ANL/EVS-14/15

Saline Water for Power Plant Cooling: Challenges and Opportunities

Environmental Science Division

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prepared by
Christopher Harto, Molly Finster, Jenna Schroeder, and Corrie Clark
Environmental Science Division, Argonne National Laboratory

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ABSTRACT

In the future, there will be increased use of alternatives to freshwater for power plant cooling. One class of alternatives consists of water sources with higher total dissolved solids (TDS) than freshwater. These include seawater, brackish groundwater, produced water from oil and gas production, and water extracted from carbon storage formations. This report presents the key characteristics of these more saline water sources, along with the technology pathways that allow their use for power plant cooling, including saline cooling towers and desalination, and the challenges and opportunities presented by the use of these water resources and the different technology pathways. This information is then used to help map the range of decision factors that will influence the use of saline water sources for cooling.

A number of site-specific factors will determine the optimum cooling system for a specific power plant. In general, if freshwater is physically, politically, and economically available in the area, it is almost certainly going to be selected as the first choice. Reclaimed water is often cited as an alternative source of cooling water, but its use does not actually reduce the physical consumption of freshwater within most basins. However, it can often be more easily acquired from a water rights standpoint in many areas, and thus is expected to be used more heavily in the future for power plant cooling. Saline sources are only expected to become viable in situations where neither of these two sources is available due to the costs and challenges associated with their use. In such cases, the primary competition for saline water sources will be dry cooling. In general, the most important variable driving the cost for dry cooling systems is the local climate (lower temperatures result in lower energy penalties for dry cooling), while the most important variable driving the cost of the use of saline water sources is the quality of the water source used (lower TDS is less costly). Ultimately, the decision of what cooling system to utilize will be driven by the economics and resource availability. While some general rules of thumb have been identified that can limit the decision space, the development and integration of detailed economic models would allow for relatively rapid economic evaluation of all cooling options based on site-specific parameters.

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1 INTRODUCTION

Withdrawals of freshwater for cooling thermoelectric power plants constitute a large portion of the total freshwater withdrawals in the United States. A report from the U.S. Geological Survey (USGS), released in September 2014, put this figure at 490 million cubic meters (129 billion gallons) per day (Diehl and Harris 2014). Much of this withdrawal is by open-cycle systems, which exacerbate impacts on affected water bodies. Figure 1 illustrates how the U.S. power generation sector uses water. While not all water that is withdrawn is ultimately consumed, the impact of these withdrawals is substantial nonetheless.

A concern for the impacts on freshwater bodies has been an impetus for regulation of the effects associated with these withdrawals. For example, in May 2014, the U.S. Environmental Protection Agency (EPA) issued a final rule determination for the regulation of cooling water intake structures under Section 316(b) of the Clean Water Act (EPA 2014). This rule regulates impingement and entrainment impacts on wildlife from cooling water intake. California was ahead of this federal regulation with a state-level policy entitled *Statewide Water Quality Control Policy on the Use of Coastal and Estuarine Waters for Power Plant Cooling*, which was passed by the State Water Resources Control Board in 2010 (SWRCB 2010). This policy has helped phase out coastal once-through cooling in the state. As the nation's water stock becomes more constrained in the future, tensions over water use are expected to grow. Use of alternative sources for cooling is therefore critical if the nation's waters are to meet the many obligations and demands they will face in the future. This is particularly true of the Southwest and other areas of low rainfall, where limited access to water means that nontraditional sources will become increasingly important in the future.

The Energy Information Administration (EIA) is in charge of collecting and organizing data on thermoelectric generators in the United States by soliciting statistical information through a series of data sheets that operators are required to submit. These forms, including forms EIA 860 and EIA 923, must be submitted annually by facilities generating more than 100 MW (EIA 2014a,b). A compilation by the DOE of data collected from these forms provided

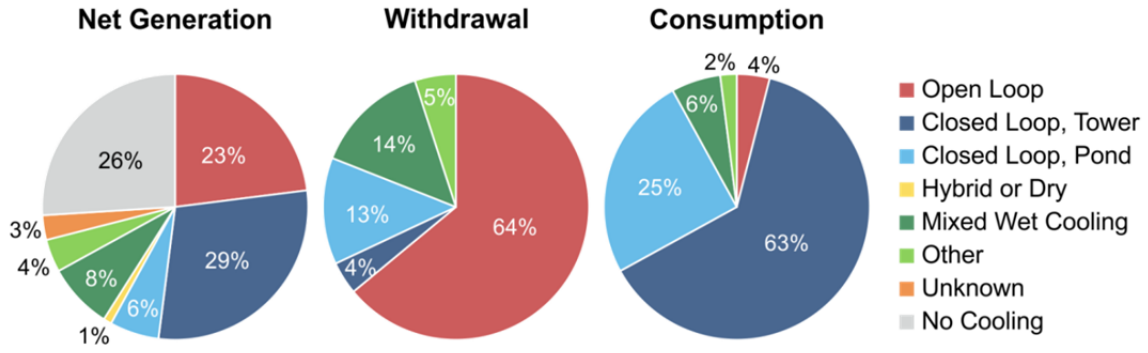

FIGURE 1 U.S. Power Generation, Water Withdrawals, and Water Consumption by Cooling Type (Source: DOE 2014)

the basis for the analysis in this section. Information analyzed included system type, in-service year, design intake flow rate, water source type, and cooling water type. A total of 1,908 proposed, existing, and retired facilities reported on the EIA data sheets were analyzed.

From this information, it was calculated that while freshwater dominates, with 76% of generators using this source, approximately 7% of currently operating facilities use saline water as their cooling source. In addition, 6% use brackish sources and 5% use reclaimed water sources (typically this is water previously discharged from wastewater treatment plants). This means a full 18% of facilities are currently using nontraditional cooling water sources, of which 13% are brackish or saline. See Figure 2 for a more detailed breakdown of these data.

Looking to the future, one can see an increased trend toward nontraditional sources (Figure 3). Of the 60 proposed systems for which the EIA has cooling water data, only approximately 43% plan to use freshwater. This is a considerable decrease from the percentage of facilities using freshwater in existing facilities. The number of facilities reporting that they will use reclaimed water, which increases to approximately 25% when considering proposed projects, makes up the majority of this difference. The number of new facilities using saline and brackish sources is actually projected to decline slightly, relative to the percentage of existing plants, to a total of 8%. This trend away from saline and brackish sources is likely at least partially a result of the move away from once through-cooling systems driven by the EPA's 316(b) regulation. Also, when available, substitution of reclaimed water for freshwater in conventional cooling towers can be accomplished relatively easily and has lower treatment

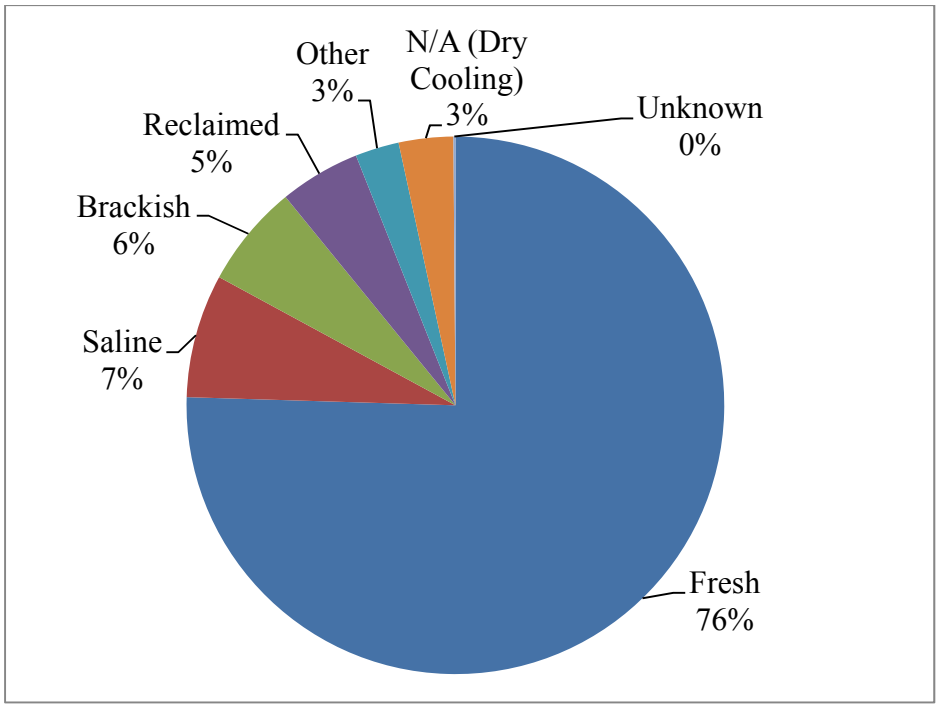

FIGURE 2 Cooling Water Sources for Existing U.S. Thermoelectric Generators

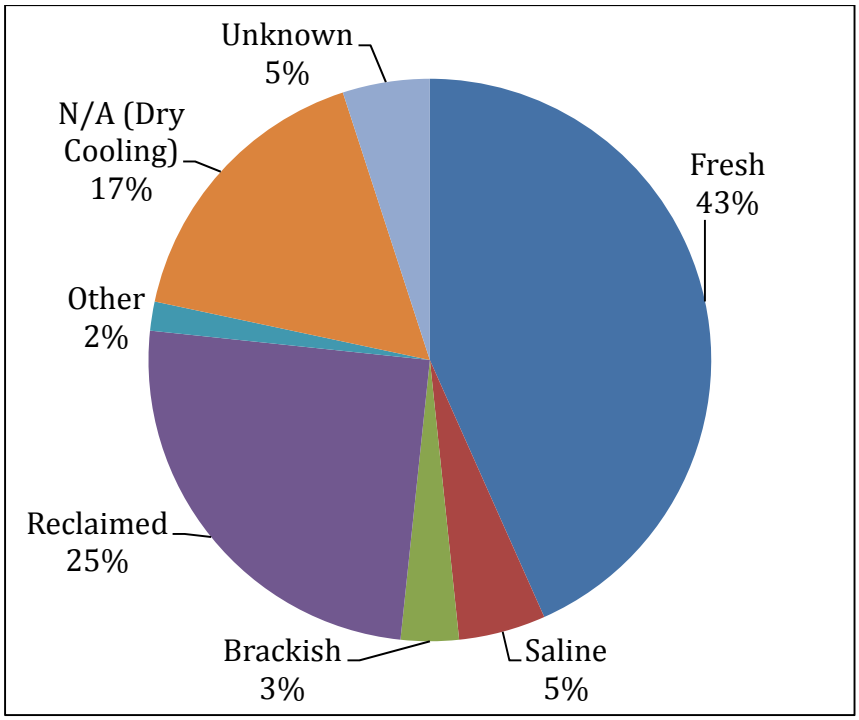

FIGURE 3 Cooling Water Sources for Proposed U.S. Thermoelectric Generators

requirements than the saline sources. The other cooling technology that is expected to see significant growth—expanding from 3% to 17%—is dry cooling, which can be considered a direct competitor to saline water sources.

Despite the fact that reclaimed water is likely to be the most widely used alternative water source in the near term, it is not discussed in detail in this paper. The reason is that although reclaimed water is often viewed as a new water source from a legal/water rights perspective, it is not a new water source from a physical perspective. In the vast majority of cases where reclaimed water is used for cooling, it was previously being discharged to a surface water body providing in-stream flows, or being used by downstream users. In addition, while reclaimed water may require some additional treatment for specific constituents (e.g., to remove nitrogen to control bacterial growth), it is typically low in total dissolved solids (TDS) and does not require desalination or the use of saline cooling towers. For these reasons, reclaimed water is more similar to freshwater and is not considered a brackish or saline water source.

Currently, 233 existing plants in the United States are using brackish or saline water sources for cooling purposes (EIA 2014a,b). Figure 4 shows a geographical breakdown of the plants using saline sources. Of these power plants, the vast majority utilize once-through cooling systems. Only 40 existing plants are utilizing recirculating cooling for saline or brackish sources (31 brackish and 9 saline). The data available do not indicate whether these systems utilize the water directly in saline cooling towers or rely on treatment and conventional cooling towers (EIA 2014a,b). For a comprehensive list of the details of some of these facilities, as well as some

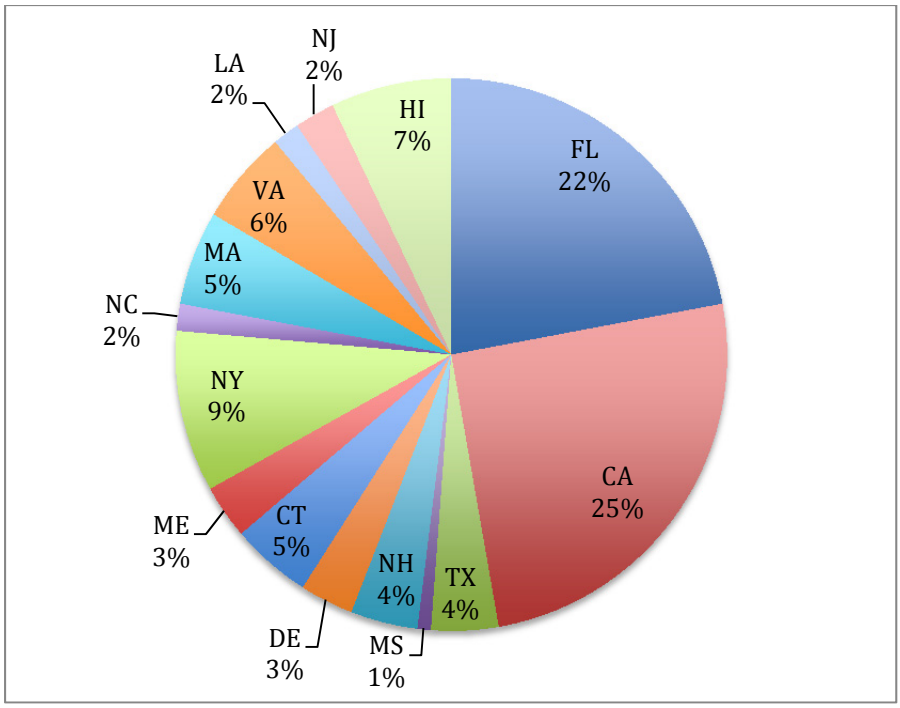

FIGURE 4 Locations of Existing Power Plants Using Saline Water for Cooling

international facilities, see Table 4-1 in the California Energy Commission (CEC) report *Performance, Cost, and Environmental Effects of Saltwater Cooling Towers* (Maulbetsch and DiFilippo 2008). To quote from the report, "The essential message from the accumulated information, however, is that towers of a wide range of size, application, construction materials, and makeup water quality have been designed, installed, and operated for several decades" (Maulbetsch and DiFilippo 2008). The report also found that the salinity of the makeup water for these facilities ranges from around 35,000 ppm, for pure seawater, to anywhere from a few hundred to a few thousand ppm for brackish groundwaters (Maulbetsch and DiFilippo 2008).

Saline waters represent one of the most widely available sources of alternative cooling water. Technologies to utilize saline water sources are already in wide use in the United States (see Figure 5). Use of saline waters for power plant cooling can proceed in two ways: either the water can be used directly in specially designed saline cooling towers, or it can be treated separately and used in conventional freshwater cooling towers. The choice between these systems is largely a factor of the type and quality of water available and the associated constituents of concern, which impact the cost of treatment. The remainder of this paper will concern itself with the differences between the different saline water sources and the factors that will influence which technology pathway should be taken for a given power plant.

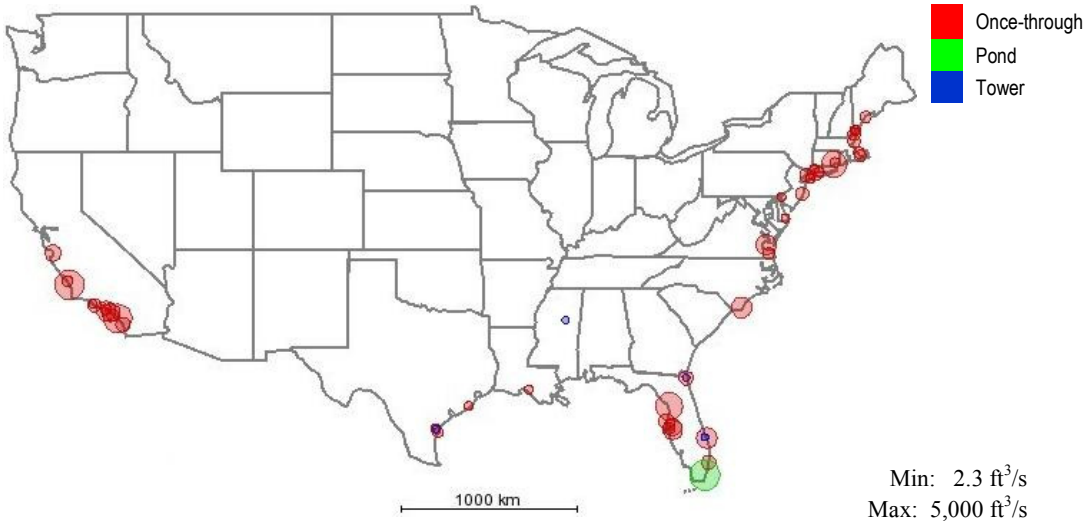

FIGURE 5 Thermoelectric Plants Using Saline Withdrawals (size of dot indicates design cooling water intake rate at 100% load) (Source: DOE 2014)

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2 NON-TRADITIONAL WATER SOURCES

There are a number of potential saline water sources that could be used for power plant cooling. The two primary saline water sources are seawater and brackish groundwater. In addition to the primary alternative water sources, there have been studies exploring the potential beneficial use of water produced and extracted during energy development. These include produced water from oil and gas development and water that might be extracted from carbon storage formations during active reservoir management, often referred to as "extracted water." Each water source has its own unique characteristics and challenges.

2.1 SEAWATER

Seawater is the most abundant water source on the planet. The salinity of seawater varies slightly around the world, but typically is around 35,000 ppm (Hoogland 2007). It is currently used in a large number of existing coastal power plants, although often in once-through configurations. The recent EPA 316(b) rule on cooling water intake structures, however, strongly favors recirculating cooling as the preferred technology for new power plants, and will make it much more difficult to acquire permits for new once-through cooling systems in the future (EPA 2014). Thus, either desalination or the use of recirculating saline cooling towers will be required for most new power plants that seek to use seawater for cooling.

Seawater is only an option for coastal power plants, which limits where it can be used. Other considerations for the use of seawater for power plant cooling include discharge of the blowdown from the cooling tower or concentrate from the desalination system. Depending on where the power plant is located, there is the potential for ecological impacts from discharging brine with significantly higher salinity. This factor could limit the allowable cycles of concentration for cooling towers or influence design parameters for desalination systems.

2.2 BRACKISH GROUNDWATER

The definition of brackish water varies, but it generally refers to water that is more salty than freshwater (defined by the EPA as 500 ppm TDS) and below the salinity level of seawater. The USGS generally restricts the definition of brackish water to waters with TDS levels of 1,000 ppm to 10,000 ppm. However, water with higher salinity may also be of use for power plant cooling. Although some brackish surface water sources exist, the vast majority of brackish water is groundwater.

The last national assessment of brackish water resources was completed by the USGS in the 1960s. An update to that study is currently underway, with an estimated completion date of summer 2016. Brackish groundwater can exist near the surface or below fresh groundwater. The salinity often varies both with location and with depth. When brackish water is located below a freshwater aquifer, care must be taken to determine if the two aquifers are hydrologically

connected to ensure that the consumption of brackish water does not result in a drawdown of the freshwater aquifer.

When using inland brackish groundwater, a few important factors must be taken into consideration. The most important is the availability of a means to dispose of blowdown from the saline cooling towers or concentrate from the desalination system. The primary means of disposal is injection into Underground Injection Control Program permitted injection wells as required by Title 40, Part 144, of the *Code of Federal Regulations* (40 CFR Part 144). Although this is a widely used brine disposal practice in the oil and gas industry, it is not without issues, and there are areas of the country where the geology is not appropriate for underground injection. Other options include evaporation, either natural or thermal, or piping water to a nearby coast for discharge into the ocean. Owing to the brine disposal costs and the cost of drilling and pumping groundwater wells, inland systems should be optimized to minimize the production of wastewater through maximizing either the number of cycles of concentration for the cooling tower, or the recovery fraction of the desalination system. These alternatives may require operating at conditions that may not be optimum from the perspective of other parameters, such as energy efficiency.

2.3 PRODUCED WATER

It has been estimated that 9 million cubic meters (2.4 billion gallons) per day of water are extracted from oil and gas formations in the United States (Clark and Veil 2009). This volume is significant, and there have been numerous successful examples of beneficial use of produced water, most notably in oilfield uses such as enhanced oil recovery and hydraulic fracturing. Given the large volumes of produced water generated, it has occasionally been discussed as a potential alternative water source for power plant cooling (Maulbetsch and DiFilippo 2008).

However, a number of factors significantly complicate the use of produced water for power plant cooling. Its composition can vary significantly across plays, within plays, and even from the same well over time. It often contains high levels of dissolved solids, suspended solids, and a range of organics that must be removed prior to use in conventional cooling towers. TDS can range from near freshwater levels to more than 300,000 ppm (USBR 2011). The production rate of produced water is also variable over the lifetime of a well and play. This variability is not compatible with power plant cooling uses, which require a steady and predictable water source. In addition, transporting small volumes from numerous locations across a large area is likely to be expensive and logistically challenging, although it may be possible to recover some of these costs from the reductions in disposal costs borne by the oil and gas producers. Costs for injection and disposal of produced water typically range from \$1.90 to \$13.00/m^3 (Harto and Veil 2011). None of these challenges absolutely preclude the use of produced water for power plant cooling, but they will complicate the economics, which are likely to favor other options in most cases.

2.4 EXTRACTED WATER

Water extracted from deep saline aquifers used for carbon storage is another potential future water source (Harto and Veil 2011; Kobos et al. 2011) This water source is most likely to be used in new power plants built with carbon capture and storage systems, owing to the ability to better optimize the system when all aspects (power production, carbon dioxide [CO_2] injection, water extraction, and cooling water demand) are controlled by a single entity. The addition of carbon capture to a coal power plant can add from 40% to over 100% to the water consumption of the plant, depending upon the power plant and capture system design. However, water extraction has been shown to have the potential to offset most if not all of the incremental water demand for carbon capture (Harto et al. 2014).

Modeling studies have shown that water extraction can lead to significant operational benefits to a carbon storage operation (Buscheck et al. 2012). One of the biggest potential challenges is the cost of managing the extracted water. Use of this water for power plant cooling could present an ideal solution, as long as the power plant is located near the storage location. A recent study has identified transportation costs and concentrate disposal as significant contributors to the energy consumption and greenhouse gas (GHG) emissions associated with treating extracted brines. Rough cost estimates indicated that extracted water could be treated for between $1 and $3 per metric ton of CO_2 stored (Harto 2014). Additional estimates place the cost of extracting water from storage formations plus treating with reverse osmosis at less than $10 per metric ton of CO_2 stored for 90% of storage formations evaluated (Klise et al. 2013).

Current law limits injection of carbon into reservoirs with TDS above 10,000 ppm, although that could potentially change if water extraction and beneficial use become widely practiced (Harto and Veil 2011). Wells for carbon storage are expected to be at least 800 m deep in order to achieve the necessary pressures for storage of CO_2 in the supercritical phase. Harto and Veil (2011) explored the chemical composition of water within 61 different formations in the United States identified as having potential for carbon storage. Water composition was found to vary significantly in TDS both across formations and within formations. Some general trends were identified, however. Formations in the Northwest generally had the lowest levels of TDS, with most formations having average concentrations around 10,000 ppm. In contrast, most of the formations in the Midwest had very high TDS levels, often exceeding 100,000 ppm. The Southeast, the region with the highest estimated carbon storage potential, had formations with TDS that ranged from 20,000 to 60,000 ppm (Harto and Veil 2011). Given this variability, the viability of water extraction and reuse for power plant cooling is likely to be fairly site specific, and may represent one important factor in siting both power plants with carbon capture and the respective storage locations.

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3 POWER PLANT COOLING TECHNOLOGIES USING SALINE SOURCES

In general, cooling towers for brackish or saline water sources are not fundamentally different from cooling towers used for freshwater. However, three main differences exist between the requirements for a traditional freshwater cooling tower and a tower designed to use saline and brackish waters. All of the differences result from the presence of dissolved minerals (salts). The differences are the lower vapor pressure of saline water, the necessity for different construction materials to protect from corrosion, and changes in the performance of drift eliminators (Hoogland 2007). These and others are described in detail below and summarized in Table 1.

Salts lower the vapor pressure of water, resulting in decreased thermal transfer efficiency and, therefore, decreased cooling tower performance. This factor will increase the cooling tower size necessary to achieve the same amount of cooling, and yield increases in power consumption as well. SPX, one of the leading manufacturers of saltwater cooling towers, calculates that there will be a performance decrease of 1.1% for every 10,000 ppm of salt concentration in the cooling water (Hoogland 2007). Similar studies by the CEC yielded a "rule of thumb" of 5% decrease in efficiency of the cooling tower for a salinity of 50,000 TDS (Maulbetsch and DiFilippo 2008). Increasing the design wet bulb temperature by a certain amount can compensate for this decrease. A general rule of thumb is to increase the wet bulb temperature 0.1°F for every

TABLE 1 Comparison of Cooling Tower Performance and Cost Factors

Factors	Saline Cooling Towers	Freshwater Cooling Towers
Vapor pressure	Lower vapor pressure due to increased salinity decreases performance	Higher vapor pressure due to low salinity
Materials	Corrosion resistant materials are necessary due to saline drift, and more expensive	Conventional materials are suitable
Drift eliminator	Improved performance due to salinity increasing surface tension, but higher concentration of impurities leading to greater PM_{10} emissions and salt deposition	Lower concentration of impurities resulting in lower PM_{10} emissions and salt deposition
Cycles of concentration	1.5–2	2–4 are common, with >6 possible, depending upon water quality
Water treatment for tower performance	Biocides, corrosion inhibitors, electrochlorination, bromation, and hardness stabilizers	Biocides, corrosion inhibitors

Sources: Maulbetsch and DiFilippo (2008); DOE (undated); EPA (2009a).

4,000 ppm of dissolved solids, which yields a 1.25°F increase for a TDS of 50,000 ppm (Maulbetsch and DiFilippo 2008).

The second main difference between conventional and saline cooling towers is the necessity of using different construction materials for a saline versus a freshwater cooling tower. This need is due to the presence of saline drift, which can corrode uncoated metallic surfaces in the vicinity of the cooling tower, as well as degrade and erode concrete and embedded reinforcing bars. The materials used to avoid these issues (such as bronze and titanium) cost significantly more than traditional materials, and this cost, combined with the need for building the tower slightly bigger to compensate for the decreased heat transfer efficiency discussed above, can lead to a cost increase of 35 to 50% when compared with freshwater towers of the same capability (Maulbetsch and DiFilippo 2008).

The third main difference between the two cooling tower technologies has to do with the performance of the drift eliminator. As salinity increases, surface tension increases as well. Surface tension is one of the main factors contributing to the performance of drift eliminators, along with size and air velocity. In general, an increase in surface tension slightly improves the performance of drift eliminators (Maulbetsch and DiFilippo 2008). Therefore, for drift eliminators of the same quality and type of installation, drift emissions should be relatively unchanged and a retrofit unnecessary (Maulbetsch and DiFilippo 2008). However, this is one area to which attention should be paid, in case there are some changes in performance over the lifetime of the cooling tower.

Some additional requirements in terms of maintaining the water in the cooling circuit may also come into play, depending on the type of water being used. While it is standard for a freshwater cooling tower to use biocides and corrosion inhibitors in the cooling water to maintain performance of the system and aid in avoiding scaling and fouling, a brackish or saltwater cooling tower may also use electrochlorination, bromation, and a hardness stabilizer (Hoogland 2007).

In terms of the operational performance of saline cooling towers, owing to the higher TDS levels of the feedwater, the number of cycles of concentration that can be achieved is typically significantly lower than the number achieved for freshwater systems. In general, the higher the concentration of TDS in the feedwater, the lower the number of cycles of concentration that can be achieved. This factor directly impacts the amount of blowdown that must be managed from the power plant. One important design consideration for saline cooling towers is the level of TDS for cooling tower operation. Higher concentrations will allow for more cycles of concentration and less blowdown to manage, but will also result in a more significant performance penalty. The optimum design conditions may vary depending on the water source and power plant location. Coastal plants will typically discharge their blowdown to the ocean, so they will need to take into account the potential ecological impacts of their discharge and will more than likely operate at lower cycles of concentration. Inland plants will have more challenges with respect to blowdown disposal. The most common method for disposing of inland brines is deep well injection (Clark and Veil 2009). The additional cost of disposal is likely to drive the design conditions to minimize blowdown through higher cycles of concentration.

3.1 DISCUSSION OF CONSTITUENTS OF CONCERN FOR COOLING TOWERS

In assessing alternative or non-traditional water sources, some water quality components are of particular concern to power plant cooling because of their potential for negative impact on system operation (e.g., scale or corrosion). These key parameters include pH, sulfate, chloride, calcium, and ammonia. The effects of these particular constituents are described in further detail in the following subsections. For reference and comparison purposes, Table 2 presents the general characteristics of fresh and saline waters with respect to these constituents. While these components are of primary concern, there are others that may be present in certain types of saline waters that may also be of concern, such as silica, which can cause scaling, and nitrates and phosphates, which can promote biological growth.

3.1.1 pH

Control of pH is critical for the majority of cooling water systems. In general, the primary effect of low pH (i.e., < 6.5) is to increase the metal corrosion rate and concrete deterioration in the cooling tower and system. On the other hand, more alkaline water with higher pH favors the formation of scale (e.g., calcium carbonate [$CaCo_3$]). It is further noted that the effectiveness of many biocides also depends on pH; therefore, high or low pH may allow the growth and development of problematic microbial populations.

3.1.2 Sulfate

Sulfates are naturally occurring species in almost all water bodies. They are generally formed from the dissolution of sulfur-containing minerals in soil and rock formations or decomposition of organic matter; however, they can also originate from municipal and/or industrial discharges. Problems caused by sulfates are most often related to their ability to form

TABLE 2 General Characteristics of Fresh and Saline Waters

	Freshwater	Brackish Water	Seawater
Total dissolved solids (TDS)	<1,000	1,000–15,000	15,000–45,000
pH	6.0–8.0	6.5–8.2	7.5–8.5
Sulfate (SO_4), ppm	<400	120–3,400	2,500–3,900
Chloride (Cl^-), ppm	<50	30–700	18,000–28,000
Calcium (Ca^{2+}), ppm	<100	20–550	600–600
Ammonia (NH_3), ppm	<1	<1-66[a]	<1

[a] Higher values correspond to ammonium (NH_4) concentration found in industrial wastewaters. In general, the concentrations of ammonia/ammonium will be in equilibrium in water.

Sources: DOI (2011); DOW (2013).

strong acids, which alter the pH of the water. Sulfate ions also are involved in complexing and precipitation reactions that affect the solubility of metals and other substances. For example, high concentrations of dissolved sulfate may be corrosive to metal surfaces. Sulfates can also react with cement or aggregate in concrete causing chemical changes that weaken and destroy the concrete matrix.

3.1.3 Chloride

Chloride, a component of salt, is one of the common anions found in water and, as salinity increases, so do chloride levels. In general, the risk of corrosion to metal surfaces and the reinforced steel in concrete increases as the chloride concentration increases. It is further noted that exposure of cement to chloride can result in expansion and cracking. However, only water-soluble chlorides promote corrosion; some acid-soluble chlorides may be bound within aggregates and, therefore, unavailable to promote corrosion.

3.1.4 Calcium

Some cations, such as calcium (Ca^{2+}), tend to precipitate out of solution with increasing temperature because their solubility decreases. This will result in significant scaling (e.g., calcium carbonate [$CaCO_3$]) on system equipment, especially on metallic surfaces at higher temperatures. One method developed to prevent calcium carbonate scaling involves the use of scale inhibitors, typically specialized and proprietary polymers.

Theoretically, controlled deposition of calcium carbonate scale may provide a film thick enough to protect metal, yet thin enough to allow adequate heat transfer. However, low-temperature conditions do not permit the development of sufficient scale for corrosion protection, and excessive scale forms in high-temperature areas and interferes with heat transfer. Therefore, this approach is not technically feasible for industrial cooling systems.

3.1.5 Ammonia

Ammonia concentrations can be quite high in some non-traditional waters. If copper or copper alloys are present in the cooling system, the ammonia can lead to corrosion issues for wetted surfaces. In addition, copper corrosion as a result of exposure to ammonia could create an environmental discharge problem in the form of soluble and complex copper species.

4 DESALINATION TECHNOLOGIES

As with any technology, saline cooling towers have certain performance limits. Some designs may completely fit the profile of the source water being used; if not, treatment may be an option. The most common form of treatment is desalination. Desalination involves removal of salts and dissolved solids from water, typically for beneficial use. Different water sources require different treatment intensities. Generally, treatment of water that either has high salinity (e.g., seawater or produced water from some oil and gas operations) or contains large amounts of organic material (e.g., municipal wastewater) has relatively high energy requirements (Hancock et al. 2012). Thus, as more nontraditional types of water are used, the associated energy requirements will generally increase. For example, desalination can be 100 times as energy-intensive as treatment of freshwater (CEC 2005).

Desalination has been practiced at commercial scales around the globe for decades. In general, there is no single best method of desalination. Presently, the total global desalination capacity is around 66.4 million m^3/day, and it is expected to reach about 100 million m^3/day by 2015 (Ghaffour et al. 2013). Desalination technologies are generally categorized as either thermal (i.e., involving a phase change) or membrane (i.e., single-phase) processes, which are further divided into subgroups. The selection of appropriate desalination technology depends on a site-specific combination of many factors, including source water quality, energy availability and form, and other local conditions (e.g., political and environmental restrictions). Figure 6 illustrates the worldwide distribution of desalination plants by technology (Bennett 2013).

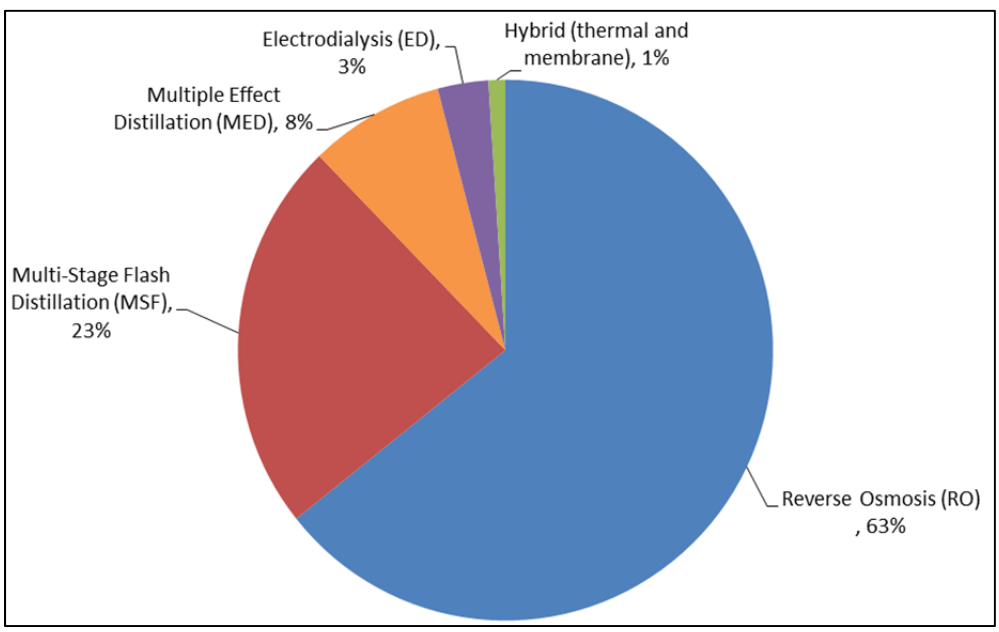

FIGURE 6 Worldwide Distribution of Desalination Plants by Technology (Note: Presented values add up to 98%; error is assumed to be due to rounding.)

All desalination processes require energy to effect separation of salts, and various energy sources can be used. In general, the more energy-intensive thermal methods are more widely utilized in areas where freshwater is scarce and the cost of energy is low, such as the Middle East (DOE 2014; NRC 2008). Thermal processes, primarily multi-stage flash (MSF) and multiple effect distillation (MED), make up about 31% of the online desalination capacity worldwide. Membrane processes such as reverse osmosis (RO), often in combination with nanofiltration (NF), have emerged as the predominant technologies used in desalination operations in the United States, as they are significantly less energy-intensive than traditional thermal techniques (DOE 2014; NRC 2008). Currently, membrane processes account for approximately 66% of the online capacity for desalination worldwide. Water can be desalted through many other processes, including small-scale ion-exchange resins and hybrid processes; however, none of these technologies have achieved the commercial success of membranes or thermal distillation (NRC 2008). Together, these other desalination processes account for only about 1% of total desalination capacity worldwide.

Many countries, aware of the energy intensity of typical desalination processes, are investing in low-carbon desalination, which utilizes solar, wind, nuclear, or geothermal energy sources. There is also increasing interest in the development of waste-heat-powered desalination. For example, in Qatar, which depends on the energy-intensive process of desalinizing seawater for municipal use, desalination facilities are co-located with power generation plants to take advantage of waste heat for energy (DOE 2014). These innovative desalination techniques, particularly those that utilize waste heat, can both reduce the energy required to treat water and enable the economic use of nontraditional waters (DOE 2014).

4.1 THERMAL METHODS

Thermal distillation represents the earliest method used to desalinate seawater on a commercial basis and has been used for well over a century. The major commercially developed thermal processes are MSF distillation, MED, and vapor compression (VC). Each of these methods is considered a mature and robust technology (NRC 2008).

The basic principle of thermal distillation involves heating a saline solution to generate water vapor, which is then condensed on a cool surface to produce a liquid water containing very little of the original salt content. Although water will boil under atmospheric pressure at 100°C, thermal processes are typically designed to boil water in a series of vessels operating at successively lower temperatures and pressures. For example, at one-quarter of normal atmospheric pressure, water will boil at around 65°C; it will boil at approximately 45°C if the pressure is decreased to one-tenth normal atmospheric pressure.

In general, thermal processes are not influenced by the feedwater salt concentration; thus, they are effective on very saline waters. In addition, thermal processes almost completely reject dissolved species (which can be problematic for membrane processes) and can produce a high-quality product water (<25 ppm TDS). However, operating at extremely high recoveries is not usually economical for desalination applications because of the boiling point elevation caused by

the salt. As a result, freshwater recovery rates for thermal seawater systems range from about 35 to 50% (NRC 2008).

Two forms of energy are required for operation of thermal distillation. Thermal energy is required for feedwater heating and constitutes the main portion of the energy input. Also, electricity is needed to drive the system's pumps and other electrical components within the system. In general, thermal processes are configured to operate in stages or series to use and reuse the energy required to evaporate water, known as the latent heat of evaporation. The efficiency of this latent energy reuse is a function of project-specific economics, considering capital and operating costs. Initial energy can come from a variety of sources, including fossil-fuel boilers, power-plant waste heat, nuclear reactors, and renewables (i.e., solar or wind).

Scale deposition and corrosion in thermal process units are commonly identified as significant concerns. However, these can be generally mitigated by pretreatment of the source water (e.g., addition of scale inhibitors) and control of the operating temperatures and concentrations. Thus, the potential for mineral-scale deposition in a thermal desalination plant is an economic optimization issue, not a limitation of the process (NRC 2008). It is further noted that thermal processes are also sensitive to volatile contaminants, which can evaporate from the feedwater and be carried over into the distilled water, where they may or may not condense (NRC 2008).

4.1.1 Multi-Stage Flash Distillation

MSF distillation is a forced-circulation process. In an MSF system, external heat energy is supplied to the intake preheated saline water to raise its temperature to the required top brine temperature of 90° to 110°C. The heated brine is then moved through a series of pressure vessels that are divided into numerous sections, each with decreasing pressures and temperatures. This setup progressively vaporizes (i.e., flashes) freshwater from the bulk brine as it moves through the system, until the concentrate is finally discharged. The freshwater vapor is then condensed using heat exchanger pipes of the inflowing unheated feedwater, thereby recovering energy from the heat of condensation and reducing the external thermal energy needed for heating the top brine. The number of stages used in the MSF process (e.g., typically ranging from 4 to 40) is directly related to how efficiently the system will use and reuse the heat with which it is provided.

MSF is generally considered the most robust of all desalination technologies (NRC 2008). It is capable of very large production capacities per unit, with systems typically ranging from 10,000 to 35,000 m^3/day (Al-Karaghouli and Kazmerski 2013).

4.1.2 Multiple Effect Distillation

MED is a thin-film evaporation approach consisting of a series of stages (usually from 2 to 16) that are maintained at decreasing levels of pressure and temperature. In MED, external heat is applied to increase the initial feed brine temperature of the first stage (i.e., effect) to

around 70°C. In each progressive stage, the feedwater is heated by steam in heat transfer tubes. The tubes can be submerged in the feedwater, but more typically the feedwater is sprayed on the top of a bank of horizontal tubes, and then drips from tube to tube until it is collected at the bottom of the stage. The water vapor produced is transferred inside the heat transfer tube to the next heating stage, where it is used for boiling additional brine, which produces water vapor in a series fashion. As with MSF, each stage essentially reuses the energy from the previous one.

The earliest distillation plants used MED, but MSF displaced MED because of its lower cost and lesser tendency to scale. However, MED technology is being used with increasing frequency when thermal evaporation is preferred or required, because this combination has reduced pumping requirements that lead to lower power use compared to MSF (NRC 2008). Typically, MED plants are built at capacities of 600 to 30,000 m^3/day (Al-Karaghouli and Kazmerski 2013); however, a plant with an output of 800,000 m^3/day currently exists in Jubail, Saudi Arabia (Marafiq 2014). It is noted that the largest MED plants typically incorporate thermal vapor compression (TVC) (discussed in Section 4.1.3) to improve the efficiency of the process (NRC 2008).

4.1.3 Vapor Compression

VC is a desalination process that relies on heat generated by the pressurization (i.e., compression) of water vapor for subsequent evaporation of feed brine. The feed brine enters the VC process through a heat exchanger, and vapor is generated in the evaporator and compressed by mechanical (MVC) or thermal (TVC) means. MVC use electricity to drive the compressor, whereas in TVC a steam jet creates the lower pressure. Compression of the vapor raises its temperature by a sufficient amount to serve as the heat source for the next stage. The concentrated brine is removed from the evaporator vessel by the concentrate reticulating pump. This flow is then split, and a portion is mixed with the incoming feed and the remainder is pumped to the waste.

VC systems can operate at very high salt concentrations (NRC 2008), and units tend to be used in small- and medium-sized applications. MVC capacity ranges between 100 and 3,000 m^3/day; TVC capacity ranges between 10,000 and 30,000 m^3/day (Al-Karaghouli and Kazmerski 2013).

4.2 MEMBRANE PROCESSES

Membranes are designed to selectively permit or prohibit the passage of certain ions, including salts. Membranes play an important role in the separation of salts in the natural processes of dialysis and osmosis. Commercially available membrane processes include RO, NF, electrodialysis (ED), and electrodialysis reversal (EDR). RO and NF are classified as pressure-driven membrane processes, whereas ED and EDR are electrically driven (NRC 2008).

In recent years, significant advances in membrane technology have been achieved and, globally, more new membrane desalination capacity is added annually than distillation capacity.

Typically for seawater, there is a 35 to 60% recovery of the feed as product water; for brackish water; recovery can range from 50 to 90%, depending on initial salinity and the presence of sparingly soluble salts and silica (NRC 2008). For both brackish water and seawater, membrane processes can reduce salinity in the product water to levels less than 500 ppm TDS.

In general, membrane processes require the least energy overall, but are highly influenced by feedwater salt concentration. In addition, pretreatment is a critical step in membrane desalination systems, particularly those that utilize feedwater from surface water sources, because suspended and colloidal particles (e.g., iron, manganese, and sulfides), organisms, and natural organic matter can result in scaling or fouling of the membranes. Feedwater pre-treatment, beyond conventional pretreatment technologies (e.g., coagulation and sand filtration), typically involves membrane filtration (e.g., microfiltration [MF] and ultrafiltration [UF]), sterilization, and the addition of chemicals to prevent scaling and biofouling. Membrane fouling can seriously impair performance by lowering productivity and salt rejection, decrease resistance to chlorine and other oxidants, and lead to an increase in energy use. The proper pretreatment of feedwater is often considered the most important factor in successful plant operation and constitutes a critical part of plant design (NRC 2008).

4.2.1 Reverse Osmosis

RO is a form of pressurized filtration that involves mechanically forcing water by applied pressure through a semi-permeable membrane filter, utilizing a solution/diffusion mechanism. The membrane (with pore diameter <0.001 μm) restricts the passage of dissolved solids. Thus, the majority of dissolved salts are concentrated in solution on the high-pressure side of the membrane, yielding permeated freshwater (at about 500 ppm TDS). RO processes are also capable of removing some larger organic contaminants (e.g., bacteria and viruses), but allow passage of small uncharged species (e.g., hydrogen sulfide and carbon dioxide) through the membrane.

Several types of membranes are available in the market; the two most commonly used types are spiral-wound and hollow fine fiber. RO membrane formulations include cellulose acetates, polyamides, polyetheramides, and polyethersulfones. The most widely used membrane material at present is a thin-film composite polymer combining a microporous polysulfone support layer with a thin polyamide layer (NRC 2008). In practice, today's best available RO membranes are operated at pressures significantly above the osmotic pressure to produce practical product water fluxes through the membranes.

Advances related to membrane materials and performance have resulted in improvements with respect to increased salt rejection capability, greater surface area per unit volume, increased permeability, higher recovery ratios, extended membrane life, and capacity to work at higher pressure. These improvements have decreased membrane cost and reduced the pressure required to produce practical water fluxes, thereby minimizing the operational and energy costs of a desalination plant (NRC 2008; Ghaffour et al. 2013). However, membrane fouling remains a major challenge. Currently, the most direct and effective way to protect against fouling is with effective pretreatment (e.g., MF and UF) to remove suspended and colloidal material and

dissolved organic matter. As an alternative, development of fouling-resistant membranes or membranes that could be cleaned easily with low-cost oxidants (e.g., chlorine) would be advantageous. However, current RO membranes for seawater and brackish water desalination are not designed to tolerate oxidants such as free chlorine, and they actually require chlorine removal from the feedwater before it is processed by the RO modules (NRC 2008).

RO is the most commonly used desalination technique worldwide. Its installed capacity ranges from 0.1 m^3/day (used in marine and household applications) to nearly 400,000 m^3/day (for commercial applications) (Al-Karaghouli and Kazmerski 2013). The amount of energy (i.e., osmotic pressure) required to push water through the membranes for separation is directly related to the salinity of the solution. This energy, primarily in the form of electricity to drive high-pressure pumps, constitutes the bulk of RO operational costs. Owing to low net recoveries of the highly pressurized feedwater, typically 40 to 60% of the applied energy in the process can be lost if the concentrate is discharged to atmosphere without any attempt to recover that energy. In general, energy recovery devices can recover from 75 to 96% of the input energy in the concentrate stream of a seawater RO plant (Sallangos 2005; NRC 2008).

Although the RO process is relatively mature, opportunities exist to further reduce its energy use by small but economically significant amounts. Over the past few decades, improvements in process control and commercially available state-of-the-art equipment (e.g., more efficient energy recovery systems) have had a significant and direct effect on reducing energy and operating costs of RO systems (NRC 2008). While further advances in pretreatment (notably, NF) and membrane technology (e.g., fouling resistance) still have some potential for enabling further improvements, they are considered to be incremental, as RO technology is nearing its practical limits (NRC 2008; DOE 2014; Carter 2013).

4.2.2 Nanofiltration

Like the RO process, NF uses hydraulic pressure to drive water through semipermeable membranes. However, the NF process runs at lower pressures (and energy) than RO and achieves removal via a combination of the usual standard solution/diffusion mechanism with steric (size) and charge exclusions (NRC 2008; Childress and Elimelech 2000; Timmer 2001). NF membranes are capable of rejecting divalent ions (e.g., Ca^{2+} and Mg^{2+}) and larger contaminants (e.g., organics, sulfate, and biologicals) very well, while providing lower retention of monovalent salt ions (e.g., Na^+ and Cl^-) (NRC 2008). They can also remove synthetic organic chemicals and disinfection by-product precursors while selectively retaining healthy trace minerals in drinking water. Thus, NF performs well for lower-salinity water and is primarily used for softening and removal of organics.

In general, the typical energy usage for NF is lower than that for RO, depending on the feedwater characteristics and the product water quality objectives. As with RO, membrane fouling is a major challenge for efficient operation of NF plants; thus, some pretreatment of feedwaters is required (USBR 2003). Pilot testing of a two-pass NF system for seawater desalination is under way at the Long Beach Water Department. The first pass removes greater than 90% of the salinity, and the second pass removes greater than 93%, resulting in a total salt

reduction of about 99.5% (Tseng et al. 2003). The overall recovery from the NF process is about 30 to 45% for seawater desalination, which is at the low end of the range observed with conventional RO desalination (NRC 2008).

4.2.3 Electrodialysis and Electrodialysis Reversal

ED is an electrochemical separation process that moves ions through ion-selective semi-permeable membranes using two electrically charged electrodes, leaving freshwater behind. ED operates at atmospheric pressure and uses direct current voltage to transfer the ions through the membrane. An ED unit can typically remove 50 to 94% of the TDS from the feedwater. As with other membrane processes, ED membranes are subject to fouling; thus, some feedwater pretreatment is necessary. The EDR process is similar to the ED process, except that the polarity of the electrodes is switched periodically to effectively reduce and minimize scaling and fouling, thus allowing the system to operate at comparatively higher recoveries (NRC 2008).

EDR and ED processes are considered a mature desalination technology. They are typically used to desalinate brackish water because the cost of these processes is directly proportional to the TDS concentration and increases significantly with higher salinity. In general, municipal applications for ED/EDR have been noted for brackish waters with TDS up to 7,500 ppm (Mickley 2006), although ED/EDR is typically cost-competitive with RO for TDS up to about 3,000 ppm (Mallevialle et al. 1996). An ED plant's typical capacity ranges from 2 to 145,000 m^3/day (Al-Karaghouli and Kazmerski 2013).

Unlike RO and thermal desalination processes, ED is only capable of removing ionic components from solution. As a result, fouling by uncharged species (e.g., silica) is less severe as compared to the RO process. In addition, current ED/EDR membranes are resistant to chlorine, making them more robust for processing feedwaters with higher levels of organic matter that would typically foul RO membranes (e.g., water reuse applications). These features are important factors that increase the practical application of ED/EDR versus RO. Also, because of the robust nature of EDR, it is being applied in hybrid applications as a concentrate reduction method for RO processes (Kiernan and von Guttberg 2008; Reahl 2006).

4.3 EMERGING DESALINATION TECHNOLOGIES

Advances in technology can increase the options available to decision makers at all scales. Thus, alternatives to the major desalination technologies continue to be investigated to enhance or replace existing desalination processes or fill niche applications where mainstream technologies are inapplicable. Several alternative approaches have been proposed, primarily to reduce the energy requirements of desalination. Some of these emerging technologies, such as forward osmosis, membrane distillation, and dewvaporation, present opportunities to improve the use of low-grade or waste heat, whereas other approaches, such as nanostructured/ nanoenhanced membranes and capacitative deionization, offer the potential to reduce the overall energy usage.

4.3.1 Forward Osmosis

Forward osmosis (FO) is a membrane-based separation process that uses a natural (as opposed to forced) osmotic pressure difference between a concentrated draw solution (or osmotic agent) and feed stream to drive water flux across a semipermeable membrane. The primary challenge in selecting the osmotic agent is to find a mixture with enough osmotic potential to power the transmembrane transfer, which is particularly problematic for high-salinity feed streams (DOE 2014). Provided sufficient difference in osmotic pressure is achieved, the magnitude of water flux and degree of salt rejection can be competitive with RO (McCutcheon et al. 2005). In general, recovery by FO has been demonstrated to be greater than 60% for seawater and 90% for brackish water (Chaudhry 2014).

FO systems have some additional challenges that are not present in RO systems. In particular, the FO process does not provide high-quality water for use in a single step, because after the FO step is complete, the product water is mixed with the osmotic agent (Thompson and Nicoll 2011). Thus, an osmotic agent must be selected that either is desirable to have in the product water or may be easily and economically removed (Li et al. 2013). For example, removal of an osmotic agent consisting of a combination of ammonia (NH_3) and carbon dioxide (CO_2) gases dissolved in water requires only small quantities of electrical power (<0.25 kWh/m^3) combined with low-quality heat (<50°C), which could be provided by waste heat from an industrial or power production process (DOE 2014; NRC 2008; McGinnis and Elimelech 2007). Other FO draw solutions are currently being evaluated, including switchable polarity solvents, which change from miscible to immiscible with the addition or subtraction of CO_2 (Stone et al. 2013). Additional challenges for FO include management of membrane fouling, maximizing boron and arsenic removal, and overcoming problems with capacitive polarization (DOE 2014).

There are numerous strong drivers to develop this process and apply it commercially, including the fact that this method of extracting high-quality permeate requires very low energy consumption, naturally low pressures, and ambient temperatures (Thompson and Nicoll 2011). There is already a commercial system (200 m^3/day capacity) in operation in Oman, on the Arabian Sea. However, while FO has demonstrated some market success, widespread deployment will require additional research and testing to prove its potential as a cost-effective desalination alternative in a variety of applications (DOE 2014; Phuntsho et al. 2012).

4.3.2 Membrane Distillation

Membrane distillation (MD) is a thermally driven separation process in which only water vapor molecules transfer through a microporous hydrophobic membrane. The driving force in the MD process is the vapor pressure difference induced by the temperature difference (which creates a pressure gradient) across the membrane (Alkhudhiri et al. 2012). This technology requires both thermal and electrical energy and has the theoretical ability to achieve 100% salt rejection.

This suite of technologies is a low-temperature alternative to traditional thermal methods. The different configurations include direct contact, air gap, sweeping gas, and vacuum. In the direct-contact configuration, the hot solution (i.e., feed) is in direct contact with the hot side of the membrane surface, leading to evaporation at the feed-membrane surface (Alkhudhiri et al. 2012). The pressure difference across the membrane moves the vapor, which condenses inside the membrane module on the permeate side. The main drawback of direct-contact MD is the heat lost by conduction. For the air gap configuration, the feed solution is in direct contact with the hot side of the membrane surface only. Stagnant air is introduced between the membrane and the condensation surface, so that the vapor crosses the air gap to condense over the cold surface inside the membrane cell. The benefit of air-gap MD is the reduced heat loss by conduction; however, additional resistance to mass transfer is created. In sweeping-gas MD, inert gas is used to sweep the vapor at the permeate membrane side to condense outside the membrane module. Similarly to air-gap MD, the gas acts to reduce heat loss, but because it is not stationary, the mass transfer coefficient is enhanced. The main disadvantage of sweeping-gas MD is that a small volume of permeate diffuses in a large sweep-gas volume, so a large condenser is required. Lastly, vacuum MD uses a pump to create a vacuum in the permeate membrane side. Condensation takes place outside the membrane module; thus, heat lost by conduction is negligible (Alkhudhiri et al. 2012).

The rejection of feed-stream solutes is high for MD and can be comparable to that of other distillation techniques (NRC 2008). In general, MD technologies share the advantage of thermal methods related to TDS-level insensitivity, but operate at lower temperatures (i.e., 30°–90°C) and energy intensities because the solution is not necessarily heated up to the boiling point (DOE 2014). This implies that it may be possible to utilize waste heat to power the desalination process (as discussed further in Section 5). In addition, the relatively small footprint required for these technologies leads to lower capital costs. Moreover, the hydrostatic pressure encountered in MD is lower than that used in pressure-driven membrane processes like RO. However, because it is a membrane process, additional potential issues include membrane degradation and fouling of various kinds, which create issues related to maintaining hydrophobicity and membrane lifetime. Other possible disadvantages include the large enthalpy of vaporization required for the phase change of water transported across the membrane and poor rejection of volatile feed-stream contaminants, which require pretreatment (NRC 2008).

This family of solutions is at an intermediate level of development and offers significant potential for advances in energy-efficient treatment of high-TDS waters (DOE 2014). The MD system also has the potential to be combined with other separation processes such as UF or RO to create an integrated separation system. Most current MD applications are still in the laboratory or small-scale pilot-plant phase, although some larger-scale pilot plants have been developed to produce freshwater (Alkhudhiri et al. 2012; Kullab and Martin 2011).

4.3.3 Dew Evaporation (Dewvaporation)

Dewvaporation is a specific process of humidification-dehumidification desalination. In this technology, a stream of heated air is humidified by a falling film of saline water along one side of a heat transfer surface, which leads to evaporation (DOE 2014; CADWR 2005;

Bruff et al. 2011). On the other side, the vapor condenses as freshwater dew under cooler conditions and the condensation process releases heat through the heat transfer surface to the evaporation side, thus recapturing much of the latent heat of vaporization (DOE 2014). The energy needed for evaporation is supplied by the energy released from dew formation. Heat sources can include combustible fuel, renewables, or waste heat (NRC 2008). Recovery rates have been reported to be greater than 90% (Chaudhry 2014).

The potential benefits of the dewvaporation process include efficient use of low-grade heat or solar energy; operation at atmospheric pressures; tolerance for high TDS levels; absence of membranes, hence reduced fouling potential; removal of heavy metals, organics, and radionuclides; relatively small footprint; and low capital costs compared to conventional thermal desalination methods (Chaudhry 2014; DOE 2014; NRC 2008; Bruff et al. 2011). Some of the disadvantages related to this type of system include requirements for large heat transfer areas; sensitivity to atmospheric conditions (e.g., temperature and humidity); energy intensiveness if waste heat is not available; and the need for a low-temperature sink to permit condensation (NRC 2008; DOE 2014; CADWR 2005).

Although the technology of dewvaporation is still being developed, two commercial-scale plants are currently in operation in Pennsylvania to treat produced waters from oil and gas operations (DOE 2014).

4.3.4 Nanostructured and Nanoenhanced Membranes

Advances in membrane technology at the nanoscale show promise for reducing various kinds of membrane fouling, which is arguably the key challenge in the cost-effective deployment of advanced membrane systems (DOE 2014). For example, nanostructured surfaces can offer control over membrane features that allow for fine-tuning of flux, selectivity, and membrane strength for optimal performance (Qi et al. 2012; DOE 2014; NRC 2008).

Alternatively, the introduction of nanomaterial membranes (e.g., carbon nanotubes) offers a unique combination of robustness, precise control over potential bonding sites, enhanced water flow, and ease of functionalization to create desirable membrane characteristics (NRC 2008; DOE 2014; Dumee et al. 2013). Although some of the existing research shows promise, this area is still in the early stage of technological development. No definitive experimental observations have been identified that demonstrated rejection of salt by nanotube membranes; thus, it is also not clear at this time how such membranes will perform with seawater and brackish waters, especially where fouling has been shown to be an important factor. Finally, even if such nanotube membranes demonstrate desalination performance, scaling to membrane modules, cost of production, and potential for undesirable release of nanoparticles will remain major obstacles (Chaudhry 2014; NRC 2008).

4.3.5 Capacitive Deionization

Capacitive deionization (CDI) is an electrosorption desalination process whereby ions are removed from water using an electric field gradient as the driving force. In its simplest form,

CDI does not utilize membranes. Instead, it relies on a relatively small direct current and voltages to attract salt ions to positively and negatively charged electrodes, leaving a relatively pure stream of water. Ions are held at the surface of the electrode and when the electrodes reach their assimilation capacity, the current is removed or reversed, allowing flushing of concentrated brine (DOE 2014; NRC 2008).

CDI is a fairly new desalination method. A main advantage is its ability to remove a wide range of ionic contaminants, such as sulfates, nitrates, iron, arsenic, fluorides, and sodium, with high recovery rates (Chaudhry 2014). It also offers the possibility of energy recovery in the desorption phase, although work remains on optimizing cycle parameters and developing anode and cathode materials with improved performance under realistic conditions (DOE 2014; Zhang et al. 2013). A variant encases the electrodes in selective membranes, improving efficiency by preserving their adsorption capacity through multiple cycles (Zhao et al. 2013a).

A major limitation of this technology is that it may only be suitable for relatively clean brackish waters (i.e., TDS less than 5,000 ppm). However, this family of technologies has the potential to be more energy-efficient than RO for these sources, and it is possible that innovations could increase the salinity of water that could be treated economically (DOE 2014; Zhao et al. 2013b). It is also less capital intensive than RO, although fouling can still be an issue under certain conditions (Mossad and Zou 2012).

4.4 HYBRID CONFIGURATIONS

Hybrid desalination configurations include combinations of processes designed to improve process efficiency or reduce energy costs. Hybrid systems typically combine two or more desalination processes, or couple desalination with a power generation system in a dual-purpose configuration. As a result, these hybrid configurations are generally characterized by flexibility in operation, resiliency to fluctuation in water and power demands, less specific energy consumption, low construction cost, high plant availability, and better power and water matching (Ghaffour et al. 2013; Hamed 2005). Thus, hybrid systems are currently considered a suitable economic alternative to traditional desalination technologies.

Frequently, hybrid thermal-membrane facilities incorporate both thermal and membrane desalting processes and are co-located with a power plant to improve overall process economics. These types of systems can optimize water production and energy costs under seasonal variations in power loads, because operation can be switched from electrically driven RO to thermally driven distillation. In periods of high power demand, there will also be associated abundant steam generation such that thermal desalination operations can be maximized; conversely, when there is low power demand (and reduced quantities of available low-grade or waste heat), water production by RO is likely to become more economical (Ludwig 2004). It is noted, however, that to utilize this operational flexibility and realize the cost benefits, the total installed capacity must be larger than the nominal demand for water (NRC 2008). For example, Fujairah in the United Arab Emirates is one facility of this type, with a total water production of about 450,000 m^3/day. Two-thirds of the production capacity is provided by MSF units, with the remaining capacity provided by seawater and second-pass brackish-water RO units. The facility

also has the capacity to use warm MSF cooling water as part of the feedwater to increase the permeability of the RO process during winter months (NRC 2008).

Other types of hybrid configurations use common intake and outfall systems to reduce pumping energy and decrease the cost of civil works. For example, the feedwater temperature for an RO process can be maintained using the available waste heat from thermal brine discharge. The use of the thermal discharge within the RO process, in turn, helps cool the concentrate to acceptable temperatures before it is returned to the sea, thus better meeting discharge regulations related to thermal discharge cooling water (Ghaffour et al. 2013). As another example, the product water from parallel RO and thermal desalination processes can be blended to enable the RO membranes to operate with higher permeate TDS, thus reducing the replacement costs of RO membranes (Hamed 2005; NRC 2008).

Hybrid desalination facilities may also integrate multiple processes in series to increase the separation or concentration capabilities of the facility. These series hybrids are typically smaller in capacity. For example, zero liquid discharge systems (i.e., facilities with no offsite liquid-waste discharges) often concentrate the desalination waste stream by separating the process into logical steps and optimizing the entire system, using RO systems followed by distillation concentrators and crystallizers. Another hybrid example is the combination of ED and RO, where ED is used to reduce the salinity of the reject stream from the RO so that the salt-depleted reject stream can be recycled to the RO to increase recovery. Hybrid configurations in series can also be used to create ultrapure water required by some industrial processes. The multitude of possible combinations of desalination processes in hybrid configurations is limited only by ingenuity and the identification of economically viable applications (NRC 2008).

The concept of a hybrid MSF/RO configuration has already been applied to a number of existing and new commercial desalination plants (Hamed 2005). NF membranes could also be used for pretreatment to significantly reduce scale-forming ions, allow high-temperature operation of thermal desalination processes, and subsequently increase water productivity. Thus, fully integrated NF/RO/MSF hybrid desalination systems for seawater applications have the potential for high water productivity and enhanced thermal performance (Hamed 2005).

Another example of combined processes is a dual hybrid membrane system that can provide water quality comparable to RO, but is powered by waste heat. The hybrid system takes advantage of combining an FO process with MD technology. Minimally treated wastewater is sent to an FO system. The resulting feedwater, consisting of mainly dissolved solids with little organic content, is subsequently passed through to an MD system that is heated by industrial waste heat. The resulting condensed vapor product is comparable to distilled water and is suitable for direct reuse. The remaining solution containing non-volatile solutes and salt is sent back to the FO system as the osmotic agent (DOE 2013, 2014).

4.5 SUMMARY

Key characteristics of many of the water treatment systems discussed are summarized in Table 3.

TABLE 3 Summary of Water Treatment Technology Characteristics

	Product-Water TDS (ppm)	Typical Accepted TDS Range (mg/L)	Recovery Rates (%)	Typical Unit Capacity Range (m^3/day)	Capacity of Existing Large Facilities (m^3/day)
Thermal Methods					
Multi-stage flash distillation (MSF)	<10	35,000–55,000	25–50	1,000–76,000	600,000–880,000
Multiple effect distillation (MED)	<10	35,000–55,000	35–65	600–45,000	800,000 (w/TVC)
Vapor compression (VC)	<10	35,000–55,000	25–50	MVC: 20–3,800 TVC: 10,000–30,000	30,000 (TVC)
Membrane Processes					
Reverse osmosis (RO)	200–500 (seawater) <200 (brackish)	50–50,000	25–60 (seawater) 50–90 (brackish)	0.1–130,000	>400,000
Nanofiltration	<200	50–35,000	30–45 (seawater) 50–90 (brackish)	<1,200	55,000
Electrodialysis and electrodialysis reversal (ED/EDR)	20–600	300–12,000 (best <3,500)	50–94	2–145,000	>40,000
Emerging Desalination Technologies					
Forward osmosis (FO)	<200	50–50,000	>60 (seawater) >90 (brackish w/RO)	50–115 (pilot scale) 100–200 (w/RO)	–[a]
Membrane distillation (MD)	<100	50–50,000	>99.8 (100 theoretical)	0.05–2 (demonstration project)	–
Dewvaporation	<10	<60,000	>90	<20 (pilot scale)	–
Capacitive deionization (CDI)	<200	<5,000	55–95	Not defined (bench scale)	–

[a] A dash indicates no data available.

Sources: Al-Karaghouli and Kazmerski (2013); Charcosset (2009); Chaudhry (2014); Coday et al. (2014); DOE (2014); DOW (2013); Dow et al. (2008); Grattan (2011); Greenlee et al. (2009); Hamed et al. (1999); Khawajia et al. (2008); Kullab and Martin (2011); Marafiq (2014); Mossad and Zou (2012); NRC (2008); Reahl (2006); Thompson and Nicoll (2011); Thye (2010); Tseng et al. (2003); UNEP (1998); USBR (2003, 2008, 2013).

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5 CHALLENGES AND TECHNOLOGY NEEDS

Seawater constitutes a virtually infinite resource, and while it has been used for once-through cooling of power plants, challenges remain in employing it for recirculating systems (DOE 2014). Brackish groundwater is also an important potential resource for energy uses, especially in landlocked, water-scarce regions. It also requires less energy to treat than seawater. Produced waters from oil and gas and potentially from carbon capture and storage operations also tend to be high in salinity. Beneficial use of these waters as an alternative water source presents a significant opportunity, but requires cost- and energy-efficient solutions in order to gain market penetration (DOE 2014).

5.1 WATER COSTS

Historically, the cost associated with technology has been the major issue for desalination, with energy use as a close second (as discussed further in the following section). As the technology has advanced, its costs have declined; at the same time, the cost of traditional water resources has increased. Consequently, desalination is increasingly being considered as a feasible alternative to freshwater sources (CADWR 2005). Table 4 presents the reported average total water production costs of the main desalination processes.

Currently, sources of energy for desalination may include fossil-fuel, nuclear, and renewable (e.g., solar, wind, or geothermal) options. In general, the cost of water produced from desalination units coupled with renewable energy resources is highly related to the cost of energy produced from these resources. This is because, despite the generally lower operational cost of renewable energy systems, the capital costs are still very high. However, with further technological developments related to renewable energy, the overall capital and water production costs associated with these resources will decrease (NRC 2008).

In some cases it may be feasible to treat cooling water to lower quality standards than required for drinking water to reduce treatment costs. Also, the combination of partial desalination with a saline cooling tower is another potential system configuration. Such systems have not been investigated in detail at this point, but they may have the potential to reduce costs in some specific instances by reducing treatment costs while increasing the number of achievable cycles of concentration in the cooling tower.

5.2 ENERGY CONSUMPTION

Numerous factors influence the energy consumption of any specific technology, including plant capacity; unit design; materials used; feedwater quality; location, labor, and maintenance; and concentrate disposal (Al-Karaghouli and Kazmerski 2013). Table 5 presents the reported average energy consumption of the main desalination processes. In general, the energy consumption associated with thermal methods (e.g., MSF, MED, and VC) is not

TABLE 4 Average Water Production Costs of the Main Desalination Processes

Type of Process	Type of Water	Cost of Water (U.S. $/m^3)
MSF		
23,000–528,000 m^3/day	Seawater	0.56–1.75
MED		
91,000–320,000 m^3/day	Seawater	0.52–1.01
12,000–55,000 m^3/day		0.95–1.5
Less than 100 m^3/day		2.0–8.0
VC		
30,000 m^3/day	Seawater	0.87–0.95
1,000 m^3/day		2.0–2.6
RO		
100,000–320,000 m^3/day	Seawater	0.45–0.66
15,000–60,000 m^3/day		0.48–1.62
1,000–4,800 m^3/day		0.7–1.72
RO		
Large capacity: 40,000 m^3/day	Brackish water	0.26–0.54
Medium: 20–1,200 m^3/day		0.78–1.33
Very small: few m^3/day		0.56–12.99
ED		
Large capacity	Brackish water	0.6
Small capacity		1.05

Source: Al-Karaghouli and Kazmerski (2013).

influenced by the salt concentration in the feedwater, whereas membrane processes (e.g., RO and ED) are highly influenced by the salinity of the feed brine.

For seawater applications, comparing the energy consumption of the most commonly used desalination processes (i.e., MSF, MED, and RO) reveals that the thermal methods require more energy than membrane processes. One of the primary reasons for this finding is the high energy need for water vaporization to run the MSF and MED processes. A second reason is continuous improvement in the technology of the RO process membrane, which has resulted in lower power consumption (Al-Karaghouli and Kazmerski 2013). When considering brackish-water desalination, the two most commonly used methods (i.e., RO and ED) are both membrane processes. In general, RO is considered to be more cost-effective when the TDS concentration is greater than 5,000 ppm; ED is more cost effective for TDS feed concentrations less than 5,000 ppm.

TABLE 5 Energy Consumption of the Main Desalination Processes

Properties	MSF	MED	MVC	TVC	RO, Saltwater	RO, Brackish	ED
Unit size (m^3/day)	50,000–70,000	5,000–15,000	100–3,000	10,000–30,000	<128,000	<98,000	2–145,000
Electrical energy consumption (kWh/m^3)	2.5–5	2–2.5	7–12	1.6–1.8	4–6 w/energy recovery	1.5–2.5	2.64–5.5
Thermal energy consumption (MJ/m^3)	190–282	145–230	None	227	None	None	None
Electrical-energy equivalent of thermal energy consumption (kW h/m^3)	15.83–23.5	12.2–19.1	None	14.5	None	None	None
Total electricity consumption (kWh/m^3)	19.58–27.25	14.45–21.35	7–12	16.26	4–6	1.5–2.5	2.64–5.5; 0.7–2.5 at low TDS
Product water quality (ppm TDS)	~10	~10	~10	~10	400–500	200–500	150–500

Source: Al-Karaghouli and Kazmerski (2013).

Overall, the energy costs of the primary thermal desalination methods (i.e., MSF, MED, and TVC) are estimated to be about 60% of water production costs. The main membrane desalination process (i.e., RO), which relies heavily on electrical energy, has associated energy costs of approximately 40% of the total water production costs. Thus, although these established technologies are relatively mature and generally efficient and reliable, opportunities do exist to improve the energy efficiency, overcome the operational limitation of a process, and reduce costs.

For thermal-based desalination, costs can be reduced by more effective use of low-grade and/or waste heat. The term low-grade heat is often used to describe heat energy that is available at relatively low (near-ambient) temperatures; waste heat, which may or may not be low-grade heat, contains energy that is released to the environment without being used. The location of low-grade or waste heat resources near the water consumers may act to reduce the cost of heat energy and offset the higher specific energy requirements of thermal desalination when compared to RO (NRC 2008). Currently, most of the largest desalination facilities in the world are dual-purpose facilities that produce both freshwater and electricity. However, the economics of co-location are highly location-specific, because they are highly dependent on local supply and demand for both water and energy (DOE 2014). Hybrid membrane-thermal desalination approaches offer additional operational flexibility and opportunities for water production cost

savings for facilities co-located with power plants. In addition, although thermal desalination technologies are themselves relatively mature, additional cost savings could be realized by improvements in system design (e.g., heat recovery units), materials (e.g., heat transfer surfaces), and process configuration (e.g., distributing of feedwater over the heat transfer surface) that can optimize low-grade and waste heat resources (NRC 2008).

For membrane-based desalination, the most significant improvements can be realized through enhanced pretreatment and the creation of fouling-resistant, high-flux (i.e., high-permeability) membranes that can operate at lower pressures. Improvements in concentrate management would have both cost and environmental implications (and are discussed further in Section 5.3).

5.3 CONCENTRATE, BLOWDOWN, AND RESIDUALS MANAGEMENT

All desalination processes produce a concentrated salt solution that may also contain naturally occurring elements from the source water along with some pretreatment and process residuals. In addition, saline cooling towers will concentrate the dissolved solids, necessitating the use of fewer cycles of concentration than conventional cooling towers, and will produce a significant quantity of blowdown that must be properly managed. The quantity and salinity of that discharge varies with the water source, plant type, and operational parameters. Management of the concentrate and residuals involves waste minimization, treatment, beneficial reuse, and disposal, and uses conventional concentrate management approaches, each of which has its own set of costs, benefits, environmental impacts, and limitations. In the United States, local and state regulations may present additional challenges and limit the concentrate management alternatives available at any individual site (NRC 2008).

There are limited data on the environmental effects of concentrate management practices, and available research has primarily been focused on seawater desalination plants, since they tend to be the largest desalination facilities found globally. The majority of desalination facilities in the United States, both in the number of plants and in total capacity, use brackish source water (NRC 2008).

In general, coastal desalination plants and saline cooling towers discharge their concentrate back into the ocean. Co-located plants can additionally utilize the existing power plant outfall systems to take advantage of dilution and mixing prior to discharge back into the ocean. Few, if any, cost-effective and environmentally sustainable concentrate management technologies have been developed for inland desalination facilities and saline cooling towers. Several methods are currently available for concentrate management (e.g., surface water discharge, sewer discharge, discharge to municipal wastewater treatment systems, deep-well injection, evaporation ponds, land application, and high-recovery/thermal evaporation systems to minimize the volume of waste produced), and each method has its own set of site-specific costs, benefits, regulatory requirements, environmental impacts, and limitations. Low- to moderate-cost inland disposal options can be limited by the salinity of the concentrate and by location and climate factors (NRC 2008). Thus, one of the best paths forward may be to improve recovery

ratios, as doing so would reduce the volume of brine requiring disposal. In general, deep-well injection is the most common disposal method for inland brines.

5.4 ENVIRONMENTAL ISSUES

In addition to the impacts from the management of waste products and concentrate from the desalination process, the environmental issues surrounding the use of saline water sources primarily include impacts from the acquisition of source water, issues with desalinated product waters, impacts on GHG emissions from these energy-intensive processes, and, in the case of saline cooling towers, drift (NRC 2008). Additional environmental effects and concerns (which are not addressed in this section) may be associated with plant construction, material use, potential releases to the air, disposal of used membranes, and socioeconomic considerations.

5.4.1 Source Water Acquisition

For each type of source water, there are distinct environmental considerations when that water is withdrawn. In coastal surface waters, issues of impingement and entrainment of marine organisms are paramount. Impingement, defined as the pinning and trapping of fish or other larger organisms against the screens of the intake structures, can cause severe injury and death to organisms. Entrainment occurs when intake pipes take in small aquatic organisms, including plankton, fish eggs, and larvae, with the intake water. Solutions to these problems include reducing intake during the times when eggs and larvae are abundant in the water; locating intake pipes in deeper parts of a water body where there are fewer organisms; reducing water intake volumes; and using rotating screens on intake structures (NRC 2008).

For inland aquifer systems, the sustainability and renewability of the resource is a significant issue. In terms of water quantity, groundwater withdrawals that exceed the recharge capacity of the aquifer may deplete the resource, create land subsidence, or affect the quality and quantity of adjacent or interconnected water bodies or aquifers. In relation to water quality, increased pumping can induce groundwater flow, which can lead to changes in water quality (e.g., changes to solute concentrations and ionic ratios) and the potential for chemical reactions and transformations with the aquifer matrix (e.g., ion exchange, dissolution, or precipitation) (NRC 2008). When brackish groundwater is being withdrawn from below a freshwater source, care must be taken to ensure that the deeper brackish water is not hydrologically connected to the freshwater aquifer, or drawdown of the freshwater aquifer can result.

5.4.2 Desalinated Product Water Quality

Because desalination processes employ advanced water treatment techniques, it is commonly assumed that desalinated water is devoid of contaminants. In reality, although desalination technologies remove various constituents to a large extent, not all constituents are fully removed, and some species are removed to a lesser extent than others. For example, in RO, a small fraction of ions, especially monovalent ions such as sodium and chloride, and dissolved

organic molecules (e.g., some pesticides or herbicides) can pass through to the permeate water. In general, desalinated product water quality depends on the raw water quality, the treatment technology used, and, for membrane technologies, the specific membranes employed and number of passes (NRC 2008).

Boron is one of the inorganic constituents associated with emerging water quality concerns in desalination. Boron is naturally present in the oceans and is a recognized micronutrient. However, at elevated levels boron may cause adverse health effects, although it is not regulated by the EPA with an enforceable drinking water standard. Current thermal desalination methods remove boron. For RO processes, the rejection of boron is dependent on the pH, with removal increasing with increasing pH. However, because traditional single-pass RO is operated at a low pH to avoid scaling, the majority of boron in the raw water is not removed. Implementation of a second pass through RO membranes, with a pH adjustment, has been proven to provide effective boron removal, but has not been routinely included in desalination projects because of significant cost implications (NRC 2008).

Bromide is another water quality consideration for membrane processes. Bromide is formed by the reaction between bromide and free chlorine, which is commonly used as a biocide to control biological growth in the intake and pretreatment systems for seawater desalination plants (NRC 2008). Bromide in its uncharged form (HOBr) passes through RO membranes, which is why it is found in the product water. If this product water is blended with water from other traditional sources (e.g., surface water) and treated to become drinking water, the bromide can be involved in the reaction between chlorine and natural organic matter to form brominated and mixed chloro-bromo disinfection by-products (e.g., trihalomethanes [THMs] or halogenated acetic acids [HAAs]), or it can react with ozone to form bromate (WHO 2009). These substances may have adverse human health effects and are regulated by the EPA under the Safe Drinking Water Act. To minimize disinfectant by-product formation, chlorine is generally used only intermittently during pretreatment, but in some cases of high organic loading, this may not be possible (NRC 2008). Alternately, chloramines (i.e., monochloramine [NH_2Cl]) can be used instead of chlorine because they have a lower tendency to react to produce regulated disinfection byproducts; however, the addition of monochloramine can make water more corrosive, which may lead to pipe corrosion and increased leaching of lead, copper, or other contaminants into the water (EPA 2009b).

5.4.3 Greenhouse Gas Emissions

Desalination is an energy-intensive process. For example, research has estimated that RO requires about 10 times more energy than traditional treatment of surface water (Cohen et al. 2004). Harto estimated that GHG emissions for desalinating extracted water would range from 4.2 kg CO_2e/m^3 of water produced for brackish water RO (10,000 ppm TDS) to 29 kg CO_2e/m^3 of water produced for multi-stage flash systems (Harto 2014). This would equate to adding between 8 and 55 kg CO_2e/MWh of emissions for a power plant consuming 1.9 m^3 of water per MWh (equivalent to 0.5 gal/kWh). Growing concern over anthropogenic climate change and GHG emissions has spurred interest in the use of alternative energy sources (e.g., nuclear, hydroelectric, wind, and solar) for desalination plants.

In general, the type of alternative energy source varies depending on location and local conditions. Current commercial applications of alternative energy sources to power desalination plants remain somewhat limited, but technologies and practical applications are continuing to grow and develop. The direct use of concentrated solar and low-temperature geothermal resources for desalination is of particular interest, due to the potential for the use of lower grade resources. In addition, the use of wellhead pressure resulting from the extraction of water from CO_2-pressurized deep saline aquifers has been investigated for the potential to reduce the cost and energy consumption of a RO system (Bourcier et al. 2011).

5.4.4 Drift

A large concern for systems using saline and brackish cooling towers is the potential for saline drift to impact nearby vegetative species, such as crops. Several field studies conducted in the late 1970s on crops, such as tobacco, corn, and soybeans, simulated aerosol deposition of water from brackish cooling towers in order to better understand the associated impact of drift on these species (Mulchi and Armbruster 1981, 1983). The studies used several different kinds of salts and several different rates of deposition. The results were then compared with real-world results from a dozen monitoring sites ranging from 1.6 to 9.6 km away from a natural-draft cooling tower using brackish water in Chalk Point, Maryland.

The studies found "no foliar injury symptoms associated with salt deposition in either the simulated drift experiments or the cooling tower monitoring program" for the tobacco plants (Mulchi and Armbruster 1983). However, soybeans and corn did exhibit some symptoms as a result of the drift (Mulchi and Armbruster 1981). Soybeans exhibited sensitivity early on in their growing cycle; however, symptoms in the corn were more pronounced as the plants matured. In addition, yields associated with the corn crops were more negatively impacted by the drift than were soybean yields. These studies show that the effects of drift on nearby vegetation are important if a brackish or saline cooling tower is being considered. If the location of the proposed plant is in a coastal area, it is likely that local vegetation has already adapted to saline spray from the ocean and is salt-tolerant, such that a slight increase from saline drift from the cooling tower is unlikely to be substantially impactful (Maulbetsch and DiFilippo 2008). Background atmospheric assessments are, therefore, very important before the construction of these kinds of facilities (Maulbetsch and DiFilippo 2008).

Also, just as drift can negatively impact vegetation, it also has the potential to similarly impact site infrastructure. Material selection for construction and support components surrounding such cooling towers is critical to avoid corrosion and resulting structural instability of these components. On a site visit to the St. Johns River Power Park in Jacksonville, Florida, in March 2006, the CEC team found extensive corrosion on unprotected metal surfaces, such as handrails, stairways, piping, and roofs (Maulbetsch and DiFilippo 2008). Corrosion of concrete and embedded rebar was also a critical issue. Similar impacts were found during later site visits to the Smith Electric Generation Plant in Lynn Haven, Florida, the Watson Electric Generating Plant in Gulfport, Mississippi, and several other interviewed facilities (Maulbetsch and DiFilippo 2008). These drift deposition effects will entail higher costs for cleaning, protection, and repair of site infrastructure, equipment, structures, and surfaces in the vicinity of the cooling

tower, contributing to the overall cost increase of these kinds of technology over traditional cooling towers (Maulbetsch and DiFilippo 2008).

6 DECISION FACTORS

A large number of factors will play into the decision-making process in selecting a cooling technology and water source for future power plants. Ultimately, the decision will be driven by the economics and resource availability. In general, if freshwater is physically, politically, and economically available in the area, it is still almost certainly going to be selected as first choice. However, as discussed in the introduction, a number of factors are likely to reduce the number of locations where that is an option in the future. The second choice is likely to be reclaimed water. A full 25% of currently proposed power plants are expected to use this source. While the use of reclaimed water does not reduce the physical consumption of freshwater, it can often be more easily implemented from a water rights standpoint in areas with limited freshwater availability. However, if no freshwater sources are available, the technology options are typically limited to the use of saline water sources or dry cooling.

Although dry cooling systems are not directly discussed in detail in this report, they are considered the primary competition for the use of saline water sources. A number of factors will determine if it is more advantageous to utilize dry cooling or saline water sources, and further, if saline water sources are preferred, whether to use saline sources directly versus treatment and use in conventional cooling towers. Dry cooling systems have an advantage in that they are relatively simple to design and operate and they can be placed almost anywhere. However, they have a number of drawbacks, which include higher capital costs and significant energy penalties compared with conventional wet cooling towers. The energy penalty for dry cooling can range from 4 to 16% for a coal power plant (DOE 2014). In general, the hotter the climate, the greater the energy penalty associated with dry cooling. Unfortunately, hot areas are also often dry areas, so dry cooling may suffer the greatest penalties in many of the areas where it is most needed.

The most important factor in the use of saline water sources is the quality of the water. Higher-quality (lower-TDS) waters allow for greater numbers of cycles of concentration in a saline cooling tower, or for higher recovery rates for water treatment, which will improve the economics. The availability of disposal options for blowdown or concentrate from treatment is one absolutely necessary consideration. If there are no viable disposal options for these waste streams in a specific location, then the use of saline sources is not going to be viable either. In selecting between the use of saline cooling towers and water treatment, the energy penalty of the cooling tower versus the energy cost of treatment must be considered. Further, the increased capital cost of saline cooling towers must be weighed against the capital costs of a water treatment system. The impact of salt drift from saline cooling towers must also be considered. It can impact both maintenance of the power plant and downwind structures and can have downwind ecological impacts, depending on the location.

In general, the use of saline water sources is likely to be more complex than the use of dry cooling systems, although the economics are unclear and site-specific. Areas with more moderate climates will tend to favor dry cooling, while warmer climates will tend to favor the use of saline sources. In areas with higher-quality brackish water (TDS under 10,000 ppm), the economics will be shifted toward saline sources, while in non-coastal areas with more saline water sources (TDS over 35,000 ppm), the economics will be shifted toward dry cooling. While

some general rules of thumb as discussed above can limit the decision space, the development and integration of detailed economic models would allow for relatively rapid economic evaluation of all cooling options based upon site-specific parameters.

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Environmental Science Division
Argonne National Laboratory
9700 South Cass Avenue, Bldg. 240
Argonne, IL 60439-4847

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