Treatment of brackish water for fossil power plant cooling

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ABSTRACT

This study evaluates the technical, economic, and environmental impacts from retrofitting treated brackish groundwater to reduce freshwater consumption for wet cooling towers at existing coal- and gas-fired electric generating units (EGUs). Based on fleet averages, retrofitting brackish water treatment decreases unit freshwater consumption by 94–100%, while increasing the cost of electricity generation by 8–10%. The unit capacity shortfalls are less than 1.1%. The resulting cost of freshwater consumption savings by brackish water treatment is \$1.7/m^3 and \$2.9/m^3 on average for coal- and gas-fired EGUs, respectively. However, these tradeoffs are highly affected by the brine disposal method. The addition of thermal zero liquid discharge for brine disposal can roughly double the average cost of freshwater consumption savings. The cost-effectiveness of brackish water treatment relative to dry cooling deployment depends on how concentrated brines are managed. The identified tradeoffs and their dependence fill knowledge gaps to better inform water management.

KEYWORDS: Brackish water, wet cooling towers, retrofits, freshwater consumption, cost, capacity shortfalls, and dry cooling.

Introduction

In the United States (U.S.), the thermoelectric power sector accounts for approximately 40% of the total freshwater withdrawals, mainly for wet cooling systems[1]. More than 61% of the U.S. thermoelectric generating capacity uses wet recirculating cooling systems[2], which are the largest water consumers at fossil fuel power plants[3]. Freshwater availability affects thermoelectric power generation, particularly in water-stressed regions[4]. Increasing droughts and climate change can reduce freshwater availability, exacerbate water scarcity, and pose high water risks for thermoelectric power plants in the western U.S.[5,6]. Without a sufficient supply of desired water, electric power generators will likely suffer from power production curtailment or even complete shutdown[7]. To alleviate such adverse impacts from freshwater shortages, the thermoelectric power industry needs to expand water supplies and explore alternative freshwater-saving options. Among these options are advanced cooling systems. Although dry cooling can significantly reduce consumptive freshwater use relative to wet recirculating cooling, it can decrease the net generating capacity of power plants and increase the cost of electricity generation[8-10]. The tradeoffs in water savings, cost, and capacity shortfalls from dry cooling deployment depend on power plant attributes and local climate conditions[8]. In addition to advanced cooling technologies, use of non-traditional water sources is another option to reduce freshwater use, including reclaimed water, brackish groundwater, produced water from oil and gas extraction, and extracted formation water from carbon dioxide storage in saline reservoirs[11-14].

Although use of non-traditional water sources is attractive, it is constrained by quantity and quality reliability[11]. Thus, incorporating non-traditional water into existing power plants requires a thorough supply assessment of both water quantity and quality. Existing studies indicate that treated municipal wastewater is a reliable source for fossil power plant cooling in many locations and it has been reused by electric utilities in practice[11,13,15,16]. In contrast, much less attention has been paid to other non-traditional sources. Abundant brackish water stored in U.S. aquifers is available for use for hundreds of years but is underutilized[4,17]. A recent study highlights the significant potential to use brackish groundwater at thermoelectric power plants in the southwestern U.S.[18].

Treated brackish groundwater can be used as makeup water for wet cooling systems to reduce freshwater use, which can limit the exposure of thermoelectric power generation to drought and climate risks[19]. Prior to use, however, brackish groundwater must be desalinated to remove excess dissolved salts and minerals. Desalination is often energy intensive and produces concentrated brines, which increase environmental impacts[20-22]. Brine discharges are regulated by effluent guidelines or discharge standards[23,24]. Traditional brine disposal methods include sewer discharge, evaporation ponds, deep-well injection, and others[25]. To minimize environmental impacts and increase water recovery, zero liquid discharge (ZLD) is a critical method for brine disposal[26]. However, ZLD is highly energy- and cost-intensive. The power required for evaporation and crystallization in a ZLD system falls within a range of 15 to 25 kWh and 50 to 70 kWh per cubic meter of feed brine, respectively[26], while the total disposal cost is approximately $1.1 per cubic meter of concentrate recovered[27]. In addition to thermal-based ZLD technologies, membrane-based technologies are emerging as alternative ZLD options[28].

Retrofit studies on treatment of brackish water for fossil power plant cooling are very limited in the literature. A scoping-level assessment indicates the feasibility of retrofitting existing thermoelectric power plants with brackish groundwater, but it lacks detailed studies of brackish water desalination fitted with power plant attributes[19]. There is a critical gap in current knowledge; namely, the lack of a comprehensive understanding of the potential freshwater savings, associated costs, and generation capacity shortfalls from implementation of brackish water desalination at the plant and fleet levels. Deployment of ZLD for brine disposal could further result in significant reductions in net generating capacity and substantial increases in electricity generation cost. The tradeoffs in major metrics may vary with power plant attributes and desalination design, but the literature currently lacks a quantitative assessment. While reducing freshwater use for power plant cooling, the cost-effectiveness of brackish water desalination relative to dry cooling deployment also remains unknown.

This study aims to fill current knowledge gaps in support of non-traditional water resource planning and the electric power industry's water decision- and policy-making. The major objectives, therefore, are to (1) assess brackish water resources and estimate the freshwater savings from treatment of brackish water for fossil power plant cooling, (2) evaluate the cost-effectiveness of brackish water treatment retrofits and associated shortfalls in net generating capacity of power plants, and (3) compare the cost-effectiveness of consumptive freshwater savings by treating brackish water for use in wet recirculating cooling towers, with dry cooling deployment at both the electric generating unit (EGU) and fleet levels. Overall, this study seeks to demonstrate the tradeoffs in freshwater savings, cost, and capacity shortfalls from deployment of brackish water treatment and then explore their dependence on key factors, such as how to dispose of concentrated brines from brackish water desalination. To achieve this goal, case studies of brackish water treatment retrofits are performed at existing fossil fuel-fired EGUs currently equipped with wet cooling towers in two western U.S. states: Arizona (AZ) and New Mexico (NM). This is part of a multi-year effort that comparatively evaluates dry cooling and the use of treated, non-traditional water sources for fossil power plant cooling under a common framework and better informs water management decisions and policies for the electric power sector, especially in water-stressed regions[8].

Current water desalination technologies

Brackish water often contains total dissolved solids (TDS) with a range from 1,000 to 10,000 milligrams per liter (mg/L). Today, there are two major categories of commercial technologies for brackish water desalination: thermal and membrane desalination[22,29]. Thermal technologies mainly include multi-stage flash distillation (MSF), multiple-effect distillation (MED), and vapor compression (VC), while membrane technologies mainly include reverse osmosis (RO) and electrodialysis (ED). Some emerging but not commercialized technologies include forward osmosis, membrane distillation, and capacitive deionization[22,30,31]. Thermal desalination is often employed for applications with high salt concentrations, though the selection of desalination technology also depends on other site-specific factors (e.g., energy penalty and cost). Among these technologies, RO is the most appropriate desalination technology in terms of market share. RO accounted for approximately 70% of the total installed capacity in 2005 and 90% of the total operating capacity in 2019 in the U.S.[32-34].

Table 1 summarizes the technical and economic metrics of major desalination technologies, which ensembles data from the literature. MSF requires both thermal and electrical energy for the distillation process with a recovery rate of 25–50%[26,35]. Compared to MSF, MED can achieve a higher recovery rate and consume less energy with a lower cost of water treatment[13,35]. There are two types of VC: mechanical vapor compression (MVC) using electricity and thermal vapor compression (TVC) using thermal energy. MVC is the state-of-the-art technology for brine concentration. TVC often has a larger production capacity than MVC[35]. In general, VC is more energy efficient but less cost efficient than other thermal technologies[13,30,35,36]. Compared to thermal desalination, membrane desalination not only is applicable for a broader range of water production capacity but also consumes less energy with a higher recovery rate[13,27,30,35]. RO is also more appropriate for feed brackish water with lower TDS concentrations. Both RO and ED can recover 50–90% of brackish water. Membrane desalination also has a lower cost of water treatment. As a comparative exercise, RO is applicable for broader ranges of water production capacity and feed TDS but consumes less energy. ED is most suitable for brackish water with a feed TDS of less than 3,500 ppm[30]. Typically, the cost of water treatment by RO processes is less than ED processes. All these comparative results clearly indicate that RO is the most appropriate desalination technology for brackish water in terms of major technical and economic metrics.

Results

This study starts by evaluating brackish water resources and then brackish water desalination at the process level. When conducting the unit-level retrofit analysis, base case studies evaluate the technical and economic effects from deployment of brackish water treatment on existing EGUs, while parametric analyses reveal the sensitivity of major performance and cost results to several key factors (see Supplementary Table 1 for the defined scenarios). This study further compares the energy penalty and cost-effectiveness of consumptive freshwater savings by brackish water desalination against dry cooling deployment, on the electric generating units of interest.

Brackish water resource assessment

This study establishes a comprehensive understanding of brackish water resources in AZ and NM, including location and availability, water quality and composition, and ownership rights. Fig. 1a indicates that there is spatial variability in annual availability of brackish water resources in the two states. Fig. 1b shows that the average TDS concentration at the Hydraulic Unit Code 8 (HUC-8) falls within the range of 1080–5216 mg/L with an average of 2097 mg/L in AZ and within the range of 1070–6491 mg/L with an average of 2679 mg/L in NM. Fig. 1c shows that the pH of brackish water falls within the range of 6–9 with an average of 7.5. For cooling applications, the pH needs to be constrained within the range of 6.7–7.2 without scale inhibitor and 7.8–8.4 with scale inhibitor[54]. Thus, small pH adjustments are required for brackish water at some HUC-8 areas. As shown in Fig. 1d, the brackish water temperature varies within the range of 15–41 °C in AZ and of 7–44 °C in NM. When the brackish water temperature in a HUC-8 area is more than 30 °C, however, it is not considered as makeup water for wet cooling towers at power plants located in the same region. In addition, the average concentrations of major cations and anions at the HUC-8 level are shown in Supplementary Fig. 1.

Beneficial use of brackish water is under the groundwater regulation in AZ. Starting in 2009[55-57], the use of deep water requires a permit from the State Engineer in NM. The owner of non-exempt wells in registration for industrial use is regarded as the holder of groundwater rights. Thus, the owners of the selected power plants have groundwater rights. Resource adequacy is evaluated conservatively with large water demands assumed for power plants. The annual brackish water requirements for fossil power plant cooling are estimated based on a high capacity factor (80%) for the selected power plants that are also shown in Fig. 1a. Supplementary Table 2 reports the annual water requirements for power plant cooling and the available brackish water at the HUC-8 level. There is sufficient desired brackish water available for wet cooling towers at the selected power plants, except for one plant in AZ and one plant in NM where the brackish water temperature is higher than 30 ^{o}C. The feasibility of using brackish groundwater in excess of 30 ^{o}C will be explored further in future work. The retrofit analysis discussed later focuses on those plants supplied with the desired quality of brackish water for a total capacity of approximately 8 GW.

Process-level performance and cost of water desalination

This section only considers the process in isolation, rather than the process as a retrofit.

The process performance and cost models were applied to determine the energy penalty, brine discharges, and cost of brackish water treatment while producing the desired quality of water for power plant cooling. The process performance is evaluated based on the quantity and quality of brackish water available for each selected power plant (shown in Fig. 1a,b,c,d and Supplementary Fig. 1), whereas the treatment cost is estimated based on the financial and economic assumptions given in Supplementary Table 3 and Supplementary Table 4 plus common assumptions of capacity factor (80%), project book lifetime (30 years, or remaining useful life of the plant, as the situation warrants), and electricity market price ($63/MWh on average for prices in the past five years in AZ)[58]. The process-level analysis was performed on an annual basis in terms of the time resolution of available data, though the variation in feedwater quality on a daily or monthly basis may affect the operating cost.

The specific energy consumption of brackish water treatment alone (not including deep-well pump energy) varies from approximately 0.5 to 0.7 kWh/m^3, which falls within the range reported in Table 1. As shown in Fig. 1e, the energy penalty generally increases when the feed TDS increases, which affects the applied pressure of RO. In the treatment process, both RO and ion-exchange steps consume electricity, which account for 72–84% and 16–28% of the total energy penalty, respectively. After the desalination, the TDS in concentrated brines increases by 3 to 6 times relative to the feed TDS, with details shown in Supplementary Fig. 2. The cost of water treatment alone (not including the deep-well pumping energy cost) varies from $0.72 to $1.67 per cubic meter, of which the ion-exchange step accounts for 31–61% due to its high variable cost for sodium chloride used to regenerate the ion-exchange resin. The specific energy consumption and cost of brackish water treatment plus brackish water well pumping are 2.1–3.7 kWh/m^3 and 0.84–1.8 $\$/m^3$, respectively, as shown in Supplementary Fig. 3.

In general, our treatment cost estimates are comparable to those reported for RO in Table 1, except for the case with the lowest water production capacity. As demonstrated in Fig. 1f, the water treatment cost is sensitive to water production capacity, which implies that a large water treatment system serving multiple end-users would lower the overall water treatment cost. We further compared our cost estimates with a new RO-based brackish water treatment study on the Kay Bailey Hutchison Desalination Plant and the Eastern Municipal Water District Desalters[37]. To avoid biased comparisons as much as possible, our performance and cost models were fed with the same production capacity, capacity factor, and project lifetime as those of the two desalination plants, respectively. As summarized in Supplementary Table 7, our overall desalination treatment cost estimates are also comparable to those reported costs. However, the specific cost distributions from our study and the literature, as shown in Supplementary Fig. 4, differ due to treatment technology and feedwater composition.

The overall cost of brackish water treatment is characterized by cost type. Supplementary Fig. 5 shows the cost distribution by cost type on capacity-weighted average for the selected fleet. The non-electricity VOM accounts for 39% of the total water treatment cost on the fleet average, in which the cost of ion-exchange regenerant accounts for 81%. Thus, we did an additional parametric analysis, which reveals that when the sodium chloride price varies from \$50 to \$200 per metric ton[59-61], the resulting average cost of water treatment ranges from \$0.98–1.4 per cubic meter, as shown in Supplementary Fig. 6. Please note that selection of pretreatment technologies is highly dependent on location or feedwater composition and can vary by location.

Base retrofit analysis of brackish water desalination

We first evaluate existing EGUs (see Supplementary Table 8 for unit details) prior to brackish water treatment retrofits. Fig. 2a shows the freshwater consumption by EGU and Fig. 2c shows the levelized cost of electricity (LCOE) by EGU, which excludes sunk capital costs and reflects only the O&M costs, including fuel costs. There is variability by EGU in these results, which is mainly driven by differences in unit attributes and climate conditions, as well as flue gas desulfurization (FGD) type for coal-fired EGUs[8]. Makeup water is still needed for wet FGD systems in this analysis.

When the EGUs are retrofitted to include newly constructed brackish water treatment systems, the size or water production capacity of a treatment system is determined in terms of the amount of makeup water required for wet cooling towers for each EGU. In the base cases, there is no ZLD for brine disposal. The performance and cost of each retrofitted EGU are evaluated based on unit-specific attributes and the quality of brackish water available for each EGU. Fig. 2a also shows the freshwater consumption by retrofitted EGU. Deployment of brackish water treatment can decrease the freshwater consumption by 94% on average for coal-fired EGUs and 100% for gas-fired EGUs. Freshwater is still consumed for wet FGD systems at four coal-fired EGUs. Fig. 2b shows the additional parasitic load from deployment of brackish water treatment, which accounts for 0.3–1.1% of the nameplate capacity for all EGUs. The total parasitic load from brackish water treatment would result in total reductions of 43.9 MW in the regional net capacity. Without ZLD for brine disposal, deployment of brackish water treatment does not substantially decrease the net generating capacity of existing EGUs; however, it does increase the LCOE. Fig. 2c also shows the LCOE of each retrofitted EGU. Implementation of brackish water treatment increases the LCOE by 5.5–17% with an average of 9% for all EGUs.

Fig. 2d presents the cost of freshwater consumption savings by brackish water treatment for each EGU. The cost of freshwater consumption savings ranges from \$1.5 to 2.2/m^3 for coal-fired EGUs with a capacity-weighted average of \$1.7/m^3, and \$1.8 to \$8.0/m^3 for gas-fired EGUs with a capacity-weighted average of \$2.9/m^3. This cost metric varies with unit attributes, especially capacity factor. As illustrated in Supplementary Fig. 7, the cost of consumptive freshwater savings decreases when the unit nameplate capacity and capacity factor increase, especially for natural gas combined cycle (NGCC) units. For example, a low capacity factor leads to the higher cost of freshwater consumption savings for N1 and N8 units than other units.

We further conducted multivariable regression analysis for major parameters to explore the key factors that affect the overall cost for freshwater savings. As detailed in Supplementary Table 9, capacity factor and water production capacity are the key parameters that influence the cost of freshwater consumption savings.

Sensitivity analysis of desalination retrofits

The type of RO element may affect the desalination performance. To limit brine discharges, ZLD can be employed but is intensive with power use and investment. The cost of freshwater consumption savings is also affected by the capacity factor of retrofitted EGUs. Thus, we further perform parametric analyses to examine the sensitivity of major techno-economic results to these factors. In each analysis, other parameters were kept at the base case values given in Supplementary Table 3 and Supplementary Table 4 unless otherwise noted.

RO element type. RO elements (or modules) are commercially available products configured by semipermeable membranes with a large packing surface area[26]. The base case studies use the Eco Pro 400i RO elements for brackish water treatment. We further evaluate two additional types of spiral-wound RO elements: BW30-400 and XLE-440. Supplementary Table 10 comparatively summarizes their major properties and operating conditions. In general, the three types of RO elements have similar properties and operating conditions, with the exception of the BW30-400 RO element, which has the lowest flux coefficients. Thus, Supplementary Fig. 8a shows that the alternative cases using the Eco Pro 400i RO elements have larger energy requirements for brackish water desalination than the cases using the Eco Pro400i and XLE-440 elements. However, Supplementary Fig. 8b also shows that the three retrofit cases that employ different types of RO elements have a similar overall cost of freshwater consumption savings on average, mainly because the parasitic load of brackish water desalination without ZLD is low and less than 1.2% of the nameplate capacity at the EGU level.

Capacity factor. Capacity factor is a key parameter affecting the cost of freshwater consumption savings[8]. An increase in capacity factor can lower the cost of freshwater consumption savings, and vice versa. Fig. 3 shows the effect of changes in capacity factor relative to the base case value highlighted in black for each retrofitted EGU. In the base cases, the capacity factor of coal-fired EGUs is higher than 45%, whereas that of gas-fired EGUs is lower than 45%. Decreasing the capacity factor from the base case values to 45% would increase the cost of freshwater consumption savings for coal-fired EGUs, while increasing it from the base case values to 85% would significantly lower the cost of freshwater consumption savings for all gas-fired EGUs. When old power plants in an existing fleet retire, some remaining plants might be utilized more while providing reliable electricity to meet the power demand. Such increased utilization may offset the added LCOE for deployment of brackish water desalination and greatly improve the retrofit viability.

ZLD for brine disposal. In the base cases, brackish water desalination is retrofitted to recover 75% water without ZLD for brine disposal. To meet increasingly stringent environmental regulations and minimize environmental impacts, ZLD can be employed for brine disposal in lieu of low-cost sewer discharge disposal. The flow rate and TDS of feed brines affect the performance and cost of a ZLD process so that the water recovery rate by RO upstream has tradeoff effects between brackish water treatment and ZLD. When the water recovery rate by RO increases from 75% to 90%, antiscalant needs to be added to maintain silica solubility at a level of approximately 350 ppm for membrane scaling control based on an experimental study[62]. We evaluated brackish water treatment with ZLD at two water recovery levels: 75% (base case) and 90%. Supplementary Fig. 9 shows the process diagrams of brackish water treatment with ZLD for brine disposal. The ZLD process includes brine concentration and crystallization and disposes of brines from both RO and ion-exchange subsystems. Mechanical vapor compression for brine concentration followed by a thermal crystallizer is the typical approach employed widely throughout the world for achieving ZLD[63,64]. Supplementary Table 11 and Supplementary Fig. 10 summarize the performance and cost of the ZLD system[26], respectively.

Fig. 4a comparatively presents the parasitic load and added LCOE for retrofits of brackish water treatment systems without and with ZLD for brine disposal. The 75% RO water recovery scenario has the feed brine flow rate of 75–496 m^3/h with the feed TDS of 7.3–17.4 g/l, while the ~90% RO water recovery scenario decreases the feed brine flow rate to 32–239 m^3/h and raises the feed TDS to 13.5–30.8 g/l. The ZLD system alone can recover 99.5% of freshwater from the brines. Increasing the brackish water recovery rate by RO would decrease the volume of brine entering the ZLD system, which in turn reduces the parasitic load and cost for brine disposal; reducing the amount of brine that goes to the ZLD section of the system is critical due to its high energy intensity relative to RO. The parasitic load for the 75% and ~90% RO water recovery scenarios with ZLD accounts for 1.4–4.2% and 0.8–2.4% of the nameplate capacity or the annual reduction in regional net capacities of 205 and 109 MW, respectively. Furthermore, retrofits of brackish water desalination with ZLD would increase the unit LCOE by 21–49% for the 75% RO water recovery scenario and 13–32% for the ~90% RO water recovery scenario. The resulting cost of freshwater consumption savings reaches \$2.7–4.2/m^3 for coal-fired EGUs and \$4.4–14.6/m^3 for gas-fired EGUs for the 75% RO water recovery scenario. It reaches \$2.2–3.4/m^3 for coal-fired EGUs and \$3.2–11.9/m^3 for gas-fired EGUs for the ~90% RO water recovery scenario. Compared to the base retrofit cases, the addition of ZLD to brackish water treatment systems increases the cost of freshwater consumption savings by 76–165% for the 75% RO water recovery scenario and 44–106% for the ~90% RO water recovery scenario, exemplifying the significance of reducing brine volumes treated by the brine concentrator and crystallizer. Implementation of ZLD also sizably decreases the net generating capacity and notably increases the cost of electricity generation.

We further develop the supply curves for brackish water desalination without and with ZLD, which show the relationship between the cost of freshwater consumption savings and the corresponding cumulative capacity. Fig. 4b demonstrates the supply curves for the existing fleet in AZ and NM including all selected gas- and coal-fired EGUs, which comparatively depict the cumulative capacity at each cost level. While limiting brine discharges, ZLD deployment can significantly increase the retrofit cost of brackish water treatment systems and result in pronounced effects on the power plant performance and cost.

Comparisons between different water-saving options

Dry cooling or use of non-traditional water in wet cooling systems can be applied to reduce freshwater consumption for fossil power plant cooling in water-stressed regions. However, their broad deployment on existing power plants can decrease net generating capacity and increase electricity generation cost. The tradeoffs in these key metrics vary with power plant attributes and climate conditions. To avoid biased assessments or decisions, it is important to compare these tradeoffs among alternative freshwater-saving options under a common power plant assessment framework in support of water management decisions. The Integrated Environmental Control Model (IECM) based common framework was employed to investigate the deployment of dry cooling in comparison with brackish water desalination for use in wet cooling towers, for identical EGUs[8].

Without ZLD for brine disposal, the parasitic loads of brackish water treatment systems are less than those from dry cooling deployment (0.8–2.3% of the gross capacity in megawatt, MWg)[8]. The use of treated brackish water would increase the baseline unit LCOE by 9% on average for all the selected EGUs, which is also less than the 15% from dry cooling deployment[8]. However, the addition of ZLD to brackish water treatment systems would increase both the energy penalty and LCOE, which are even higher on average than those from dry cooling deployment, depending on the brackish water recovery rate.

Fig. 5 further compares the cost of freshwater consumption savings between brackish water desalination and dry cooling deployment on each EGU for the scenarios without and with ZLD. As shown in Fig. 5a, the cost of freshwater consumption savings by brackish water desalination with 75% water recovery by RO is \$1.7/m^3 on capacity-weighted average for coal-fired EGUs and \$2.9/m^3 on capacity-weighted average for gas-fired EGUs, which are approximately 34% and 52% less than those by dry cooling deployment, respectively.

For the retrofit cases with ZLD, the comparative analysis accounts for two levels of brackish water recovery by RO: 75% and ~90%. It turns out that the cost of freshwater consumption savings by brackish water desalination with ZLD is similar to or even higher than that by dry cooling deployment. As shown in Fig. 5b and Fig. 5c, the costs of freshwater consumption savings by brackish water desalination with ZLD are \$3.5/m^3 and \$2.8/m^3 on capacity-weighted average for coal-fired EGUs for the 75% and ~90% RO water recovery scenarios, respectively. For gas-fired EGUs, they are \$6.6/m^3 and \$5.3/m^3 on capacity-weighted average for the 75% and ~90% RO water recovery scenarios, respectively. Thus, the choice of freshwater savings between brackish water desalination and dry cooling deployment highly depends on how the concentrated brines are handled.

Discussion

Increasing droughts and climate change threaten freshwater supplies, decrease freshwater availability, and increase competition for freshwater resources among various economic sectors, especially in water-stressed regions with rapid population and economic growth. Limited availability of freshwater for thermoelectric cooling in water-stressed regions would drive power plant operators to explore alternative water sources. While transitioning to a low-carbon energy future, carbon capture and storage is a key option for deeply reducing carbon dioxide emissions from fossil fuel-fired power plants but its deployment would nearly double consumptive water use[3]. Non-traditional water sources can be deployed to cope with climate-induced water risks and tackle the increasing water demand for decarbonization of fossil fuel-fired power plants. This study reveals the trade-offs in freshwater savings, capacity factor shortfalls, and cost of electricity generation from deployment of non-traditional water sources at existing fossil fuel-fired power plants in support of climate change adaptation and energy transition.

Thermoelectric generation often requires an abundant reliable source of water for wet cooling. The amount of brackish groundwater available in the U.S. is more than 35 times that of fresh groundwater so that brackish groundwater is a substantial source for potential use[17]. Treatment of brackish groundwater for thermoelectric generation cooling can help to alleviate potential competition for freshwater resources between the power sector and other sectors in water-stressed regions. Our resource adequacy assessment reveals the technical feasibility of such an application.

Treatment of brackish groundwater through RO can improve the water quality to the level required for wet cooling tower makeup water. While significantly reducing freshwater use, retrofits of brackish water treatment systems at existing fossil fuel-fired power plants using wet cooling towers can affect the net generating capacity and cost of electricity generation—this impact highly depends on how the concentrated brines are managed. There are tradeoffs from brackish water treatment in freshwater savings, cost, and net capacity shortfalls. The overall cost of freshwater consumption savings by brackish water treatment without ZLD is \$1.7/m^3 and \$2.9/m^3 on capacity-weighted average for coal- and gas-fired EGUs, respectively. As shown in Supplementary Fig. 7, this economic metric correlates with capacity factor and nameplate capacity, especially for NGCC units. In particular, improvements in the utilization of retrofitted EGUs can improve the economic viability of brackish water treatment. However, as discussed above, deployment of current commercial ZLD technology can substantially increase the cost of consumptive freshwater savings while limiting brine discharges. Thus, there is a critical need for advancing ZLD systems to enhance the economic viability of large-scale applications. If additional freshwater and salts recovered by ZLD are sold as by-products, these revenues can help to decrease the added cost for ZLD.

Deployment of treated brackish water as makeup for wet cooling towers has tradeoff effects at a regional level. Fig. 4b and Supplementary Fig. 11 show “supply curves” for three different brackish water treatment scenarios at a regional level. For any scenario, the cost of freshwater consumption savings improves with the cumulative nameplate capacity and cumulative annual water savings. As shown in Fig. 4b, 85% of the selected regional capacity in the base case (75% brackish water recovery by RO without ZLD) has a cost of freshwater consumption savings of less than $2.8/m^3, corresponding to a 95% reduction in regional freshwater consumption by these plants (Supplementary Fig. 11a) and just a 1% reduction in regional net capacity (Supplementary Fig. 11b). However, the addition of ZLD for brine disposal would significantly increase the cost of freshwater consumption savings and the regional capacity shortfalls relative to the scenario without ZLD.

Although deployment of both dry cooling and brackish water treatment can significantly reduce freshwater use for cooling systems, the magnitude of their effects on the net generating capacity and cost of electricity generation of EGUs is different, which also highly depends on how the concentrated brines are managed. Without ZLD for brine disposal, treatment of brackish water for power plant cooling produces a lower cost of freshwater use savings and energy penalty than dry cooling deployment. With ZLD for brine disposal, however, brackish water desalination is more intensive on average.

Reuse of non-traditional water sources for thermoelectric generation cooling is one of the strategies to address water scarcity and secure energy production. In addition to brackish water, treated municipal wastewater and produced water from oil and gas extraction and carbon dioxide storage reservoirs are also alternative options to reduce freshwater use for wet cooling systems. To support planning and decision-making on these alternative resources, a multi-criteria assessment should be made under a common framework, which accounts for not only water availability and quality but also these tradeoffs in technical, economic, and environmental impacts from deployment of non-traditional water sources. Additionally, extraction of groundwater should be accounted for since many aquifers are already over-pumped, especially in water-scarce regions. Thus, planning treated brackish water for thermoelectric power plant cooling should avoid overexploitation of aquifers[65]. An integrated resource assessment can identify sustainable pathways to cope with increasing pressures on freshwater resources and better inform water resources planning and management. A new paradigm for close partnerships between water and electric power stakeholders should also be established to secure electric power generation in a sustainable manner. Potential new public or private programming on legal and administrative issues can somewhat increase the marginal cost of retrofit projects, which are empirically estimated to be on the order of 10% of the capital expenditure.

There are potential opportunity costs from economically inefficient allocations of water (e.g., lost generation due to insufficient water supplies and increased costs due to falling groundwater levels) unless the cost of curtailment is borne by the stakeholder investing in the retrofit. Opportunity costs depend on how much users value end-uses expected to be met by the estimated water saved. Opportunity costs could sweeten the decision to retrofit if new potential users are willing to pay more (e.g., value it more) than current users. These costs can be considered while estimating the true of water, which takes into account social benefits.

Methods

This study first assesses brackish groundwater resources in the region of interest: AZ and NM. It determines the adequacy of resources for power plant cooling. Given that RO is typically the most appropriate technology for conventional water desalination, treatment of brackish groundwater through RO for use in wet cooling towers is the strategy of this study for reducing freshwater consumption at existing fossil fuel power plants. The Water Application Value Engine (WAVE), an industrial water-treatment modeling tool developed by DuPont™[66], is employed for integration with newly developed engineering-economic models to evaluate the performance and cost of RO-based desalination processes for brackish water treatment. To quantify the effects of brackish water treatment retrofits on power plant performance and cost, the process-level techno-economic models of RO-based desalination are further coupled with a power plant modeling tool. The retrofit analysis of brackish water treatment systems is conducted on an annual basis at an EGU level and then aggregated to the fleet level. To evaluate the overall cost-effectiveness of the use of treated brackish water for reducing freshwater use against dry cooling deployment, this study uses a metric called the cost of freshwater consumption savings[8].

This study makes a two-level assessment, including process and unit levels. At the unit-level, base case studies and a range of parametric analyses are performed. The process- and unit-level case scenarios with major design settings made for brackish water desalination are summarized briefly in Supplementary Table 1.

Brackish water resource databases

In this study, brackish water refers to water that has a higher salinity than freshwater and contains TDS from 1,000 to 10,000 mg/L[67]. Brackish groundwater resources in AZ and NM are identified in terms of this definition and then evaluated with respect to water location and availability, water quality, and ownership rights of water resources at the HUC-8 level. In the U.S., watersheds are classified by a national system based on surface hydrologic features, including regions, subregions, basins, subbasins, watersheds, and sub-watersheds. HUC-8 means a watershed at the sub-basin scale. The HUC-8 provides high-resolution mapping of resource availability between water supply and use[19].

The data on brackish groundwater location and annual resource availability at the HUC-8 level are collected from the Sandia National Laboratories' Water Atlas Features Database[68]. The physical and chemical property data of brackish groundwater are collected from the U.S. Geological Survey's comprehensive brackish water assessment report, including water temperature, pH value, alkalinity, silicon dioxide (SiO_2), boron (B), and a variety of cations and anions[17]. The average water quality and composition are estimated at the HUC-8 level, which are needed for the water desalination process simulation. The availability and quality of brackish groundwater resources are shown at the HUC-8 level using ArcGIS Pro[69].

A water right refers to the use of a specific amount of water from a specific source[70]. The doctrine of prior appropriation is adopted in some western U.S. states, such as NM, Colorado, Nevada, and Utah[71]. In contrast, the applicable groundwater laws in AZ are complicated, depending on the water location. In AZ, outside areas designated under the Groundwater Management Act (GMA) adopt the doctrine of reasonable use, whereas areas designated under the GMA face different requirements[71]. In this study, the rights of brackish groundwater are determined in terms of the ownership of groundwater wells registered for industrial use, which can be obtained from the well registration databases of state agencies including the AZ Department of Water Resources[72] and the NM Office of the State Engineer[73]. If power plant operators do not have permitting or rights in its HUC-8 or neighboring areas, they may request permitting from state agencies or trade water rights with other entities. Considering the transportation cost, however, the physical distance between water sources and sinks should not be more than 40 km[19,74]. Supplementary Fig. 12 presents the assessment framework of water resource adequacy.

Water desalination process modeling and cost estimation

An RO-based desalination process treats brackish water prior to its use for fossil power plant cooling. The process is designed based on the following assumptions:

- If the inlet temperature is more than 30 ^{o}C or above the cooling water temperature[8], brackish water is not considered as makeup water for wet cooling towers.
- The desired quality of product water is similar to that of surface freshwater with TDS of approximately 500 mg/L[75]. Brackish water desalination is designed to enhance the brackish water quality to the level of surface freshwater so that the existing facility for makeup water treatment can still be used for further quality improvements necessary to meet the industrial cooling water standard.
- The RO recovery rate is designed to be 75%, which is helpful to mitigate silica scaling[37,38]. For the designed recovery rate, a two-stage configuration with bypass is adopted for RO vessels in terms of a rule of thumb that relates the configuration of a process to its water recovery rate[76].

- The Langelier Saturation Index (LSI) and the Stiff & Davis Stability Index (SDSI) of the concentrate, which predict the potential to form mineral scale of calcium carbonate[26], are at a value less than zero. Salts, such as magnesium hydroxide and SiO_2, are not oversaturated. When the feedwater or the RO concentrate has a high LSI, SDSI, or high mineral scale potential, ion-exchange is applied as a pre-treatment softening step.
- Brines are subject to sewer discharge disposal as it is cost-effective unless otherwise noted[26]. In AZ, facility owners or operators with an Aquifer Protection Permit may discharge brines into a publicly owned treatment system[24,77]. Furthermore, wastewater treatment facilities are available within an average distance of about 8 km for all the selected EGUs based on a spatial analysis using the Arizona Department of Environmental Quality's Emaps[78].

Supplementary Table 13 presents additional details about RO modules, which use the Eco Pro 400i RO elements from the WAVE library[79]. The process diagram is shown in Supplementary Fig. 13a, which mainly includes water intake infrastructure, a cartridge filter, an ion-exchange softener, RO modules and associated equipment, and solid and waste handling facilities. To minimize brine discharges, ZLD can be added to the brackish water desalination process, which will be discussed in the sensitivity analysis later.

WAVE v1.82 is able to simulate industrial-level water desalination processes with commercialized technologies[66]. Thus, for the given process and RO module design, WAVE is applied to model the desalination process and provide systematic estimates of feedwater flow requirements, brine flow rate and concentration, RO module size, chemicals use, and electric power use in response to the feedwater quality (e.g., temperature, composition, and pH).

Supplementary Fig. 13b conceptually demonstrates the WAVE-based process simulation. Additional technical details are described in Supplementary Section S9.

The process performance modeling results are linked to engineering-economic models that estimate the total capital requirement (TCR), annual operating and maintenance (O&M) costs, and total annualized cost of a brackish water treatment system. The engineering-economic models use the same costing method and nomenclature as those in our previous dry cooling study and the IECM[8-10,80,81]. The detailed estimation methods of TCR and O&M costs are summarized in Supplementary Table 14 and Supplementary Table 15, while major financial and economic assumptions are summarized in Supplementary Table 3 and Supplementary Table 4 unless otherwise noted. At the process level, the cost of water treatment ($\$/m^3$) is calculated as:

$$\text{Cost of water treatment} = \frac{TCR_D \cdot FCF + FOM_D}{Q_p \cdot CF \cdot 24 \cdot 365} + VOM_D \qquad (1)$$

Where TCR_D is the total capital requirement of a water desalination system (\$); FOM_D is the annual fixed O&M cost (\$/year); VOM_D is the variable O&M cost based on the actual operating time ($\$/m^3$); Q_p is the water production rate (m^3/h); FCF is the fixed charged factor (fraction/yr), which is a function of project lifetime and discount rate; and CF is the capacity factor (%).

Existing power plants considered for desalination retrofits

Existing coal- and gas-fired EGUs in AZ and NM that use wet cooling towers are considered for use of treated brackish water. However, those EGUs that have announced retirement dates are not under consideration. Supplementary Table 8 summarizes the selected EGUs. This study acquired the selected EGUs' plant attributes and operating conditions (e.g., location, nameplate capacity, unit online time, heat rate, and annual generation) and local climate conditions from the integrated database of our previous dry cooling study, which originally collected power plant data from several databases including the ABB Ability™ Velocity Suite, the National Electric Energy Data System, and the Energy Information Administration Survey Forms 860 and 923[8].

Power plant modeling and desalination retrofit analysis

The IECM (v11.4), a power plant modeling tool developed by Carnegie Mellon University[82], is applied to configure and model the selected EGUs in terms of unit-specific attributes, operating conditions, and climate conditions[82]. Additional IECM modeling details are available in our previous dry cooling study[8]. The process-level performance and cost models of brackish water desalination discussed above are further coupled with the IECM so that the integrated framework is able to assess the unit-level freshwater consumption, net generating capacity, and cost of electricity generation before and after water treatment systems are retrofitted to make up cooling water losses. When a brackish water treatment system is retrofitted on site, the parasitic power is provided by the EGU itself instead of an electric power grid. To measure the overall cost-effectiveness, the cost of consumptive freshwater savings by brackish water treatment is calculated[8]:

$$\mathrm{CFWS} = \frac{\mathrm{LCOE}_{\mathrm{retrofit}} - \mathrm{LCOE}_{\mathrm{existing}}}{\mathrm{FWC}_{\mathrm{existing}} - \mathrm{FWC}_{\mathrm{retrofit}}} \tag{2}$$

Where CFWS is the cost per metric meter of freshwater consumption saved ($\$/m^3$); FWC is the freshwater consumption rate for an existing or retrofitted EGU (m^3/MWh); and LCOE is the levelized cost of electricity for existing or retrofitted EGU ($/MWh). The LCOE calculation is detailed in Supplementary Equations 7 and 8. Please note that the cost of consumptive freshwater savings is analogous to the carbon dioxide avoidance cost[8], a widely used cost metric for evaluating carbon capture technologies and equals the breakeven water price required for deployment of brackish water treatment. This economic metric is used for the comparison between brackish water treatment and dry cooling deployment. To reduce freshwater consumption, on-site wastewater streams (e.g., wet tower blowdown) can be recycled after advanced treatment is made to reach the desired water quality. However, such advanced wastewater treatment also incurs additional energy and cost penalties. This scenario is beyond the scope of this study.

The cost results are reported in 2017 constant dollars. The assumptions made for retrofit analysis include the following:

- The retrofit analysis is conducted at the EGU level on an annual basis, including both brackish groundwater pumping and treatment costs unless otherwise noted.
- The production capacity of a brackish water treatment system is determined based on the amount of makeup water required for wet cooling towers.
- Nominal values of power plant and ambient parameters are based on the recent database year, which are consistent with our previous dry cooling retrofit study[8].
- Unit retirement age is 50 years for coal-fired EGUs and 30 years for gas-fired EGUs, if that information is not publicly available[8]. Unit age and remaining lifetime are estimated relative to the unit's online year[8].
- For each EGU, annual capacity factors are kept constant for the pre- and post-retrofit cases.
- For LCOE calculations, existing units are treated as fully amortized. Brackish water treatment system capital costs are amortized over 30 years or the remaining lifetime of an EGU if it is less than 30 years.

Data Availability

The data used in this paper are available in a public data repository: https://edx.netl.doe.gov/dataset/brackish-water-for-cooling. This study used two simulation tools, in which IECM is public available at: http://www.iecm-online.com/, and WAVE is public available at: https://www.dupont.com/water/resources/design-software.html.

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Author Contributions

H.Z. and E.J.G. designed research; Z.W. conducted experiments; Z.W. and H.Z. performed data analysis; E.J.G., C.M.A., and N.S.S. contributed to data analysis; Z.W. and H.Z. wrote the draft manuscript, and all the authors reviewed and edited the manuscript.

Competing Interests Statement

The authors declare no competing interests.

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Table

Table 1. Performance and Cost of Water Desalination Technologies Reported in Literature

Technology	Production Capacity[a,b] (m^3/day)	Feed TDS[a] (mg/L)	Energy Penalty[a,b,c] (kWh/m^3)	Recovery Rate[a,b,c,d] (%)	Cost of Water Treatment[a,b,e] (\$/m^3)	Major Operating Issues[a]
MSF	1,000–76,000	35,000–55,000	19.6–27	25–50	0.56–1.75	Thermal desalination has a low recovery rate and large parasitic loads; the scale formation and corrosion from salt deposition can alter the equipment surface and performance and increase the energy consumption; the air pollutants and greenhouse gases emitted from thermal energy generation need to be controlled.
MED	600–45,000	35,000–55,000	14.5–21.4	35–65	0.52–1.5	
VC	20–3,800 (MVC); 10,000–30,000 (TVC)	35,000–55,000	7–16	25–50	0.87–2.6	The scale formation and corrosion of evaporator components need to be controlled; defrosting the vapor-compression refrigeration system consumes a significant amount of energy.
RO	0.1–130,000	50–50,000	0.2–2.5	50–90	0.12–1.33	The low permeation flux requires large membrane areas for large-scale RO systems; there are concerns on membrane fouling and scaling, especially for the high recovery case; it may be difficult for RO to reject very small uncharged species; membrane durability needs improvements to reduce the cost; inappropriate brine discharges with high salinity cause severe environmental impacts; brine management is a great challenge for inland brackish water desalination;
ED	2–145,000	300–12,000; Best < 3500	2.6–5.5	50–90	0.6–1.05	ED is unable to remove contaminants other than charged species; membrane cleaning can reduce the membrane durability; and ED membranes are more expensive than RO membranes, which increases the annual material replacement cost.

[a.] Sources of data: Al-Karaghouli and Kazmerski, 2013; Harto et al., 2014; Islam et al., 2018; Park et al., 2015; Tripathy et al., 2019; Al-Othman et al., 2018; Wu et al., 2021; She et al., 2018; Plata et al., 2022; Xu et al., 2022.[13,35-43]

[b.] Sources of data: Curto et al., 2021; Pan et al., 2020; Vince et al., 2008.[30,44,45]

[c.] Sources of data: Patel et al., 2021; Karabelas et al., 2018; Ruiz-García et al., 2020; Alsarayreh et al., 2020.[46-49]

[d.] Sources of data: Hamed, 2020; Feria-Díaz et al., 2021; Wenten, 2016; Mohammadi, 2021.[50-53]

[e.] The cost takes into account water pretreatment.

Figure Legends/Captions

Fig. 1 Brackish water resources and associated treatment energy consumption and cost, not including deep-well pumping power use and cost (a) annual water availability, (b) average TDS, (c) water pH, (d) water temperature, (e) specific energy consumption for brackish water treatment, (f) cost of brackish water treatment. The colorful dots represent different conditions of water quantity and quality of brackish water available at different EGUs, in which triangles represents gas units and circles represent coal units.

Fig. 2 Performance and cost effects by unit from brackish water treatment (BWT) deployment including deep-well pumping energy and cost (a) freshwater consumption intensity of unit with and without brackish water treatment, (b) power use for brackish water treatment, (c) LCOE of unit with and without brackish water treatment, (d) cost of freshwater consumption savings by brackish water treatment; MWg: gross capacity

Fig. 3 Effect of capacity factor (CF) on cost of freshwater consumption savings. Note: In each base case, the capacity factor of each retrofitted EGU is identical to that of the existing EGU prior to the retrofit.

Fig. 4 Comparisons of unit-level impacts of brackish water treatment deployment with and without ZLD (a) parasitic load and added LCOE for brackish water treatment, (b) supply curve of brackish water treatment as a function of cumulative power plant capacity with respect to cost of freshwater consumption savings. Note: To maintain silica solubility at a level of 350 ppm for membrane scaling control, the water recovery rate by RO at units N8, N9, and N10 has an upper limit of 88%.

Fig. 5 Comparison of cost of freshwater consumption savings between brackish water treatment and dry cooling (a) brackish water treatment without ZLD, (b) brackish water treatment using RO for 75% brackish water recovery with ZLD, (c) brackish water treatment using RO for ~90% brackish water recovery with ZLD. Note: The cost estimates of dry cooling systems come from a previous study[8]; the green markers represent units with capacity factors (CF) of less than 40%; the dots with error bars represent the mathematical average estimates with 95% confidence intervals are based on 8 coal units and 10 natural gas units, respectively; and specific numeric results shown in the figure are reported in Supplementary Table 12.

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