D) Chemistries that have demonstrated the ability to resist protein or organic macromolecule adhesion: poly(ethylene oxide) (31), zwitterions such as poly(sulfobetaine) (33), sugar-derived molecules (30), and polyglycerol (34).

would require a redesign of membrane modules because concentration polarization induced by high water fluxes already hinders performance of current thin-film composite membrane modules (29). Additionally, membrane fouling is exacerbated at higher water fluxes, further diminishing the value of ultrahigh-permeability membranes for SWRO desalination.

The development of fouling-resistant membranes would improve the energy usage, reliability, and environmental impact of SWRO. Despite extensive research efforts on fouling-resistant membranes, to date, no such membranes have been developed that are suitable for desalination applications. Still, these efforts have helped to establish structure-property relationships between surface chemistry and the ability of a thin film to resist adhesion of biomolecules such as proteins, which is key to understanding fouling by organic matter and microorganisms. Surfaces that are hydrophilic, contain hydrogen-bond acceptors, and are electroneutral, but do not contain hydrogen-bond donors, tend to be best at resisting protein adhesion (30). It is hypothesized that films with these chemical properties can bind a thin layer of water to their surface, providing a steric or energetic barrier to adhesion (2, 30, 31). In addition, evidence suggests that surface roughness of thin-film composite membranes can increase the adhesion of substances to the membrane surface (32). Surface properties of thin-film composite polyamide membranes, however, do not possess several of the key characteristics for fouling resistance (Fig. 3C). Several chemistries that do meet the above criteria for fouling resistance have been found (Fig. 3D) (30, 31, 33, 34), and undoubtedly, many others will be. Another potential route for fouling prevention is to develop fouling release membranes that do not resist the adhesion of foulants, but have an active layer with a low surface energy so that adhered foulants can readily be washed away by hydrodynamic mixing in the membrane module (35). However, a major challenge is to implement these chemistries such that the water flux and salt rejection of the resulting membrane are not compromised.

Recent research has examined the possibility of using sulfonated block copolymers (36) or self-assembled lyotropic liquid crystals (37) to fabricate chlorine-resistant membranes. Most work on these new materials has involved thick films on the order of 50 μm , but the reported intrinsic water and salt permeabilities are close to those of thin-film composite membranes when normalized for thickness. If these films could be made at a thickness of 100 to 250 nm, they may perform as well as thin-film composite membranes and thus improve the energy usage and reliability of SWRO.

Are There Innovative Systems and Technologies That Can Reduce Energy Demand?

Reverse osmosis desalination consumes more energy than the theoretical minimum energy required for desalination (Fig. 2A), but developing

more-permeable membranes will not substantially close this gap. This apparent contradiction is a direct consequence of current SWRO system designs. To reduce capital costs, SWRO plants desalinate seawater using a single membrane stage fed by a high-pressure pump that brings the feed volume to P_H (Fig. 4A) (12, 15). If we assume operation at the thermodynamic limit ($P_H = \Pi_c$), ideal equipment (i.e., 100% efficient pumps and energy recovery devices), and no concentration polarization or frictional losses down the channel, then a single-stage reverse osmosis operation consumes an energy per volume of fresh water produced equal to Π_c . As an example, recovering 50% of a 35 g/liter feed will have a practical

minimum energy of 1.56 kWh/m³ (SOM text) compared to the thermodynamic minimum energy of 1.06 kWh/m³ (Fig. 2). Thus, 0.50 kWh/m³ is expended because the system has a finite size and is not operating as a reversible thermodynamic process. This ideal energy consumption of 1.56 kWh/m³ is not too far off from reported energy consumptions of ~ 2 kWh/m³ from well-designed SWRO systems or controlled pilot-scale studies (Fig. 2A).

One system design that can bring the actual energy use closer to the theoretical minimum energy is a staged membrane operation (15). This design uses two high-pressure pumps and membrane modules in series (Fig. 4B). The first stage

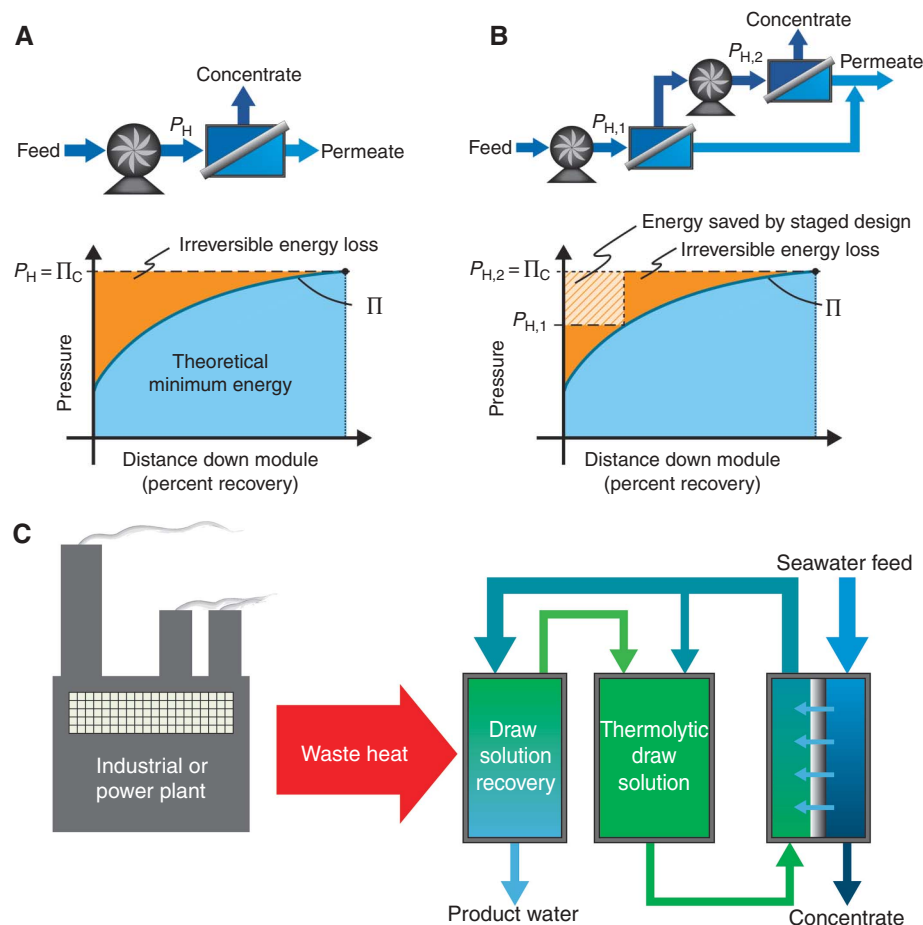


Fig. 4. (A) Energy use of a single-stage reverse osmosis (RO) desalination operation. The theoretical minimum energy required for desalination is equal to the energy needed to bring seawater to the osmotic pressure of fluid permeating across the membrane (represented by the area under the osmotic pressure curve). In practice, to ensure that water permeates across the membrane at all points along the membrane channel, the pressure applied to the feed volume must be at least equal to the osmotic pressure leaving the membrane channel ($P_H = \Pi_c$); this energy can be represented by the area of the rectangle. The difference between these two areas represents the energy that must be used to operate with a single stage. (B) Staged membrane operations can save RO desalination energy costs. The first stage operates at a lower applied pressure $P_{H,1}$ and percent recovery. The concentrate from the first stage is then pressurized to $P_{H,2} = \Pi_c$ to achieve the desired percent recovery. This configuration needs to bring a smaller volume to Π_c , thus saving the energy represented by the smaller hatched rectangle. (C) Waste heat as the energy source for desalination by forward osmosis. A "draw solution," which has a higher osmotic pressure than seawater, is used to extract water from seawater into the draw solution. The diluted draw solution is then fed to a draw solution recovery unit that uses waste heat to separate product water from the draw solutes. The separated draw solutes can then be recovered and recycled.

operates at a lower applied pressure and, hence, a lower percent recovery. The concentrate from this stage is then brought to a higher pressure before being fed to a second stage, where the overall desired percent recovery is achieved. This mode of operation allows smaller volumes of water to be brought to higher pressures, thereby consuming less energy. The optimal configuration is to operate each stage at the same relative percent recovery (15). Under these conditions and using ideal equipment, the energy needed to recover 50% of a 35 g/liter feed is reduced to 1.28 kWh/m³ (SOM text). In theory, for an infinite number of stages (i.e., infinite equipment size), the system would operate as a reversible thermodynamic process, thus using the minimum amount of energy required for desalination. However, this design is impractical, and even for systems with two stages, the energy savings might not offset the additional capital costs.

Other designs of SWRO operations have been considered. For example, cyclic desalination operations obviate the need for energy recovery devices by recirculating the pressurized feed until the desired percent recovery is achieved (38). This design saves capital costs, but will use an amount of energy similar to that of current reverse osmosis configurations, and questions remain about membrane stability during the repeated loading and unloading of fluid from the recirculation loop. Another recently proposed design involves a hybrid system that combines an osmotic contactor with reverse osmosis for osmotic dilution of the seawater feed (39). In this design, the seawater is used as a “draw solution” to de-water treated wastewater effluent or impaired water, which reduces the energy consumption of reverse osmosis desalination by diluting the feed concentration. However, this scheme requires that the two operations be colocated and adds additional capital cost. It is also likely that such a scheme would need to overcome negative public perception of utilizing wastewater effluent.

Several technologies have been proposed as alternative routes for desalination (40–42). One recent example is ion concentration polarization (40). In this method, an ion depletion zone evolves when a potential drop is applied across a nanochannel containing fixed charges, which thereby prevents ionic species from flowing into a freshwater reservoir. This method may be suitable for small-scale use in remote regions, because minimal pretreatment of the feed is needed, and the necessary equipment is lightweight and easy to use. However, the cost associated with fabricating systems capable of producing high water fluxes will likely prevent the technology from being used for large-scale desalination operations. In addition, the energy consumption for large-scale desalination will likely exceed the energy used by state-of-the-art SWRO.

Waste heat, a by-product of power plants and several industrial operations, that cannot be used to produce electricity or as the energy source for evaporative desalination techniques may provide

an opportunity to develop systems that can supplement reverse osmosis desalination. The technologies that use this waste heat to produce the desired separation will consume more total energy than reverse osmosis, but their electric energy use will be much lower (43, 44). Thus, because the energy source to drive the separation process is waste heat, which would otherwise be discharged to the environment, such systems may be economically viable.

Forward osmosis is one emerging technology capable of desalinating seawater using low-grade or waste heat (Fig. 4C) (42). This process uses a solution with a lower chemical potential than seawater to draw water across a semipermeable membrane. The solutes in this draw solution are then recovered to accomplish the desalination. One potentially suitable draw solution is ammonia-carbon dioxide, and the feasibility of desalinating seawater with a heat source <60°C has been examined (43). The use of thermolytic salts as a draw solution may give forward osmosis an advantage over membrane distillation, which must evaporate water to produce fresh water (41). The low vapor pressure of water below 60°C may preclude the use of waste heat as a viable energy source for membrane distillation. The requirements placed on membranes for the forward osmosis process are different than those for the reverse osmosis process. Fabricating robust membranes designed to meet these requirements will allow for the use of lower draw solution concentrations, and thus lower the energy requirements of forward osmosis (42, 43).

Is Seawater Desalination a Sustainable Technological Solution to Global Water Shortages?

There are several concerns with desalination because of the potential for adverse environmental impacts. One is that thermoelectric energy, the main power source for SWRO desalination plants, results in the emission of air pollutants and greenhouse gases that further exacerbate climate change. Current state-of-the-art SWRO plants consume between 3 and 4 kWh/m³ and emit between 1.4 and 1.8 kg CO₂ per cubic meter of produced water (4, 5, 45). To put this in perspective, Spain would require as much as 4000 GWh annually to produce its projected desalination capacity of 1 billion m³/year (5). Even when considering that the overall energy consumption of future SWRO plants will drop below 3 kWh/m³, the carbon footprint of large-scale desalination plants can be substantial. Hence, to minimize greenhouse gas emissions, renewable energy sources could directly power SWRO desalination plants. Alternatively, indirect compensation or offset measures, such as the installation of renewable energy plants that feed energy into the grid, could also power desalination plants (46), which would resolve problems with intermittent and variable intensities of wind and solar sources.

A major problem associated with seawater intake is the impingement and entrainment of

marine organisms (8, 46, 47). Entrainment can kill a large number of juvenile-stage fish, although the impact on a population level is not clear given the naturally high mortality of larval organisms in marine systems (8). Open surface intakes, commonly used in large desalination plants, can minimize impingement of large organisms through a combination of appropriate screens and low intake velocity. Entrainment of small planktonic organisms (e.g., larvae, eggs) can be substantially reduced or eliminated by locating the intakes away from biologically productive areas, such as in deeper water farther offshore, or by using underground beach wells (8, 46). The latter would also improve the quality of the feed water, reducing the process pretreatment demands. Beach wells, however, are difficult to implement for large-scale desalination plants because the hydraulic permeability of the underlying aquifer limits the rate of water uptake. Where possible, collocation of desalination and power plants should also be considered for larger plants (8). The total volume of the intake water can be reduced if the cooling water from the power plant serves as feed water for the desalination plant, thereby minimizing the impacts from entrainment and impingement.

The elevated salinity of SWRO brines (about twice that of seawater) and the chemicals used in pretreatment and membrane-cleaning protocols also pose environmental risks to organisms when discharged to the marine environment (8, 46). The main chemicals that reverse osmosis plants discharge are antiscalants, coagulants, and cleaning chemicals (e.g., surfactants, alkaline and acid solutions, and metal-chelating agents) (4, 46). Despite myriad studies discussing the potential for adverse environmental impacts of desalination plant effluents (8), there is a lack of useful experimental data from laboratory tests or field monitoring to assess these impacts. For example, published data are inadequate to establish the salinity level at which marine organisms can tolerate long-term exposure.

To avoid impacts from high-salinity brines, the desalination plant brine can be diluted with other waste streams, such as power plant cooling water and treated wastewater effluent, providing they are available (8, 46). Mixing and dispersal of the discharge plume can be enhanced by installing efficient diffuser systems, and by situating the discharge stream at a marine location where favorable hydrodynamics for rapid mixing and dissipation of the salinity load exist. Different coastal and marine ecosystems vary in their sensitivity to brine and chemical waste discharges. The least sensitive are high-energy oceanic coasts that have strong waves and exposed rocky shores, whereas the most sensitive are coral reefs, salt marshes, and mangroves (46). The environmental impact of discharged concentrate streams can be further reduced with the use of more robust, membrane-based (microfiltration or ultrafiltration) pretreatment methods that use less chemicals than conventional seawater pretreat-

ment (coagulation followed by sand filtration). More effective pretreatment will also reduce the fouling rate and frequency of chemical cleaning. Lastly, the development of fouling-resistant membranes will minimize fouling and reduce chemical cleaning.

Because limited research exists on the long-term effects of desalination on marine ecosystems, there is considerable uncertainty regarding the environmental impacts of desalination. Further, there is a lack of site-specific information necessary to assess the ecological impacts of both seawater intake and brine discharge. Regardless, the widely accepted view is that the environmental impact of seawater desalination on marine environments will not be substantial if appropriate measures, such as those discussed above, are implemented.

Outlook

The energy demand for seawater desalination by state-of-the-art reverse osmosis is within a factor of 2 of the theoretical minimum energy for desalination, and is only 25% higher than the practical minimum energy for desalination for an ideal reverse osmosis stage. Yet, the overall energy consumption of new SWRO plants is three to four times higher than the theoretical minimum energy due to the need for extensive pretreatment and posttreatment steps. Because thermodynamics set the limit on the energy demand for the desalination step, we argue that future research to improve the energy efficiency of desalination should focus on the pretreatment and posttreatment stages of the SWRO plant.

Eliminating the pretreatment stage or reducing the pretreatment demands would substantially reduce the energy consumption, capital cost, and environmental impact of desalination plants, but this requires the development of fouling-resistant membranes with tailored surface properties, as well as membrane modules with improved hydrodynamic mixing. Accomplishing this goal is a daunting task because it requires the development of surface chemistries that resist the adhesion of a wide range of foulants while maintaining the high membrane permeability and selectivity necessary for seawater desalination. To aid in the development of such high-performance, fouling-resistant desalination membranes, it is imperative to develop detailed molecular models that establish structure-property relationships between membrane surface structure and chemistry, and membrane performance. Additionally, these models will assist in the development of oxidant-resistant membranes, which can also reduce the extent of pretreatment. Molecular simulation tools are used routinely in a variety of fields, including the development of drugs, catalysts, and chemicals, but their use for the development of water purification membranes is lagging considerably. Alternatively, developing new, energy-efficient desalination technologies that are inherently less susceptible to fouling compared to high-pressure, membrane-based de-

salination methods could also reduce or eliminate pretreatment.

Advances in membrane technology can also reduce the need for posttreatment in SWRO plants, thereby improving energy efficiency and reducing capital cost. Reducing boron and chloride levels in desalinated water for agricultural use to levels that crops can tolerate necessitates posttreatment. However, developing thin-film composite membranes with higher selectivity, particularly for boron, will be difficult. This is a direct consequence of the separation mechanism of thin-film composite membranes, where increasing selectivity to allow higher removal of boron and chlorides will substantially reduce the membrane permeability, which will increase energy consumption. Developing reverse osmosis membranes with higher selectivity without sacrificing water permeability will necessitate a major paradigm shift, as it will require membranes that do not follow the solution-diffusion mechanism for desalination. Molecular simulations can aid in determining how membrane chemistry and structure can be tuned to produce high permeability and selectivity.

In the coming decades, surging population growth, urban development, and industrialization will increase worldwide demand for fresh water, requiring new sources of water. Although several options currently exist to augment freshwater sources—including the treatment of low-quality local water sources, water recycling and reuse, water conservation, regional water transfers that do not adversely impact the environment, and the implementation of smart land-use planning—these options alone will not be enough to meet this need. Seawater desalination offers the potential for an abundant and steady source of fresh water purified from the vast oceans, and although it must be considered after all other options have been implemented, it should be viewed as a crucial component in the portfolio of water supply options. For water-scarce countries that already implement all other measures for freshwater generation, desalination may serve as the only viable means to provide the water supply necessary to sustain agriculture, support population, and promote economic development.

References and Notes

1. R. F. Service, *Science* **313**, 1088 (2006).
2. M. A. Shannon *et al.*, *Nature* **452**, 301 (2008).
3. Q. Schiermeier, *Nature* **452**, 260 (2008).
4. C. Fritzmann, J. Lowenberg, T. Wintgens, T. Melin, *Desalination* **216**, 1 (2007).
5. G. L. M. von Medeazza, *Desalination* **185**, 57 (2005).
6. Y. Dreizin, A. Tenne, D. Hoffman, *Desalination* **220**, 132 (2008).
7. A. Tal, *Science* **313**, 1081 (2006).
8. National Research Council (U.S.), Committee on Advancing Desalination Technology, *Desalination: A National Perspective* (National Academies Press, Washington, DC, 2008).
9. R. Semiat, *Environ. Sci. Technol.* **42**, 8193 (2008).
10. M. Busch, W. E. Mickols, *Desalination* **165**, 299 (2004).
11. J. MacHarg, T. F. Seacord, B. Sessions, in *Desalination and Water Reuse* (Faversham House Group, South Croydon, Surrey, UK, 2008), vol. 18, pp. 30–39.

12. K. S. Spiegler, Y. M. El-Sayed, *Desalination* **134**, 109 (2001).
13. R. W. Stoughton, M. H. Lietzke, *J. Chem. Eng. Data* **10**, 254 (1965).
14. R. L. Stover, *Desalination* **203**, 168 (2007).
15. A. Z. Zhu, P. D. Christofides, Y. Cohen, *Ind. Eng. Chem. Res.* **48**, 6010 (2009).
16. L. F. Song *et al.*, *Desalination* **155**, 213 (2003).
17. M. Wilf, *Desalination* **113**, 157 (1997).
18. K. P. Lee, T. C. Arnot, D. Mattia, *J. Membr. Sci.* **370**, 1 (2011).
19. S. Loeb, S. Sourirajan, in *Saline Water Conversion II* (American Chemical Society, Washington, DC, 1963), vol. 38, pp. 117–132.
20. R. E. Larson, J. E. Cadotte, R. J. Petersen, *Desalination* **38**, 473 (1981).
21. D. R. Paul, *J. Membr. Sci.* **241**, 371 (2004).
22. G. M. Geise, H. B. Park, A. C. Sagle, B. D. Freeman, J. E. McGrath, *J. Membr. Sci.* **369**, 130 (2011).
23. J. Glater, S. K. Hong, M. Elimelech, *Desalination* **95**, 325 (1994).
24. J. K. Holt *et al.*, *Science* **312**, 1034 (2006).
25. M. Majumder, N. Chopra, R. Andrews, B. J. Hinds, *Nature* **438**, 930 (2005).
26. M. Kumar, M. Grzelakowski, J. Zilles, M. Clark, W. Meier, *Proc. Natl. Acad. Sci. U.S.A.* **104**, 20719 (2007).
27. B. Corry, *J. Phys. Chem. B* **112**, 1427 (2008).
28. K. Falk, F. Sedlmeier, L. Joly, R. R. Netz, L. Bocquet, *Nano Lett.* **10**, 4067 (2010).
29. J. Johnson, M. Busch, *Desalination Water Treat.* **15**, 236 (2010).
30. E. Ostuni, R. G. Chapman, R. E. Holmlin, S. Takayama, G. M. Whitesides, *Langmuir* **17**, 5605 (2001).
31. S. Kang, A. Asatekin, A. M. Mayes, M. Elimelech, *J. Membr. Sci.* **296**, 42 (2007).
32. M. Elimelech, X. H. Zhu, A. E. Childress, S. K. Hong, *J. Membr. Sci.* **127**, 101 (1997).
33. S. Y. Jiang, Z. Q. Cao, *Adv. Mater.* **22**, 920 (2010).
34. C. Siegers, M. Biesalski, R. Haag, *Chemistry* **10**, 2831 (2004).
35. J. A. Callow, M. E. Callow, *Nat. Commun.* **2**, 244 (2011).
36. H. B. Park, B. D. Freeman, Z. B. Zhang, M. Sankir, J. E. McGrath, *Angew. Chem. Int. Ed.* **47**, 6019 (2008).
37. M. J. Zhou *et al.*, *J. Am. Chem. Soc.* **129**, 9574 (2007).
38. A. Efraty, U.S. Patent 7,695,614 B2 (2010).
39. T. Y. Cath, N. T. Hancock, C. D. Lundin, C. Hoppe-Jones, J. E. Drewes, *J. Membr. Sci.* **362**, 417 (2010).
40. S. J. Kim, S. H. Ko, K. H. Kang, J. Han, *Nat. Nanotechnol.* **5**, 297 (2010).
41. J. Giron, L. Song, K. K. Sirkar, *Ind. Eng. Chem. Res.* **46**, 2324 (2007).
42. J. R. McCutcheon, R. L. McGinnis, M. Elimelech, *Desalination* **174**, 1 (2005).
43. R. L. McGinnis, M. Elimelech, *Desalination* **207**, 370 (2007).
44. W. J. Koros, *AIChE J.* **50**, 2326 (2004).
45. G. Raluy, L. Serra, J. Uche, *Energy* **31**, 2361 (2006).
46. S. Lattemann, T. Hopner, *Desalination* **220**, 1 (2008).
47. H. Cooley, P. H. Gleick, G. Wolff, "Desalination, with a Grain of Salt" (Pacific Institute for Studies in Development, Environment, and Security, Oakland, CA, 2006).
48. F. A. Pacheco, I. Pinnau, M. Reinhard, J. O. Leckie, *J. Membr. Sci.* **358**, 51 (2010).
49. C. Y. Y. Tang, Y. N. Kwon, J. O. Leckie, *Desalination* **242**, 168 (2009).
50. O. Coronell, B. J. Mariñas, X. J. Zhang, D. G. Cahill, *Environ. Sci. Technol.* **42**, 5260 (2008).

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References
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