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Article

Zero Liquid Discharge and Water Reuse in Recirculating Cooling Towers at Power Facilities: Review and Case Study Analysis

Sophia L. Plata, Connie L. Devenport, Ariel Miara, Kurban A. Sitterley, Anna Evans, Michael Talmadge, Kurt M. Van Allsburg, Parthiv Kurup, Jordan Cox, Samuel Kerber, Andrew Howell, Richard Breckenridge, Cheyenna Manygoats, Jennifer R. Stokes-Draut, Jordan Macknick, and Amy E. Childress*

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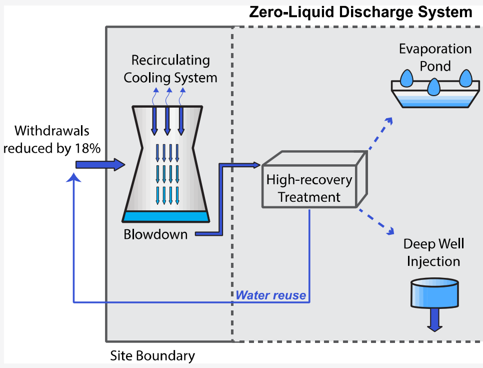

ABSTRACT: Zero liquid discharge (ZLD) systems installed at power facilities with the primary purpose of meeting water discharge regulations have the added benefit of providing high quality effluent that can be reused in the facility. This paper provides a review of water use in power sector recirculating cooling towers and a baseline assessment of on-site water reuse at natural gas combined cycle (NGCC) power facilities. Two NGCC facilities with reverse-osmosis (RO) or brine-concentrator processes followed by evaporation ponds were selected as case studies; data from these facilities were used to quantify the water, energy, and cost implications of implementing conventional and emerging ZLD technologies. At one case study facility, model results show that implementation of ZLD would reduce water withdrawals by 18%, which is less than savings associated with implementation of dry cooling but comparable to current efforts to reduce water withdrawals by increasing cycles of concentration. Implementation of ZLD using high-recovery RO resulted in a doubling of the levelized cost of water (LCOW). LCOW increased more when a brine concentrator was used. For both case studies, the ZLD system using high-recovery RO required less than 0.1% of a facilitiy's annual electricity generation and the ZLD system using a brine concentrator process required less than 0.8%. Additionally, increasing the evaporation pond area to minimize required ZLD system recovery rates and reduce system electricity costs does not reduce the LCOW. Instead, the LCOW increases because less water is recovered and more water is lost to evaporation. However, if water availability decreases or water competition/cost increases, facilities may be incentivized to maximize water recovery from ZLD systems.

KEYWORDS: *zero liquid discharge, thermoelectric recirculating cooling towers, closed-circuit reverse osmosis, brine concentrator, levelized cost of water*

1. INTRODUCTION

Concurrent with the global transition away from fossil fuels to meet climate change goals, the fossil fuel power generation mix is shifting as well: from heavier carbon-emitting and water-consuming sources, such as coal, to sources that can potentially reduce climate and water stress, such as natural gas.[1−5] Even though the relative share of fossil fuel generation is generally declining, there are still new fossil facilities being built, with many being natural gas.[6−8] As of 2020, natural gas generation accounted for 40.3% of total US electricity generation[9] and natural gas is projected by the U.S. Energy Information Administration (EIA) to occupy the majority of electricity production through 2050.[10] At the same time as the shift in power generation mix, cooling systems for thermoelectric power facilities are shifting from once-through cooling, with high water-withdrawal requirements to recirculating cooling, with much lower water-withdrawal requirements but higher water consumption.[11−17]

At thermoelectric power facilities with recirculating cooling, regulations on the water quality of discharges as well as increased cost and competition for water supplies are contributing to decreased water withdrawals.[1,2,18,19] Regarding wastewater discharges, facilities are subject to regulations on constituents in their wastewater such as nutrients (e.g., total organic nitrogen), metals, and total dissolved solids (e.g., chloride and sulfate) that can negatively impact downstream environments.[20] In particular, as more facilities transition from once-through to recirculating cooling systems, the concentration of dissolved solids in the wastewater will increase.[21,22]

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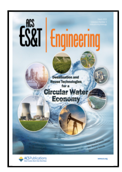

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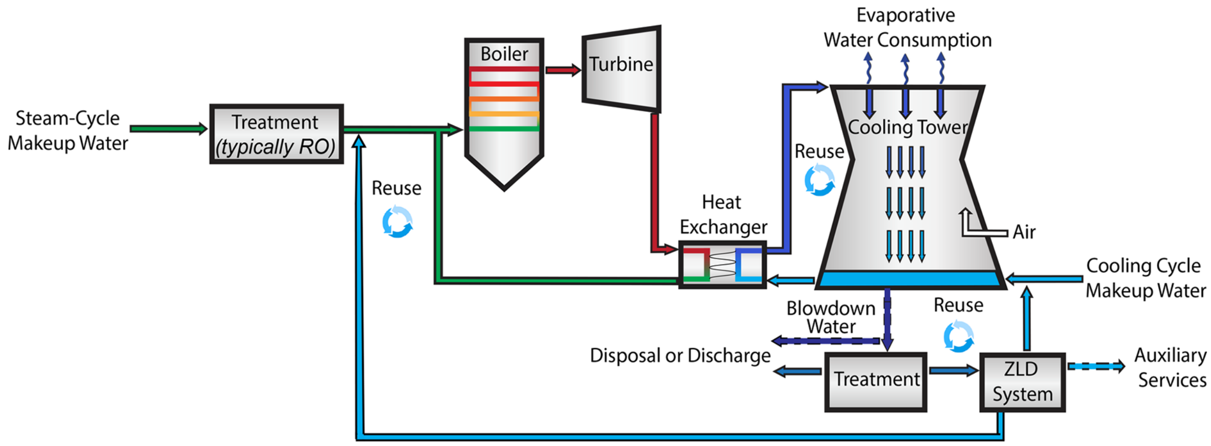

Figure 1. Water flow diagram of a thermoelectric power facility with a recirculating cooling tower and a ZLD system. Water reuse occurs in the cycles of concentration of the cooling tower. Water reuse also occurs when ZLD systems typically installed to meet discharge regulations provide high-quality effluent that is recycled back to the facility.

Discharge regulations have forced the power industry to take leadership in zero liquid discharge (ZLD) implementation. Facilities affected by discharge regulations, the majority of which are in the western US,[23] have implemented ZLD approaches to eliminate off-site discharge. Though installed for the main purpose of meeting discharge regulations, ZLD systems have the added water resource benefit of providing high-quality effluent that can be reused in the facility,[24] perhaps decreasing the volume of water withdrawals.

The objective of this study is to review water-reuse practices and opportunities for recirculating cooling tower systems in the thermoelectric power sector, provide a baseline assessment of on-site water reuse at natural gas combined-cycle (NGCC) power facilities, and consider water-reuse opportunities associated with ZLD implementation. In addition, operating information from two representative NGCC case-study facilities is assessed using water and energy metrics. The benefit of on-site water reuse as the result of ZLD implementation is weighed against the energy and monetary cost of implementing and operating brine-concentrator (BC) and high-recovery reverse-osmosis (RO) ZLD systems.

2. REVIEW OF WATER WITHDRAWALS, WATER USE AND REUSE, AND ZLD APPROACHES FOR RECIRCULATING COOLING TOWERS IN THE THERMOELECTRIC POWER SECTOR

2.1. Water Withdrawals. Water withdrawals, which refer to water taken from surface water, groundwater, or a municipality's drinking water or treated wastewater supply are influenced by water availability, water competition, and water cost.[25−27] Water availability, which may be limited by physical scarcity or local water rights, is a major issue for power facilities throughout the US. Although an existing facility may have secured a legal right to water allocation through riparian or prior appropriation rights,[28] there is still risk of not receiving allocations because of the physical unavailability of water.[29] This is more of a concern for facilities in arid and semiarid regions that struggle with water scarcity;[29−31] however, it also impacts other regions that are subject to changes in water rights as water demands from other sectors increase.[32] Moreover, water availability can be impacted by intake water temperatures. If intake water temperatures rise as a result of discharges from upstream facilities and/or climate change,[33−35] the availability of water that is cool enough to maintain optimal thermal efficiency can become limited.[36,37]

Competition for water is dictated by the type of water right (i.e., riparian or appropriative rights and, in some cases, federal-reserved, adjudicated, or Pueblo rights) and for appropriative water rights, the effective date of the water right.[38−40] Regulators may also subject facilities to water supply reductions or reallocations based on regional needs.[32,41] Regional needs may include saving water for the environment (i.e., making water available for surface water and groundwater ecosystems).[42] Finally, by locating thermoelectric power facilities in regions where competition is lower,[43−46] water prices are also typically lower.[47]

2.2. Water Use and Reuse. *2.2.1. Water Use.* Figure 1 shows a basic water flow diagram of a thermoelectric power facility with a ZLD system; the ZLD system is described more in Section 2.3. The two primary purposes for water use at power facilities are steam generation (the boiler in Figure 1) and cooling of the steam cycle (the cooling tower in Figure 1). This paper focuses on the water cooling cycle because cooling accounts for the majority of water use at power facilities,[1,48] and specifically, this paper focuses on systems with recirculating cooling towers because these are more common than systems with cooling ponds.[49−51]

In the cooling cycle shown in Figure 1, heated water leaving the heat exchanger enters the top of the cooling tower where it cascades down and is broken into droplets as it contacts the cooling tower fill. The water droplets are cooled by the lower temperature of the countercurrent flow of air and heat is released as water evaporates. The cooled water at the bottom of the cooling tower is returned to the heat exchanger where the cooling loop begins again. As water evaporates to release heat, the dissolved and suspended solids become more concentrated in the cooling water. Eventually, removal of solids is necessary to avoid deposition and/or scale formation, so the cooling water is discharged in a process called blowdown.

The loss of water to evaporation and blowdown accounts for the majority of water consumption at thermoelectric power facilities, and drift, or water carried away as mist, accounts for a substantially smaller portion of water consumption (less than 1%[52,53]). With approximately 70% loss to evaporation[25,54] and approximately 30% loss to blowdown,[25,54] a recirculating cooling tower consumes an average of 4.5×10^6 m^3 (1.2×10^9 gal) of water per year.[17] Consumed water is replaced by makeup water that is withdrawn from a surface water, groundwater, or a municipality's water supply.

2.2.2. Water Savings via Increasing Cycles of Concentration. The ratio of the total dissolved solids concentration in the blowdown water to the total dissolved solids concentration in the makeup water is known as "cycles of concentration", or simply as "cycles".[55] Cycles can also be approximated as the ratio of blowdown water volume to makeup water volume because total dissolved solids only enter via makeup and exit via blowdown.[55] As the number of cycles increases, blowdown occurs less frequently and less water is required for makeup. For example, increasing from three to six cycles reduces blowdown by 50% and associated makeup water requirements by 20%; makeup water requirements are reduced less because makeup water requirements are comprised of evaporation (which remains constant) and blowdown.[21,56] Also, as the number of cycles increases, concerns for corrosion and scaling increase.[21,22] The number of cycles varies but can generally range from two to ten cycles.[21,56] Cycles are often limited by the quality of the makeup water;[57] if the makeup water comes from a lower-quality source and does not undergo on-site treatment,[55,58] the number of cycles is lower.

Approaches to increase cycles have been the main path taken to achieve water savings at thermoelectric power facilities with recirculating cooling systems.[21,59,60] Other approaches, including capturing water vapor[61−63] or reducing drift loss, windage loss, and heat loss from the cooling tower, have also been used to achieve water savings, albeit at lower net savings compared to that for increasing cycles.[22,60,64,65]

2.2.3. Water Savings via Dry Cooling. Dry-cooling systems, which use approximately 95% less water than wet-cooling systems,[66] can also offer substantial water savings.[66−68] Currently, there are at least 70 dry-cooling systems throughout the US, with 40% of them in California, Nevada, New York, and Virginia. Dry- and hybrid-cooling facilities consume an average of 7.6 L (2 gallons) of water per MWh.[48] Although dry-cooling systems offer a valuable solution for water-scarce regions, they have high capital costs[68−72] and high energy requirements.[66,73,74] Comparing NGCC facilities in California with dry and wet cooling, Maulbetsch and DiFilippo[71] found that dry-cooling facilities increase installation costs by 22.1 million dollars ($M). Loew et al.[69] found that dry-cooling facilities in Texas increase capital costs by 23−143 $M. And Njoku and Diemuodeke[72] found that dry-cooling facilities in dry, hot regions of Nigeria increase annual operating and maintenance costs by 19−38%.

In general, dry-cooling systems are less efficient than wet-cooling systems because air does not transfer heat as efficiently as water does.[75] Moreover, dry facilities become less efficient as ambient air temperatures increase[76] because of increased condensing temperature.[36,37] At ambient air temperatures greater than 25 °C, one study (Hamanaka et al.[37]) showed that efficiency decreases even more because of decreased turbine efficiency in addition to increased condensing temperature. The efficiency of wet-cooling systems also decreases as ambient temperatures increase, but the efficiency of wet-cooling systems typically decreases at a lower rate than dry-cooling systems due to factors such as humidity.[72]

2.2.4. Water Reuse. Aside from cycles of concentration, water reuse in power facilities occurs when water from upstream processes is used (with or without treatment and/or dilution) in downstream processes. For example, cooling tower blowdown water can be used as flue-gas desulfurization (FGD) makeup water,[77,78] FGD blowdown water can be used for ash sluicing, and ash pond runoff can be used for dust control.[79] For example, the Coronado Generation Station (a coal facility in St Johns, AZ) reuses cooling tower blowdown water as makeup water for ash system surge tanks and the Springerville Generating Station (a coal facility in Springerville, AZ) uses cooling tower blowdown water as makeup water for FGD scrubber reagents. Cooling tower blowdown water from power facilities can also be reused for peripheral services (e.g., road dust suppression).

Upstream water reuse, where lower-quality water from downstream processes is used in upstream processes, has been less common because of significant treatment and/or dilution requirements.[80] However, upstream reuse is becoming more common with ZLD implementation. As shown in Figure 1 and discussed more in the next section, ZLD facilities treat cooling tower blowdown for reuse as cooling-cycle makeup water, steam-cycle makeup water, and/or water for auxiliary services. Auxiliary services use "service water" for cooling systems that have small-diameter tubing (as small as 6.35 mm (1/4 in.)). Higher-quality water is required for auxiliary services than for the main cooling system (that typically uses 25.4 mm (1 in.) tubing) because smaller diameter tubing plugs more readily.

2.3. Zero-Liquid Discharge Approaches to Achieve Discharge Standards and Provide Additional Supply for Water Reuse.

2.3.1. ZLD Management Strategies. In the past, blowdown water from the cooling cycle has either been discharged to a receiving water (e.g., the source water body) without or with treatment (e.g., a settling pond) or injected into a deep well (Figure 2a). Now, it is becoming more common to treat blowdown water with a ZLD system (Figure 2b) to eliminate the need for off-site discharge or, in the case of deep-well injection, to reduce the volume of water disposed to the subsurface. ZLD is a wastewater management strategy where no wastewater is discharged and water recovery is maximized.[81,82] ZLD does not just refer to an additional series of unit operations but is considered a holistic philosophy that affects how an entire power facility operates. Given the cost implications, power facilities do not choose to implement ZLD freely—facilities being retrofit for ZLD generally do so only if necessary to meet more stringent discharge regulations;[80,83] facilities being newly designed for ZLD operation intend to avoid the more extensive permitting processes and monitoring requirements associated with off-site discharge. Both retrofit and new ZLD facilites also benefit from reduced requirements for water withdrawals.

At power facilities, ZLD operation typically refers to the elimination of wastewater being discharged to an off-site receiving water, not the elimination of wastewater leaving the facility. It should also be noted that although the wastewater injected into on-site deep wells will enter an aquifer that likely extends beyond the site boundary, power facilities consider deep-well injection to be a ZLD process. In keeping with this construct, this paper considers ZLD at power facilities as the use of high-recovery treatment processes followed by discharge of the residual stream to an evaporation pond or injection of the residual stream in a deep well, as shown in Figure 2b. Evaporation ponds and deep wells are discussed more in section 2.3.4.[84] As mentioned previously, the high-quality water produced by the ZLD system can be used as cooling-cycle makeup water, steam-cycle makeup water, and/or service

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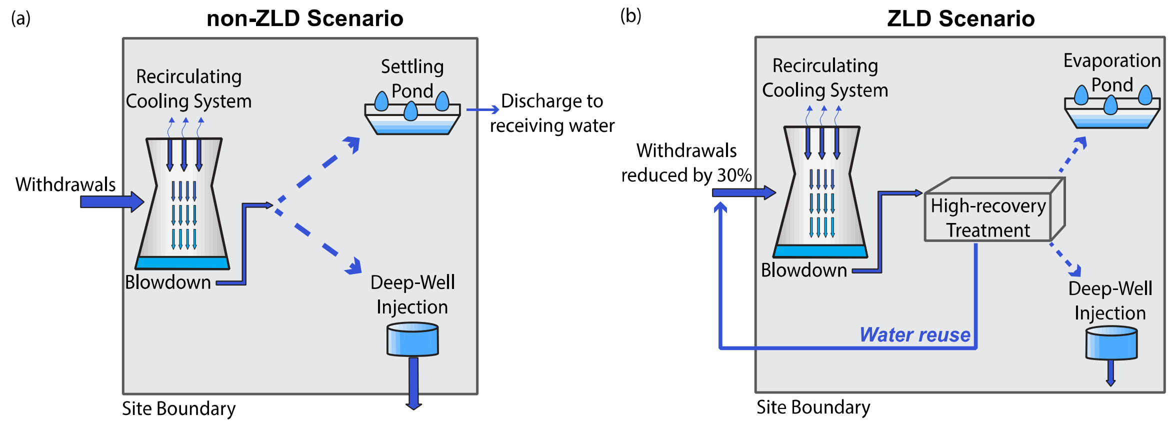

Figure 2. Schematic of water balance at power facilities (a) without a ZLD system and (b) with a ZLD system. A power facility without a ZLD system can treat cooling tower blowdown with a settling pond before discharge to a receiving water or can discharge directly to a deep well. A power facility with a ZLD system treats cooling tower blowdown with a high-recovery treatment system. The product water can be reused for cooling tower makeup (or other upstream uses), which reduces withdrawal requirements. The residual from the high-recovery treatment system can either be discharged to an on-site evaporation pond or injected in a deep well.

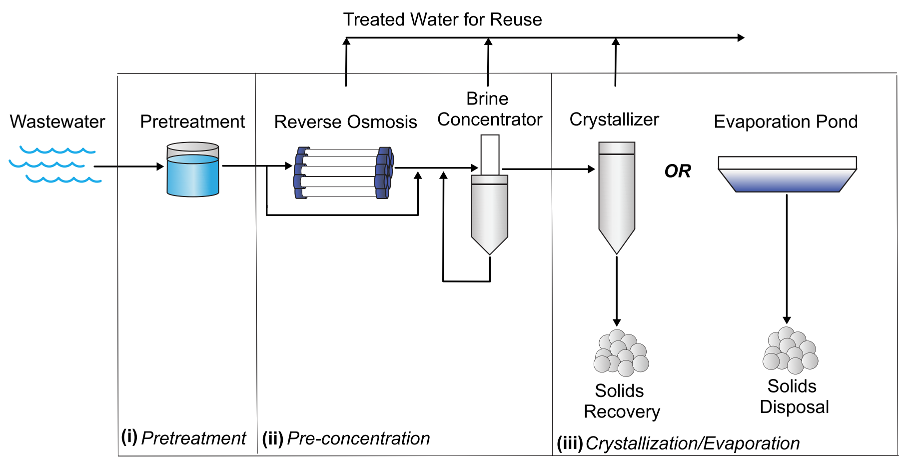

Figure 3. Conventional zero liquid discharge (ZLD) treatment scheme with (i) pretreatment, (ii) preconcentration by reverse osmosis and/or a brine concentrator, and (iii) crystallization/evaporation by crystallizers and/or evaporation ponds. Figure adapted from Global Water Intelligence.[93]

water. Because recirculating cooling tower systems consume 70% of water withdrawals on average,[25,54] ZLD systems have the potential to treat and reuse the 30% of water withdrawals that become cooling tower blowdown (shown in Figure 2b).

2.3.2. ZLD with Conventional Brine-Concentrator Systems. Conventional thermally driven ZLD systems are typically bespoke systems supplied by different manufacturers. Their design depends on influent water quality and discharge requirements for volumes, flow rates, and water quality. Thermally driven ZLD systems typically consist of three steps (Figure 3): (i) pretreatment, (ii) preconcentration, and (iii) crystallization and/or evaporation.[82,85−88] In pretreatment, suspended solids, metals, hardness, and silica are typically filtered and/or precipitated out. Preconcentration typically recovers 90−98% of the water[86,88] and consists of either a BC process alone or a BC process that is pretreated with a desalination process (e.g., RO).[89] Finally, a crystallizer or evaporation pond is used. The resulting solids are typically mixed salts that cannot be reused and must be disposed in landfills.[31,90] If high-purity salts could be obtained, the potential exists for reuse or marketing as industrial materials.[91,92] Product water from the preconcentration and crystallization step can be reused upstream.[24,86,88]

The BCs in these systems are known to be challenging to operate and can suffer frequent breakdowns that can create an unwanted domino effect on other processes of the system.[80] Also the BC and crystallizer can be dependent on the steam cycle and, thus, can be affected by facility pauses and shutdowns of the facility's boiler system.[84] Moreover, BCs and crystallizers are energy intensive, which may affect a facility's net power output. For example, a BC's specific energy consumption ranges from ∼20 to 30 kWh/m^3 at salinities of ∼250 000 mg/L while a crystallizer's specific energy consumption ranges from ∼50 to 65 kWh/m^3 at salinities of ∼300 000 mg/L (values estimated from Tong and Elimelech[81]). To minimize scaling, BCs are typically pretreated with scale inhibitor.[94−96]

2.3.3. ZLD with High-Recovery RO Systems. Emerging high-recovery RO membrane systems are also being used as part of ZLD systems at power facilities. As of 2016, there were 72 power facilities in the US that employed ZLD systems with a total combined capacity of 1.19 × 10^5 m^3/day.[97] According to a report by Mordor Intelligence LLP,[98] "the market for ZLD systems is expected to register a compound annual growth rate of over 9%" from 2020 to 2025. The power industry is expected to occupy the majority of the ZLD market as

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wastewater disposal costs and demand for freshwater resources are expected to rise.[98] Advancements in high-recovery RO (e.g., high-efficiency RO and closed-circuit RO (CCRO)) processes have made ZLD systems simpler to operate and able to achieve high water recovery with relatively low energy consumption.[85,99] For example, the average power required by a typical 1.4 m^3/min (300 gallon/min) high-recovery RO system (160 kW) is generally an order of magnitude less than that of a BC (1200 kW).[100] Water recoveries up to 98% have been reported for some systems at power facilities.[101]

The Griffith Energy Facility and Magnolia Power Project are NGCC facilities that were the first to use a HERO[102] system upon commissioning in 2002 and 2003.[103−106] The HERO system operated at recoveries up to 90%.[107,108] Hardness and carbon dioxide were removed to reduce scaling potential and retard biofouling prior to operating RO at a higher pH. Arlington Valley Power Station, an NGCC facility that was reported as having the largest ZLD system in the US in 2016,[97] utilizes HERO to treat 9100 m^3 of water per day.[109] In 2017, the power industry's first implementation of Desalitech CCRO technology,[110,111] a semibatch process, occurred when Southern California Edison implemented CCRO systems at five of its gas-fired combustion turbine facilities.[112] CCRO was implemented with the goals of saving 44 million gallons of water per year, improving reliability, and cutting annual water operating costs by more than 1 $M per facility (i.e., 85% of annual water operating costs). In particular, implementation of CCRO was expected to reduce water disposal costs because the CCRO brine could be disposed of at a lower-cost brine-disposal facility.[112]

In 2019, Global Water Intelligence[113] stated that high-recovery RO systems are "encroaching on the part of the treatment train for brine concentration that an evaporator would traditionally operate in". Because BCs are known to suffer frequent breakdowns and are operationally complex, high-recovery RO systems appear to be a strong competitor.[80,114−116] Although other alternatives to brine concentrators (e.g., forward osmosis, membrane distillation, and humidification-dehumidification) have entered the market over the last 10−15 years, emerging RO processes have the advantage that they are based on mature, familiar RO desalination technology.

2.3.4. ZLD On-Site Discharge: Evaporation Ponds and Subsurface Injection. As mentioned earlier and shown in Figure 2b, the concentrate stream from high-recovery treatment (either thermally driven or pressure-driven water-recovery processes) is typically discharged to an evaporation pond or injected into the subsurface. Evaporation ponds are relatively simple, low-technology processes to dispose of residual streams; solar energy evaporates the water while salts accumulate at the bottom of the pond. Accumulated salts are periodically disposed of in landfills.[31,90] Evaporation ponds are primarily designed on the basis of the flow rate of water that will be discharged to the pond and the regional evaporation rate. Higher flow rates and/or lower evaporation rates require larger evaporation pond area. Evaporation ponds are more common in arid and semiarid climates where evaporation rates are high.[117] Although evaporation ponds can have high capital costs (e.g., to acquire land area and purchase liner materials),[118] the low electricity costs, low operating costs in general, and simplicity of operation currently give them treatment primacy over other processes that recover water, instead of evaporating it.[114]

Deep-well injection is another low-technology process often used to dispose of residual streams (e.g., concentrate streams), particularly in parts of the US that experience heavier rainfall.[119] Residual streams are injected into subsurface porous rock formations.[120,121] Because deep-well injection is not as limited by discharge flow rate,[122,123] facilities may choose to discharge greater volumes and reduce electricity costs by operating the upstream ZLD system at a lower recovery.Challenges associated with deep-well injection include earthquakes, scaling, corrosion, and possible pollution of the groundwater.[123−126] Similar to the case for evaporation ponds, the most significant drawback of deep-well injection is that the water resource is not recovered and available for reuse.

The second objective of this paper, after the review of water reuse in the thermoelectric power sector, is to use operating information from two representative case-study facilities to (i) quantify the electricity and monetary costs of retrofitting a non-ZLD facility to ZLD operation, (ii) compare the electricity and monetary costs of a ZLD system using a pressure-driven CCRO process with one using a thermally driven BC process, and (iii) evaluate the opportunity for on-site water reuse when retrofitting a non-ZLD facility with ZLD. Finally, the role of evaporation ponds (the more common of the two final disposal methods[118]) is considered as well as its impact on water and electricity metrics.

3. CASE-STUDY ANALYSES

3.1. Methodology. *3.1.1. Natural Gas Combined Cycle Case-Study Facilities.* Two NGCC power facilities with water-reuse practices were selected as the case-study facilities. As of 2018, NGCC facilities accounted for ∼90% of total natural gas generation and are expected to be the most prominent source of electricity generation for the foreseeable future.[127,128] Both of the NGCC case-study facilities are located in semiarid/arid regions[129,130] and face challenges with water availability, water cost, and discharge regulations; as such, these facilities are representative of facilities that are most likely to employ ZLD technologies. In addition, these facilities were chosen as case-study facilities because of the availability of data from them.

Cherokee Generating Station. The Cherokee Generating Station ("Cherokee") is an 886-MW power facility located in Denver, CO.[131] Two-thirds of Cherokee's 886-MW capacity (591 MW) comes from NGCC; the remaining capacity is from a natural gas steam turbine that was converted from a coal-fired unit in 2017. The shift from coal to natural gas contributed to the facility's 15% reduction in water withdrawals in 2016.[132] The facility has two combustion engines and two heat-recovery steam generators supplying one steam-turbine generator. In 2003, Cherokee began using 8400 m^3/day (1.8 MGD) of secondary-treated wastewater from Denver's Metro Water Recovery (Denver, CO) for cooling tower makeup in addition to their 2400 m^3/day (0.53 MGD) withdrawal from Clear Creek and 230 m^3/day (0.05 MGD) withdrawal from the Platte River.

Aside from cooling water, Cherokee uses 1900 m^3/day (0.41 MGD) of potable water from Denver Water; half of it for steam-cycle water and the other half for service water. The service water is not treated prior to use and is concentrated approximately twice in the small service water cooling tower before it is blown down and combined with the main cooling tower blowdown water. In total, Cherokee discharges approximately 4100 m^3/day (0.9 MGD) to the Platte River. Due to a 2017 permit, the following limits have been placed on

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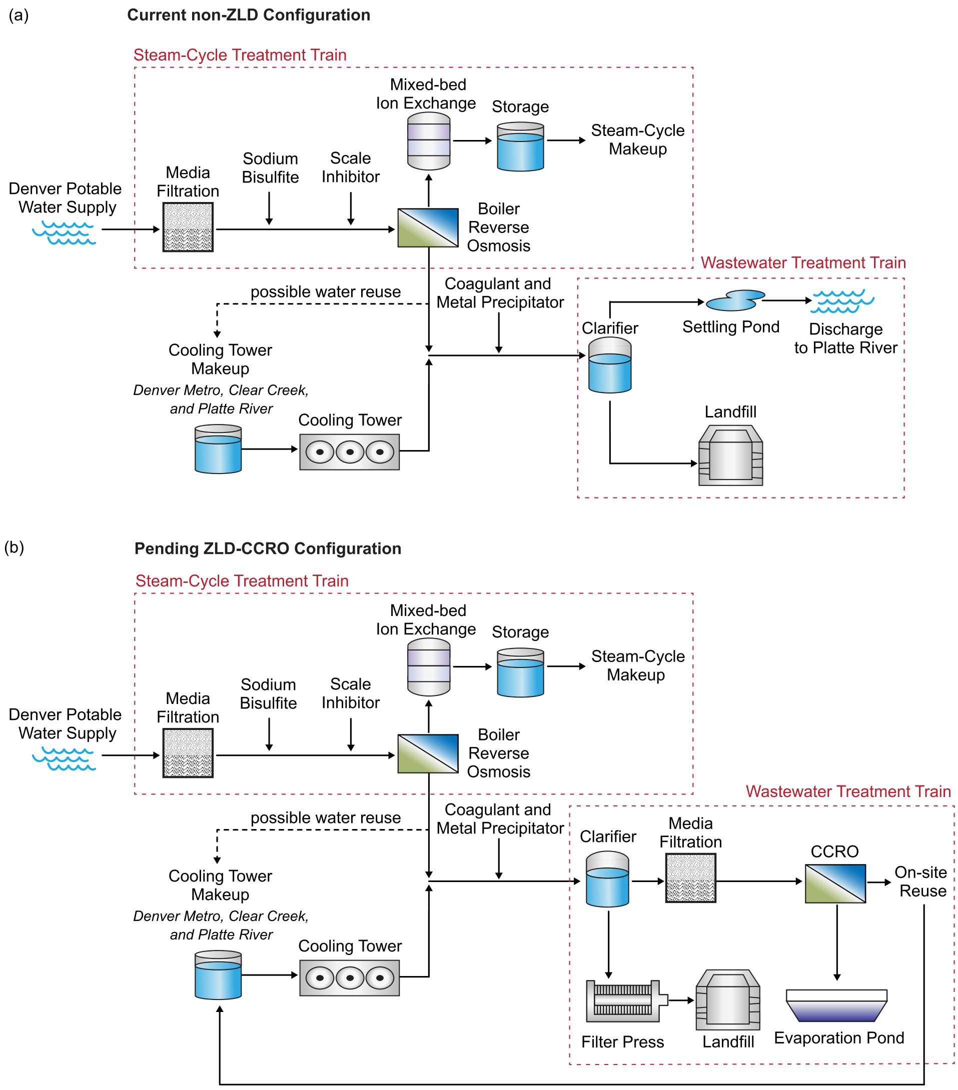

Figure 4. Process flow diagram showing water treatment for Cherokee Generating Station's (a) current, non-ZLD configuration and (b) pending ZLD-CCRO configuration. The Steam-Cycle Treatment Train treats Cherokee's steam-cycle water, and the Wastewater Treatment Train treats both the steam-cycle RO concentrate and cooling-cycle blowdown water. Flow rates are reported in Table S1, source water constituents are reported in Table S2, and water-recovery and constituent-removal rates are reported in Table S4.

discharges to the Platte River: 10 mg/L daily maximum of total inorganic nitrogen by 2022; 250 mg/L over a 30-day average of chloride by 2023; and 553 mg/L over a 30-day average of sulfate by 2023. Because Cherokee could not meet these discharge regulations with its current non-ZLD system, Cherokee is currently being retrofit for ZLD operation.

Figure 4 shows the process flow diagram for Cherokee's current non-ZLD configuration (Figure 4a) and Cherokee's pending ZLD-CCRO configuration (Figure 4b). The Steam-Cycle Treatment Train, which is the same for both configurations, treats the steam-cycle water supplied by Denver Water. Prior to RO, the steam-cycle water passes through media filtration to remove particulates, then is dosed with sodium bisulfite and scale inhibitor to remove chlorine and reduce likelihood of precipitation. RO permeate is passed through mixed-bed ion exchangers as a final polishing step for dissolved solids and silica before storage. The treated water in the storage tank is then available for steam-cycle makeup. The RO concentrate from the Steam-Cycle Treatment Train is combined with cooling tower blowdown; the combined stream is dosed with coagulant and metal precipitator prior to clarification to remove particulates and metals as part of the Wastewater Treatment Train. Although the cooling cycle and hence, Wastewater Treatment Train, are the focus of this study, the Steam-Cycle Treatment Train is also presented because its RO concentrate is treated in the Wastewater Treatment Train. In the non-ZLD configuration (Figure 4a), the supernatant from the clarifier is discharged to a settling pond and then the Platte River. The solids from the clarifier are landfilled. The only water reuse in the current non-ZLD configuration occurs if the steam-cycle RO (i.e., the boiler RO) concentrate is of high enough quality to be used for cooling tower makeup.

In the pending ZLD-CCRO configuration (Figure 4b), CCRO is added to the Wastewater Treatment Train with media filtration as pretreatment. The CCRO system will operate at 98% recovery to maximize the permeate available for reuse and minimize the concentrate discharged to the

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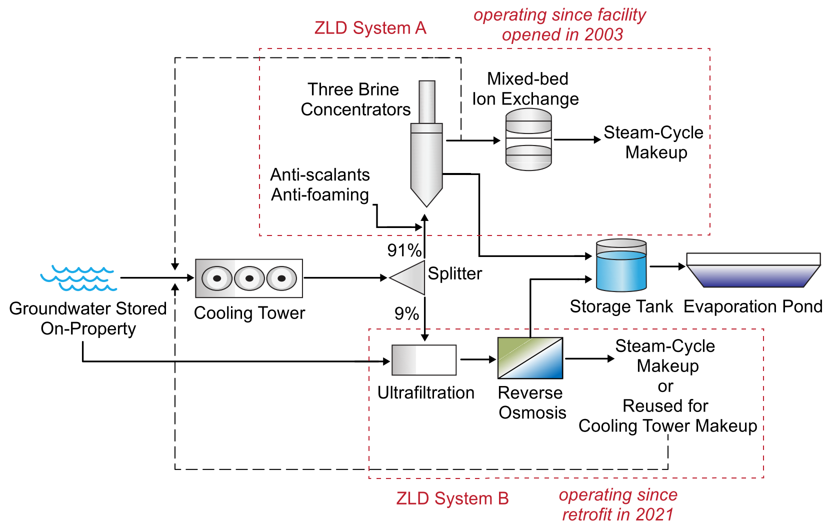

Figure 5. Gila River Power Station process flow diagram. The cooling towers use groundwater that is stored on-site. Cooling tower blowdown water is treated with ZLD System A or ZLD System B before it is reused for cooling tower makeup or steam-cycle makeup. ZLD System A treats the majority of cooling tower blowdown water (modeled as 91% in this study) and is composed of three brine concentrators followed by mixed-bed ion exchange. ZLD System B treats a smaller fraction of the cooling tower blowdown water (modeled as 9% in this study) and is composed of ultrafiltration and reverse-osmosis processes. Concentrate from ZLD System A and ZLD System B is combined in a storage tank before discharge to on-site evaporation ponds. Flow rates are reported in Table S1, source water constituents are reported in Table S2, and water-recovery and constituent-removal rates are reported in Table S4.

evaporation pond. Permeate from the CCRO system will be reused for either cooling-tower makeup or service—water makeup. Concentrate from the CCRO system will be collected in a 28 300 m^2 (seven-acre) evaporation pond.

Gila River Power Station. The Gila River Power Station ("Gila") is a 2200 MW NGCC power facility located in Gila Bend, AZ. This facility has been in operation since 2003, is owned by the Salt River Project and Tucson Electric Power, and has been operated by the Salt River Project since mid-2018. Gila has four power blocks, each composed of two combustion turbine generators, two triple-pressure heat-recovery steam generators, and one steam-turbine generator. Unlike Cherokee that was retrofit to become a ZLD facility, Gila was designed and built as a ZLD facility because of strict discharge regulations that would have required Gila to treat its wastewater to a high level prior to discharge. Once high-recovery treatment became necessary to meet discharge regulations, it became more economically feasible to pursue ZLD implementation.

Gila uses groundwater that is stored on-site[133] for cooling tower makeup, service water, and fire protection. The facility originally operated only with ZLD System A shown in Figure 5. ZLD System A has three BCs that each produce 1.4−1.6 m^3/min (300−350 gallons/min) of distillate flow and three evaporation ponds that are 64 750 m^2 (16 acres) each. Before the cooling tower blowdown is processed through the BCs, pH is adjusted, scale inhibitor is added to reduce precipitation of sparingly soluble salts, and antifoaming agents are added to reduce foam formation. BC distillate is either reused for cooling tower makeup or can be further treated with mixed-bed ion-exchange that serves as a final polishing step for dissolved solids and silica prior to use for steam-cycle makeup. In the event that one or more BCs in ZLD system A goes offline, less water is available for steam-cycle makeup and the volume of cooling tower blowdown water discharged to the evaporation ponds increases.

In 2013, a water conservation plan was implemented at Gila to limit the volume of water discharged to the evaporation ponds. As a result of a water-chemistry program to increase the number of cycles in the cooling tower, cooling tower blowdown was reduced by 33% and as a result of new scale inhibitors and antifoaming agents, the service life of the BCs was extended by 25%.[134] Still, due to unreliable operation of the BCs, the evaporation ponds were being filled to near-capacity.

In 2021, an additional system was installed at Gila to treat cooling tower blowdown and reduce the volume of water sent to the evaporation ponds. The new treatment system (ZLD System B in Figure 5) includes ultrafiltration and RO processes that can be run in single- or double-pass. At the same time the new system was commissioned, improvements to BC operation reduced BC downtime so that less blowdown water was being discharged directly to the evaporation ponds. The new RO treatment system was no longer needed to solely treat cooling tower blowdown water but did provide the added capability of treating raw groundwater for steam-cycle makeup if needed. In Figure 5, the cooling tower blowdown is split between the thermal brine concentrators in ZLD System A and the UF/RO system in ZLD System B. Although the volume of blowdown split between ZLD Systems A and B varies, this study is modeled with 91% of the blowdown water sent to ZLD System A and 9% sent to ZLD System B.

3.1.2. Evaluation Using Water Techno-economic Assessment Pipe-Parity Platform (WaterTAP3). The Water Techno-economic Assessment Pipe-Parity Platform (WaterTAP3)[135] was used to model the current baseline and two alternative scenarios for both Cherokee and Gila. Technoeconomic assumptions and system- and unit-level configuration assumptions for Cherokee and Gila are reported in Tables S3 and S5. For Cherokee, the facility's current non-ZLD scenario is compared with the pending ZLD scenario using CCRO (ZLD-CCRO) and a comparison scenario with a conventional BC (ZLD-BC). For Gila, the facility's baseline ZLD operation

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utilizing a BC and a supplemental RO (ZLD-BC/RO) is compared with alternative scenarios of operation with two BC processes (ZLD-2BC) or with two RO processes (ZLD-2RO). Additional analysis was performed to determine how evaporation pond area influences ZLD system design considerations and costs. The pipe-parity metrics evaluated include water recovery, levelized cost of water (LCOW), percent of LCOW attributed to electricity, electricity cost, electricity intensity, auxiliary electricity consumption, and the water treatment cost component of the levelized cost of electricity ($LCOE_{water}$). Equations to calculate these metrics can be found in Miara et al.[135] Some equations specific to the objectives of this paper are shown below.

Water recovery (WR) is the percentage of water recovered for beneficial use and is calculated using

$$WR = \frac{Q_{out}}{Q_{in}} 100\% \tag{1}$$

where Q_{out} is flow rate of useful water out of the system (m^3/s) and Q_{in} is flow rate of water into the system (m^3/s). Water recovery can be determined for an individual process (e.g., CCRO or BC) or an entire ZLD system.

LCOW is the cost per unit volume of product water from a wastewater treatment system ($\$/m^3$). It is the sum of the following individual components:

$$LCOW = LCOW_{TCI} + LCOW_{chem} + LCOW_{elec} + LCOW_{O\&M} \tag{2}$$

where $LCOW_{TCI}$ is the portion of LCOW attributed to the total capital investment (TCI), $LCOW_{chem}$ is the portion attributed to chemical costs, $LCOW_{elec}$ is the portion attributed to electricity costs, and $LCOW_{O\&M}$ is the portion attributed to operation and maintenance (O&M) costs. $LCOW_{TCI}$ is calculated using

$$LCOW_{TCI} = \frac{f_{recov}\, TCI}{V_{treat} f_{util}} \tag{3}$$

where f_{recov} is the capital recovery factor calculated using eq 4 below, TCI is total capital investment ($M) calculated using eq 5 below, V_{treat} is the volume of water treated (m^3), and f_{util} is the percent of facility capacity being utilized. f_{recov} is calculated using

$$f_{recov} = \frac{WACC(1 + WACC)^L}{(1 + WACC)^L - 1} \tag{4}$$

where WACC is the weighted average capital cost (debt interest rate in percentage) and L is plant lifetime (years). TCI from eq 3 is calculated using

$$TCI = FCI + C_{land} + C_{work} \tag{5}$$

where FCI is fixed capital investment, C_{land} is land cost, and C_{work} is working capital (all in $M).

$LCOW_{chem}$ from eq 2 is calculated using

$$LCOW_{chem} = \frac{C_{chem}}{V_{treat} f_{util}} \tag{6}$$

where C_{chem} is annual chemical costs measured in $M/yr. C_{chem} is calculated by summing the costs of all chemicals used:

$$C_{chem} = \sum_k^n D_k C_k Q_{in} f_{util} \tag{7}$$

where D_k is dose of chemical k (up to n chemicals) measured in mass of chemical per unit volume of water treated (kg/m^3) and C_k is unit cost of chemical k measured in dollars per mass of chemical ($/kg).

$LCOW_{elec}$ from eq 2 is calculated using

$$LCOW_{elec} = \frac{C_{elec}}{V_{treat} f_{util}} \tag{8}$$

where C_{elec} is the annual electricity cost ($M/yr), which is calculated by summing the electricity costs for all treatment processes:

$$C_{elec} = \sum_k^n E_k Q_{in} f_{util} P \tag{9}$$

where E_k is electricity intensity of unit k (up to n units) and P is price of electricity for the facility locale (0.074 $/kWh for Cherokee and 0.0628 $/kWh for Gila). E_k is modeled differently for each unit. For example, E_k values for units that utilize pumps (e.g., chemical dosing systems) are based on pumping efficiencies and flow rates and E_k values for desalination units (e.g., RO systems) are based on flow rates, total dissolved solids concentrations, and water-recovery rates.

$LCOW_{O\&M}$ from eq 2 is calculated using

$$LCOW_{O\&M} = \frac{C_{op,an}}{V_{treat} f_{util}} \tag{10}$$

where $C_{op,an}$ is annual operating cost ($M/yr), which is calculated using

$$C_{op,an} = C_{chem} + C_{elec} + C_{op,tot} \tag{11}$$

where $C_{op,tot}$ is total fixed operating cost ($M).

The percent of LCOW attributed to electricity (% LCOW attributed to electricity) does not consider capital costs or the amount of water treated; it is calculated using

$$\%\ \text{LCOW attributed to electricity} = \frac{LCOW_{elec}}{LCOW} 100\% \tag{12}$$

Electricity intensity (E_{sys}) is the measure of electricity consumed per volume of product water from the entire system (kWh per m^3 of product water) and can be calculated by summing E_k values for all electricity-consuming units. It can also be calculated using

$$E_{sys} = \frac{C_{elec}}{P V_{treat}} \tag{13}$$

Quantification of the electricity required by a ZLD system is also important because facilities are often interested to know how much reduction of total electricity generated will result from ZLD implementation. Auxiliary electricity consumption (E_{aux} in MWh) is the electricity required for all treatment processes and is calculated using

$$E_{aux} = E_{sys} V_{treat} h_{annual} \tag{14}$$

where h_{annual} is the annual hourly operation. Although power facilities do not operate at full capacity at all times, full capacity (8760 h) was modeled in this study to represent cases where cooling systems are kept operational even when facilities are

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Table 1. Summary of Water-Related Metrics for Cherokee Generating Station

	Cherokee Generating Station				
	non-ZLD baseline	ZLD-CCRO	variation from baseline	ZLD-BC	variation from baseline
water recovery from blowdown (%)	0	93		88	
water reuse (m^3/s)	0	0.033		0.031	
water withdrawals (m^3/s)	0.23	0.19	0.82X	0.19	0.82X
levelized cost of water, LCOW ($\$/m^3$)	0.47	0.97	2.1X	2.9	6.3X

not generating electricity. Alternatively, E_{aux} can be calculated using

$$E_{aux} = h_{annual} \sum_{k}^{n} E_k Q_{in} \tag{15}$$

Finally, the annualized cost of water treatment per unit of electricity generated by a power facility ($LCOE_{water}$ in \$/MWh) is calculated using

$$LCOE_{water} = \frac{LCOW\, V_{treat}}{\text{annual electricity generation}} \tag{16}$$

where the denominator is the annual electricity generation of the facility for a specified scenario measured in MWh. According to 2020 EIA data, annual electricity generation values for the baseline scenarios are 3×10^6 MWh for Cherokee (NGCC portion only) and 11×10^6 MWh for Gila.[136] Annual electricity generation values for the alternative scenarios were calculated (using annual electricity generation $-$ ($E_{aux,alternative} - E_{aux,baseline}$)); the differences from the baseline values were found to be insignificant so the baseline values were used for all scenarios.

Metrics are compared between scenarios using "variation from baseline", which is simply the ratio of the alternative scenario to the baseline scenario. Variation from baseline was selected because the values, which ranged from 0.1 to 370 times, could be more easily conceptualized than values of percent difference, which ranged from 5 to 5000%.

Unit processes in WaterTAP3 achieve mass balance subject to water-recovery and constituent-removal factors or equations that represent key physical constraints. In addition, there are technical and costing parameter options for each unit process that can be customized for a given treatment train and unit process. For the reverse-osmosis processes, mass balances across the membrane, feed and osmotic pressures, and required membrane areas are calculated on the basis of LCOW optimization and the known volumetric flows across the treatment systems. Major costs include capital expenses for membranes and pumps and variable operating expenses for membrane replacement and electricity consumption. The BCs are modeled as thermal evaporative processes and costs are a function of flow rates, influent total dissolved solids concentrations, and water-recovery rates. Additional details on the desalination and other units can be found in WaterTAP3 documentation (Miara et al.[135]).

3.2. WaterTAP3 Results. *3.2.1. Summary of results. Water-Related Metrics for Cherokee.* Table 1 summarizes the water-related metrics for Cherokee's baseline and ZLD scenarios. In general, water-recovery, -reuse, and -withdrawal values for the two ZLD scenarios are similar to each other because the water recoveries for the CCRO and BC processes are similar (95 and 90%). In the non-ZLD baseline, no water is recovered from the cooling tower blowdown. When the CCRO or BC process is implemented, 93 or 88% of the cooling tower blowdown is recovered and used as cooling tower makeup water or service water. The availability of this on-site reuse water (0.033 or 0.031 m^3/s) decreases the amount of source water that must be withdrawn from Denver's Metro Water Recovery, Clear Creek, or the Platte River. In both ZLD scenarios, 18% less water withdrawal (0.82 times baseline withdrawals) are required. According to dry-cooling numbers from Loew et al.,[137] if Cherokee's wet recirculating cooling system was retrofitted as a dry-cooling system instead of a ZLD system, it would result in a 35% reduction in water withdrawals, saving 0.08 m^3/s (0.7 billion gal/yr). However, as discussed in section 2.2, the capital costs, energy requirements, and ambient air temperatures required for dry cooling may make dry cooling impractical. For example, Zhai et al.[138] reported a 1.2% average monthly reduction in net capacity for dry cooling at NGCC facilities, which, if translated to Cherokee, would reduce NGCC capacity from 591 to 584 MW. On the other hand, reducing water withdrawals by 18% though ZLD implementation is comparable to efforts to reduce water withdrawals through increasing cycles of concentration. According to the Federal Energy Management Program,[21] by increasing cycles of concentration from three to six, water withdrawals can be reduced by approximately 20%.

The data in Table 1 also show that the ZLD scenarios result in higher LCOW values (2.1 and 6.3 times higher) than the non-ZLD baseline scenario. The higher LCOW values for the ZLD scenarios are attributed to increases in TCI and electricity costs (Figure 6). Figure 6 shows LCOW broken down by

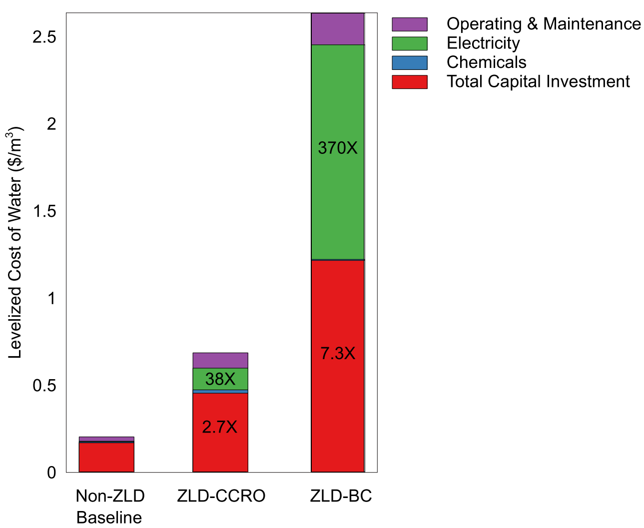

Figure 6. Levelized cost of water (LCOW) for the two ZLD scenarios (ZLD-CCRO and ZLD-BC) are compared with LCOW for the non-ZLD baseline scenario for Cherokee Generating Station. LCOW values are broken down into general cost categories. Further breakdown of the cost categories (i.e., detail of the $LCOW_{TCI}$ and $LCOW_{elec}$ values) is shown in Figure 7.

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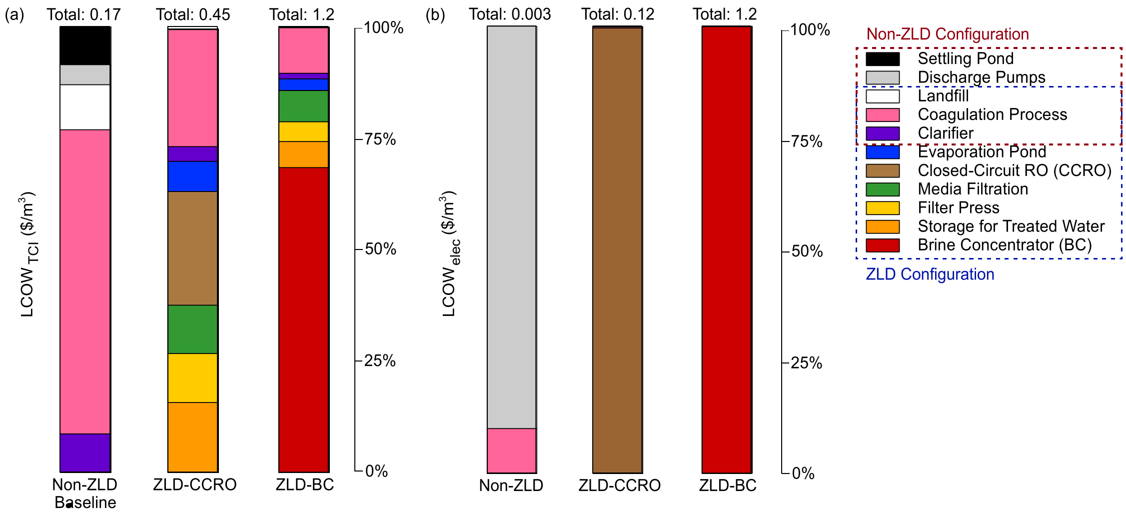

Figure 7. (a) $LCOW_{TCI}$ (as given by eq 3 and shown by the red bars of Figure 6) and (b) $LCOW_{elec}$ (as given by eq 8 and shown by the green bars of Figure 6) broken down by individual treatment processes/units at the Cherokee Generating Station. The units/processes included in the non-ZLD baseline configuration are boxed by the red-dashed line in the legend and the units/processes included in the ZLD configurations are boxed by the blue-dashed line in the legend. LCOW values for the two ZLD scenarios are compared with the non-ZLD baseline scenario. To discern between the processes/units that have smaller contributions to $LCOW_{TCI}$ and $LCOW_{elec}$, the *y* axes are given in percentages (from 0 to 100%). The total LCOW for each scenario is given at the top of each bar.

Table 2. Summary of Electricity Metrics for the Cherokee Generating Station

	Cherokee Generating Station				
	non-ZLD baseline	ZLD-CCRO	variation from baseline	ZLD-BC	variation from baseline
electricity costs, C_{elec} ($M/yr)	0.031	0.20	6.4X	1.6	53X
auxiliary electricity consumption, E_{aux} (MWh)	420	2700		22000	
electricity intensity, E_{sys} (kWh/m^3)	0.30	2.0	6.7X	17	57X
levelized cost of electricity for water treatment, $LCOE_{water}$ ($/MWh)	0.22	0.44	2.0X	1.3	5.8X

general cost category for Cherokee's Wastewater Treatment Train. The Steam-Cycle Treatment Train is excluded because it is the same for the three scenarios. In Figure 6, $LCOW_{TCI}$ (shown in red) increases approximately 2.7 times in the ZLD-CCRO scenario (from 0.17 to 0.45 $/m^3) and 7.3 times in the ZLD-BC scenario (from 0.17 to 1.2 $/m^3); $LCOW_{elec}$ (in green) increases approximately 38 times in the ZLD-CCRO scenario (from 0.003 to 0.12 $/m^3) and 370 times in the ZLD-BC scenario (from 0.003 to 1.2 $/m^3). $LCOW_{O\&M}$ (in purple) increases for the ZLD scenarios but still only comprises 13 and 7% of the LCOW for the CCRO and BC scenarios and $LCOW_{chem}$ (in blue) comprises less than 3% of the three scenarios.

The increases in $LCOW_{TCI}$ and $LCOW_{elec}$ can be explained by considering $LCOW_{TCI}$ and $LCOW_{elec}$ for the individual treatment processes/units in the Wastewater Treatment Train. In Figure 7, the total values (given at the top of each bar) for $LCOW_{TCI}$ and $LCOW_{elec}$ increase significantly between the non-ZLD and ZLD scenarios. In Figure 7a, for the ZLD-CCRO scenario, $LCOW_{TCI}$ increases by 0.29 $/m^3 because the settling pond (shown in black) and discharge pumps (in gray) were replaced with an evaporation pond (in blue); the ZLD-CCRO system, which includes CCRO (in brown), media filtration (in green), a filter press (in yellow); storage for treated water (in orange). The CCRO process accounts for 41% of the increase in $LCOW_{TCI}$ (0.12 $/m^3). The landfill (in white), coagulation process (in pink), and clarifier (in purple) have the same nominal contribution to $LCOW_{TCI}$ but at different percent contributions for each. Similar to results for the ZLD-CCRO scenario, the increase in $LCOW_{TCI}$ for the ZLD-BC scenario (1.05 $/m^3) is attributed to the replacement of the settling pond and discharge pumps with a BC (in red) and an evaporation pond. The BC accounts for 79% of the increase in $LCOW_{TCI}$ (0.83 $/m^3).

In Figure 7b, $LCOW_{elec}$ for the non-ZLD baseline scenario is composed of the coagulation process (shown in pink) and discharge pumps (in gray). The pump energy required to discharge to the Platte River comprises 90% of the non-ZLD scenario but does not appear in the ZLD scenarios because there is no off-site discharge in the ZLD scenarios. The coagulation process comprises approximately 10% of the $LCOW_{elec}$ in the non-ZLD scenario and although the nominal value is unchanged (0.003 $/m^3), coagulation comprises less than 0.3 and 0.03% in the ZLD-CCRO and ZLD-BC scenarios. In the ZLD-CCRO scenario, the CCRO process comprises the overwhelming majority (99%) and in the ZLD-BC scenario, the BC comprises essentially 100%.

Electricity Metrics for Cherokee. The data in Table 2 show the electricity costs for the non-ZLD baseline and ZLD scenarios at Cherokee (including the Steam-Cycle Treatment Train). Comparing the ZLD scenarios to the non-ZLD baseline scenario shows electricity costs increase by 1 order of magnitude for the ZLD-CCRO scenario (from 0.031 to 0.20 $M/yr) and by 2 orders of magnitude for the ZLD-BC scenario (from 0.031 to 1.6 $M/yr). It is clear that the CCRO process offers electricity savings over the BC process—and does this for the higher recovery that was modeled (95 versus 90% for the BC process).

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Again comparing the ZLD scenarios to the non-ZLD baseline scenario shows auxiliary electricity consumption and electricity intensity increase by 1 order of magnitude for the ZLD-CCRO scenario and by 2 orders of magnitude for the ZLD-BC scenario. Comparison of auxiliary electricity consumption values for the ZLD-CCRO and ZLD-BC scenarios (2700 and 22 000 MWh) with the 3 × 10^6 MWh annual electricity generation of Cherokee shows that ZLD implementation results in 0.09 and 0.7% decreases in total electricity generated (taken as a percent difference in comparison to the annual electricity generation). Thus, implementation of either ZLD process will result in minimal reduction in Cherokee's energetic output. In addition, $LCOE_{water}$ values for the ZLD-CCRO and ZLD-BC scenarios (0.44 and 1.3 \$/MWh) account for 1.3 and 3.7% of an average LCOE for a combined-cycle facility (34.51 \$/MWh from[139]) (taken as a percent difference in comparison to the average LCOE for a combined-cycle facility). Therefore, retrofitting a non-ZLD combined-cycle facility to ZLD can decrease water-withdrawal requirements for a relatively small fraction of the entire facility's LCOE. In the interest of electricity savings (regardless of scale), the CCRO process has lower electricity cost, electricity intensity, and LCOE than the BC process. Moreover, CCRO processes may have greater reliability and simpler operation than the BC process,[80,114] which can sometimes be more valued than electricity and cost savings.[80,92]

Water-Related Metrics for Gila. Table 3 summarizes the water-related metrics for Gila's baseline and ZLD scenarios.

Table 3. Summary of Water-Related Metrics for the Gila River Power Station

	Gila River Power Station				
	ZLD-BC/RO baseline	ZLD-2BC	variation from baseline	ZLD-2RO	variation from baseline
water recovery of blowdown (%)	87	90	1.0X	69	0.80X
water reuse (m^3/s)	0.071	0.073	1.0X	0.056	0.80X
water withdrawals (m^3/s)	0.65	0.65	1.0X	0.78	1.2X
levelized cost of water, LCOW (\$/m^3)	4.8	4.9	1.0X	3.5	0.72X

Comparing the ZLD-2BC scenario with the baseline scenario shows there is little change, if any, in water use and cost metrics because the BC process is replacing the supplemental RO process that treats only 9% of cooling tower blowdown water (System B). Comparing the ZLD-2RO scenario with the baseline scenario shows water use and cost metrics change more substantially because the RO process is replacing the BC process that treats 91% of cooling tower blowdown water (System A). Water recovery, water reuse, and LCOW decrease 0.72−0.80 times. Although the ZLD-2RO scenario offers LCOW savings with respect to the baseline scenario (3.5 vs 4.8 \$/m^3 for the baseline), the ZLD-2RO scenario necessitates 1.2 times greater water withdrawals than the baseline scenario. This is because the RO process is currently operated at a relatively low recovery (71%) so the RO process provides less water for reuse. If RO water recovery cannot be increased, then more source water would be needed for the ZLD-2RO scenario to be viable.

In Figure 8, $LCOW_{TCI}$ (shown in red) and $LCOW_{elec}$ (in green) are lowest for the ZLD-2RO scenario, $LCOW_{chem}$ (in blue) is highest for the ZLD-2RO scenario, and $LCOW_{O\&M}$ (in purple) is the same (and only a small percentage of total LCOW) for all three scenarios. Upon comparison of an RO process instead of a BC process in System A, it can be seen that the lower chemical costs of the ZLD-2BC scenario are outweighed by the lower TCI and electricity costs of the ZLD-2RO scenario.

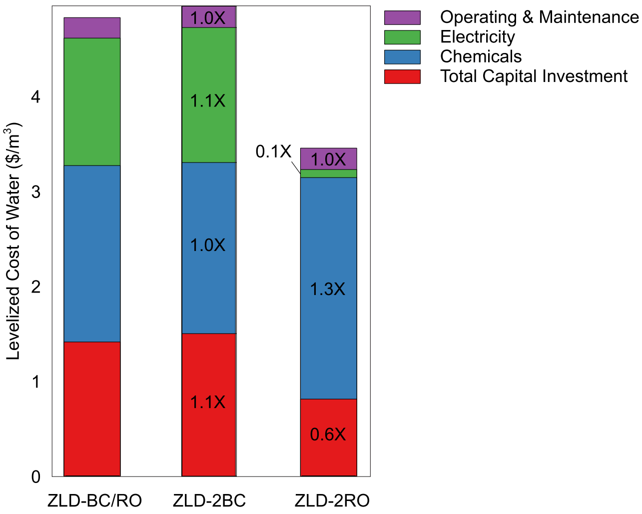

Figure 8. Levelized cost of water (LCOW) for the two alternative ZLD scenarios (ZLD-2BC and ZLD-2RO) compared with LCOW for the ZLD-BC/RO baseline scenario for Gila River Power Station. LCOW values are broken down into general cost categories. Further breakdown of the cost (i.e., detail of the $LCOW_{TCI}$ and $LCOW_{elec}$ values) is shown in Figure 9.

Differences in $LCOW_{TCI}$ and $LCOW_{elec}$ can be explained by considering $LCOW_{TCI}$ and $LCOW_{elec}$ for the individual treatment processes/units. In Figure 9, the total values (given at the top of each bar) for $LCOW_{TCI}$ and $LCOW_{elec}$ are significantly lower for the ZLD-2RO scenario than for the BC scenarios (ZLD-BC/RO and ZLD-2BC). $LCOW_{TCI}$ results (Figure 9a) are similar for the ZLD-BC/RO and ZLD-2BC scenarios where the BCs (System A BC in red and System B BC in orange) comprise the majority of $LCOW_{TCI}$. In the ZLD-2RO scenario, the evaporation ponds (in yellow) comprise 43% of the $LCOW_{TCI}$ and the RO processes (System A RO in blue and System B RO in brown) comprise 37%. $LCOW_{elec}$ results (Figure 9b) are also similar for the ZLD-BC/RO and ZLD-2BC scenarios where the BC processes comprise almost all of the $LCOW_{elec}$. In the ZLD-2RO scenario, the RO processes comprise 88% of $LCOW_{elec}$. The remaining 22% of $LCOW_{elec}$ is composed of mixed-bed ion exchange (in green), pumping energy to transport reuse water (in purple), and ultrafiltration (in gray); these processes have the same nominal contribution to $LCOW_{elec}$ in all scenarios but larger percent contributions in the ZLD-2RO scenario.

Electricity Metrics for Gila. The data in Table 4 show electricity metrics for Gila's baseline and alternative ZLD scenarios. Similar to the water-related metrics, results for the BC scenarios (ZLD-BC/RO and ZLD-2BC) have similar values and the ZLD-2RO scenario has lower values. Similar to the results for Cherokee, comparison of auxiliary electricity consumption values for the ZLD systems to the 11 × 10^6

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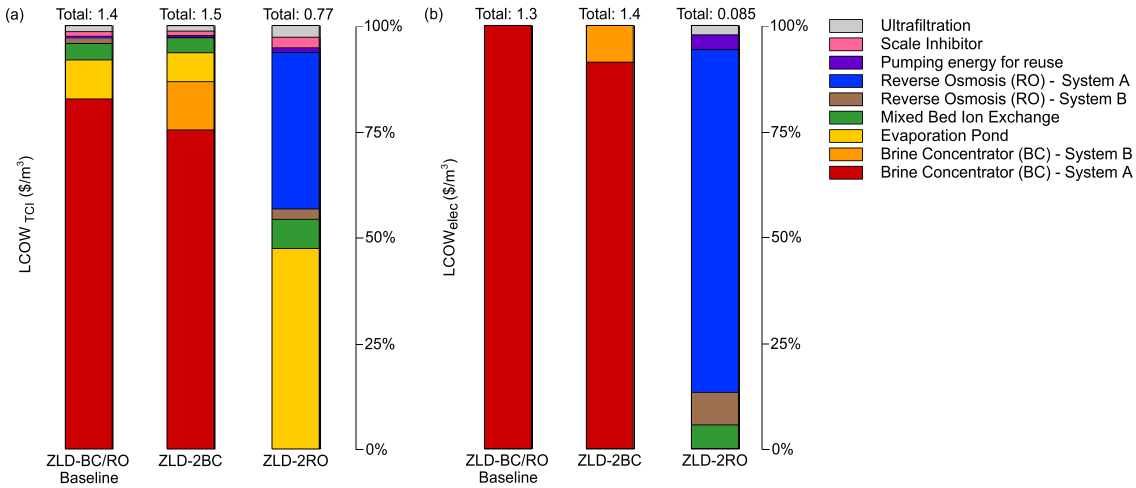

Figure 9. (a) $LCOW_{TCI}$ (as shown in eq 3 and red bars in Figure 8) and (b) $LCOW_{elec}$ (as shown in eq 8 and green bars in Figure 8) broken down by individual treatment processes/units at Gila River Power Station. LCOW values for the two alternative ZLD scenarios are compared with the ZLD-BC/RO baseline scenario. To discern between the processes/units that have smaller contributions to $LCOW_{TCI}$ and $LCOW_{elec}$ the y axes are given in percentages (from 0 to 100%). The total LCOW for each scenario is given at the top of each bar. are still discernible.

Table 4. Summary of Electricity Metrics for Gila River Power Station

	Gila River Power Station				
	ZLD-BC/RO baseline	ZLD-2BC	variation from baseline	ZLD-2RO	variation from baseline
electricity costs, C_{elec} ($M/yr)	3.0	3.3	1.1X	0.15	0.050X
auxiliary electricity consumption, E_{aux} (MWh)	47000	52000		2400	
electricity intensity, E_{sys} (kWh/m^3)	21	23	1.1X	1.4	0.067X
levezed cost of electricity for water treatment, $LCOE_{water}$ ($/MWh)	1.0	1.0	1.1X	0.56	0.57X

MWh annual electricity generation shows that the ZLD systems reduce the total electricity generated by less than 0.5% (taken as a percent difference in comparison to the annual electricity generation). In addition, $LCOE_{water}$ values for the ZLD systems account for less than 2.9% of an average LCOE for a combined-cycle facility (34.51 $/MWh[139]) (taken as a percent difference in comparison to the average LCOE for a combined-cycle facility). It is again noted that the RO process provides substantial electricity cost savings over the BC process.

3.2.2. Evaporation-Pond Area and Water Recovery Required from ZLD Technology. Decisions regarding the water recovery at which the ZLD technology should operate must consider that operation at lower water recovery reduces energy requirements but increases capital and O&M costs associated with larger evaporation pond area. As seen in Figures 10a (Cherokee) and 10b (Gila), as the evaporation pond area increases, the required facility water recovery decreases; this is because more water can be discharged to the evaporation pond so less water must be recovered. Recovery is presented as total recovery within the facility, which accounts for residual water discharged from the RO or BC process and, also, water lost to evaporation in the cooling tower. For Cherokee, the facility water recovery of 18.5% (indicated by the black star) corresponds to a CCRO water recovery of 95% and for Gila, the facility water recovery of 11% (indicated by the black star) corresponds to a BC/RO water recovery of 90%. Figure 10 panels c−h show additional metrics as a function of both increasing water recovery (now on the bottom axis) and decreasing evaporation pond area (on the top axis).

The data in Figure 10c,d generally show that LCOW decreases with increasing water recovery (decreasing evaporation pond area) for Cherokee and Gila. On the basis of eq 2, LCOW considers both energetic costs, which increase with water-recovery rate, and monetary (capital and operating) costs, which increase with evaporation pond area. Although there are energetic savings as water recovery decreases, there is a lower volume of product water, which results in a higher LCOW. However, there is an exception for Cherokee (Figure 10c); at facility recoveries greater than approximately 18% (ZLD CCRO system recovery greater than 93%), higher water recoveries result in higher LCOWs, indicating that the increasing costs of LCOW (e.g., membrane area and electricity) outweigh the increasing volume of product water.

LCOW results for Cherokee below approximately 18% facility recovery (93% ZLD system recovery) and for Gila over the entire recovery range show that facilities may be incentivized to operate at higher recoveries and limit evaporation pond area. However, on the basis of interviews with facilities (see ref 80), this is generally not done in practice. Instead, facilities may prefer to use all evaporation pond area available to maintain status quo, simplify operation, and limit auxiliary electricity consumption caused by increased recovery rates. Especially for facilities that already have evaporation ponds or own the land (and do not have to make a capital purchase), this may be the case.

Figure 10 panels e and f show %$LCOW_{elec}$, which excludes capital costs for land acquisition. %$LCOW_{elec}$ decreases with increasing evaporation pond area, even for Cherokee above 18% facility recovery. Thus, if considering only electricity costs of LCOW, operating at lower recovery rates (with larger evaporation ponds) is indeed more desirable.

Similar to LCOW, electricity intensity (Figure 10g,h) is normalized to the volume of product water. For Gila (Figure 10h), electricity intensity decreases with increasing water recovery or decreasing evaporation pond area due to the

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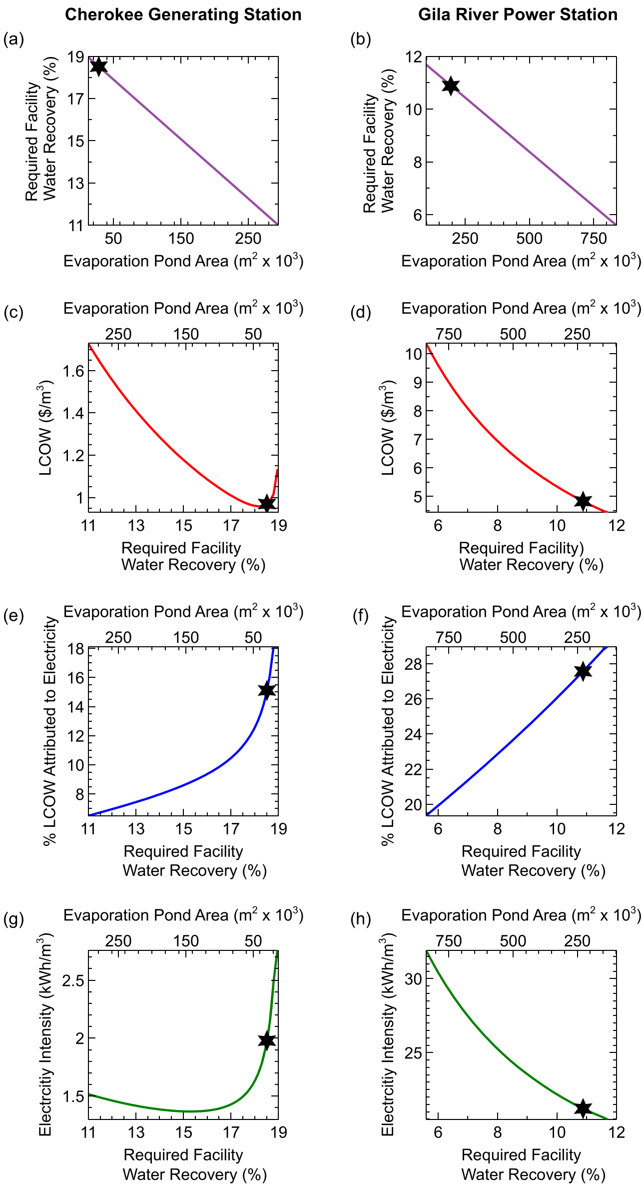

Figure 10. Relationship between required facility water recovery and evaporation pond area for (a) Cherokee Generating Station and (b) Gila River Power Station. Analyses evaluating the impact of facility water recovery and evaporation pond area on (c) Cherokee's LCOW, (d) Gila's LCOW, (e) Cherokee's percent LCOW attributed to electricity, (f) Gila's percent LCOW attributed to electricity, (g) Cherokee's electricity intensity, and (h) Gila's electricity intensity. The black stars indicate the existing evaporation pond areas for Cherokee (28 300 m^2) and Gila (194 250 m^2); the corresponding facility water recoveries (18.5% for Cherokee and 11.4% for Gila) were used in the modeling.

smaller volume of product water. For Cherokee (Figure 10g), at recoveries greater than 16% (evaporation pond areas less than 142 000 m^2 (35 acres)), electricity intensity increases with increasing water recovery; at recoveries less than 16%, electricity intensity decreases with increasing recovery. The reason there is a difference in water recovery at which LCOW reaches a minimum (18%) and that at which electricity intensity reaches a minimum (16%) is the nonelectricity costs that contribute to LCOW (e.g., evaporation pond liners).

To further evaluate the relationship between electricity intensity and water recovery for Cherokee, the electricity intensity of the CCRO process alone is shown in Figure 11a and the electricity intensity of the rest of the ZLD system (excluding the CCRO process) is shown in Figure 11b. Electricity intensity of the CCRO process increases as water recovery increases (Figure 11a) because higher operating pressures are needed to achieve higher recoveries. The electricity consumption of the rest of the ZLD system (Figure 11b) remains relatively constant. The slight decrease in electricity intensity with increasing water recovery is because of the increasing volume of permeate. Combination of the curves in Figure 11a,b gives the electricity intensity of the overall system in Figure 11c, which is the same curve as in Figure 10g but with a different *y*-axis range. At water recoveries less than 16%, the relatively constant electricity intensity of the system (excluding the CCRO process) dominates and the system operates with slightly more energy efficiency with increasing recovery. At water recoveries greater than 16%, the increasing electricity intensity of the CCRO process dominates and the system operates with lower energy efficiency with increasing recovery. Electricity intensity is an important parameter to identify the minimum that does not appear in the graph of %LCOW attributed to electricity (i.e., Figure 10e).

However, it should be noted that the electricity needed to reach consistently high recoveries in ZLD systems varies between systems and depends on the water quality of the blowdown.[116] Also, power facilities often experience transient operation and shutdowns (both scheduled and unscheduled) because of fluctuating demand from the grid and power source availability;[140−143] this results in varying water usage,[144] volume of cooling tower blowdown, and water quality, all of which affect the recoveries of RO and BC processes and ZLD system performance[80,116] In particular, future research should aim to understand the impact of transient operation on the performance and lifetime of RO membranes in ZLD systems.

4. CONCLUSIONS AND IMPLICATIONS

Facilities affected by increasingly stringent discharge regulations are implementing ZLD approaches that use thermally driven or pressure-driven desalination processes along with onsite evaporation ponds or deep-well injection. WaterTAP3 results show that for a case study NGCC facility, implementation of a ZLD-CCRO system results in a doubling (a two-times increase) of LCOW and implementation of a BC system results in a 6-times increase. Comparison of the relatively new high-recovery RO process with a conventional BC process shows that for similar water recoveries, the CCRO process requires an order of magnitude less electricity than the BC process. Although decreased costs can be a motivating factor to opt for high-recovery RO processes over BC processes, facilities may be more incentivized to implement RO processes because of their operational simplicity and reliability. Future research should consider other emerging high-recovery RO systems, including flow-reversal systems and others shown in the Water Desalination Report.[145] Technologies that combine semibatch and flow-reversal techniques may be the best path toward reducing scaling potential and decreasing reliance on scale inhibitors and other chemicals.

For both case study facilities, auxiliary electricity consumption of the ZLD systems was less than 0.8% of the annual electricity generation. Knowing that ZLD systems require so little of the electricity generated, facilities may have greater motivation to implement these systems and to operate at high

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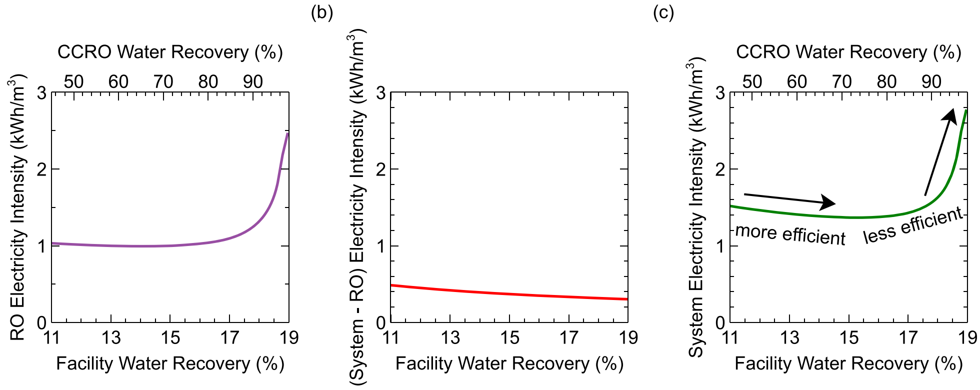

Figure 11. Relationship between electricity intensity and facility recovery for Cherokee Generating Stations' (a) CCRO process and (b) all processes/units in ZLD system aside from CCRO (c) the overall ZLD system.

water recoveries. As it is now, facilities may prefer to maximize available evaporation pond area and operate ZLD processes at lower recovery rates. Using a high-recovery RO process as the ZLD technology instead of the BC process results in lower electricity and monetary costs.

A positive corollary of ZLD implementation is that the desalinated product water can be reused in the facility and can decrease required water withdrawals, which could lower costs if water is purchased from a municipality or reduce the environmental impact if water is withdrawn from surface or groundwater sources. However, model results show that reducing water withdrawals through increased water reuse does not result in substantial cost savings. At a case study NGCC facility, where water withdrawals decreased by 18% with ZLD implementation (which is comparable with current efforts to decrease withdrawals by increasing cycles of concentration[21]), LCOW and electricity supply costs increase by an order of magnitude. This seeming contradiction is in large part due to the low cost that the facility pays for its source water. This is also the experience of other facilities (e.g., Southern California Edison that was discussed in the Introduction) that do not see substantial cost savings as the result of reducing water use. Thus, discharge regulations are currently the main driver for increased water-reuse practices at power facilities; however, as the cost of water increases, the incentive for water reuse will increase as well. Also, in striving to build more sustainable power and water systems, power companies may see corporate−community value in reducing water withdrawals even though it does not result in electricity or monetary cost savings.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsestengg.1c00377.

WaterTAP[3] model inputs specific to the case studies presented in the main text, including source water flow rates, source water constituent levels, technoeconomic assumptions, recovery rates, and system configuration assumptions (PDF)

■ AUTHOR INFORMATION

Corresponding Author

Amy E. Childress − *Sonny Astani Department of Civil and Environmental Engineering, University of Southern California, Los Angeles, California 90089, United States*; orcid.org/0000-0002-7829-9861; Email: amyec@usc.edu

Authors

Sophia L. Plata − *Swarthmore College, Swarthmore, Pennsylvania 19081, United States*

Connie L. Devenport − *Sonny Astani Department of Civil and Environmental Engineering, University of Southern California, Los Angeles, California 90089, United States*

Ariel Miara − *National Renewable Energy Laboratory, Golden, Colorado 80401, United States*; orcid.org/0000-0001-7089-4765

Kurban A. Sitterley − *National Renewable Energy Laboratory, Golden, Colorado 80401, United States*

Anna Evans − *National Renewable Energy Laboratory, Golden, Colorado 80401, United States*

Michael Talmadge − *National Renewable Energy Laboratory, Golden, Colorado 80401, United States*

Kurt M. Van Allsburg − *National Renewable Energy Laboratory, Golden, Colorado 80401, United States*

Parthiv Kurup − *National Renewable Energy Laboratory, Golden, Colorado 80401, United States*

Jordan Cox − *National Renewable Energy Laboratory, Golden, Colorado 80401, United States*

Samuel Kerber − *Colorado School of Mines, Golden, Colorado 80401, United States*

Andrew Howell − *Electric Power Research Institute, Palo Alto, California 94304, United States*

Richard Breckenridge − *Electric Power Research Institute, Palo Alto, California 94304, United States*

Cheyenna Manygoats − *Salt River Project, Tempe, Arizona 85281, United States*

Jennifer R. Stokes-Draut − *Lawrence Berkeley National Laboratory, Berkeley, California 94720, United States*

Jordan Macknick − *National Renewable Energy Laboratory, Golden, Colorado 80401, United States*

Complete contact information is available at: https://pubs.acs.org/10.1021/acsestengg.1c00377

Notes

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