ACS ES&T Engineering

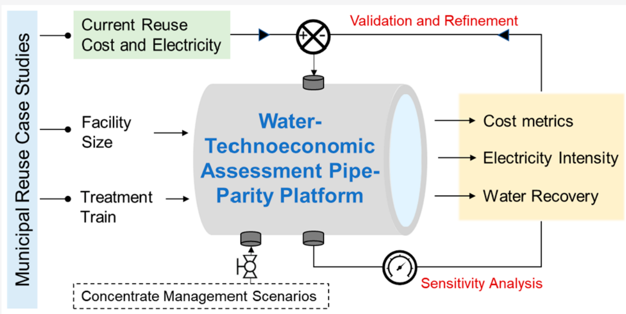
pubs.acs.org/estengg Article

Cost and Energy Metrics for Municipal Water Reuse

Daniel E. Giammar,* David M. Greene, Anushka Mishrra, Nalini Rao, Joshua B. Sperling, Michael Talmadge, Ariel Miara, Kurban A. Sitterley, Alana Wilson, Sertac Akar, Parthiv Kurup, Jennifer R. Stokes-Draut, and Katie Coughlin

Cite This: https://doi.org/10.1021/acsestengg.1c00351 Read Online

ACCESS | Metrics & More | Article Recommendations | Supporting Information



ABSTRACT: Municipal water reuse can contribute to a circular water economy in different contexts and with various treatment trains. This study synthesized information regarding the current technological and regulatory statuses of municipal reuse. It provides process-level information on cost and energy metrics for three potable reuse and one nonpotable reuse case studies using the new Water Techno-economic Assessment Pipe-Parity Platform (Water-TAP3). WaterTAP3 enabled comparisons of cost and energy metrics for different treatment trains and for different alternative water sources consistently with a common platform. A carbon-based treatment train has both a lower calculated levelized cost of water (LCOW) (\$0.40/m^3) and electricity intensity (0.30 kWh/m^3) than a reverse osmosis (RO)-based treatment train (\$0.54/m^3 and 0.84 kWh/m^3). In comparing LCOW and energy intensity for water production from municipal reuse, brackish water, and seawater based on the largest facilities of each type in the United States, municipal reuse had a lower LCOW and electricity than seawater but higher values than for production from brackish water. For a small (2.0 million gallon per day) inland RO-based municipal reuse facility, WaterTAP3 evaluated different deep well injection and zero liquid discharge (ZLD) scenarios for management of RO concentrate. Adding ZLD to a facility that currently allows surface discharge of concentrate would approximately double the LCOW. For all four case studies, LCOW is most sensitive to changes in weighted average cost of capital, on-stream capacity, and plant life. Baseline assessments, pipe parity metrics, and scenario analyses can inform greater observability and understanding of reuse adoption and the potential for cost-effective and energy-efficient reuse.

KEYWORDS: *Water Reuse, Technoeconomic Analysis, Zero Liquid Discharge, Levelized Cost of Water*

1. INTRODUCTION

1.1. Overview of Municipal Water Reuse.

Improving the security, cost effectiveness, and energy efficiency of water treatment and reuse has significant implications for the economy, environment, and adaptations to future water demands or risks to supply. Integrated approaches to reuse of treated municipal wastewater can enable sustainable and efficient water management. In this paper, we refer to these approaches as "municipal reuse" and to the product they produce as "recycled water". Expanding municipal reuse is critical as cities respond to and plan for population growth, rising water demands, and climate change and related stressors due to declines in or competition for existing water supplies, groundwater overuse impacts, increased frequency and intensity of droughts, and saltwater intrusion.[1,2] Brown et al.[3] estimates that by 2071 nearly half of the 204 freshwater basins in the United States (U.S.) may not be able to meet monthly water demands. In recent years, the deployment of new facilities to augment existing water supplies with municipal reuse has increased significantly.

Municipal reuse involves the treatment of municipal wastewater for the purposes of potable and nonpotable reuse in municipal, electric power, agriculture, industrial, and other water end-use sectors.[4,5] Potable reuse is the deliberate introduction of advanced treated water as part of a drinking water supply. Nonpotable reuse (NPR), which represents the majority of current and planned reuse, meets end uses that do not involve drinking water supply. These uses range from irrigation to use by industry and thermoelectric power plants. The value of different classifications, including reclaimed water for power plant cooling,[6,7] and a review of definitions and key sustainability performance metrics for reuse are available in several reports[4] and studies at various scales.[8−11] Another category, de facto reuse, occurs when a drinking water supply

Special Issue: Technology Baselines and Innovation Priorities for Water Treatment and Supply

Received: September 23, 2021
Revised: November 18, 2021
Accepted: November 22, 2021

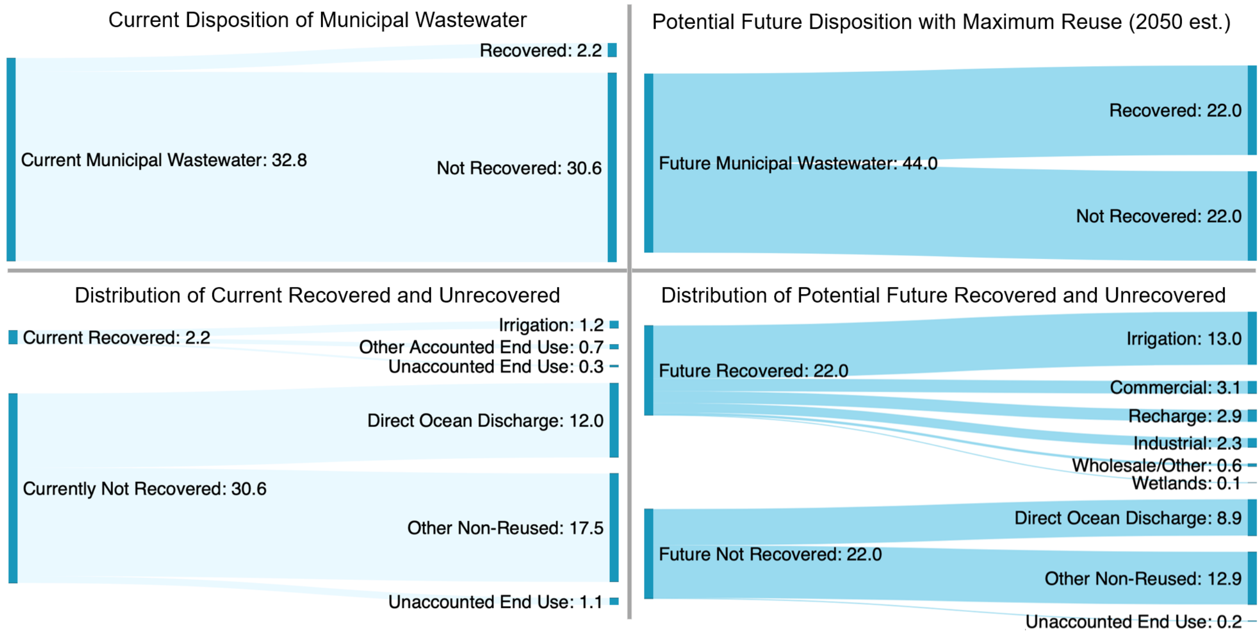


Figure 1. Current and potential future dispositions of municipal wastewater in the United States. Volumes given in billions of gallons per day. Figure prepared using information from the National Water Reuse Action Plan[42] and National Database of Water Reuse Facilities Summary Report.[43]

contains a significant fraction of treated wastewater discharges,[12,13] and it is the most common form of reuse in the United States and probably globally.

Recent California legislation grouped potable reuse into four types of applications: (1) groundwater augmentation, (2) reservoir water augmentation, (3) raw water augmentation, and (4) treated water augmentation.[5,14] Treated water augmentation is the introduction of advanced treated water directly into a public potable water system. Raw water augmentation is the introduction of recycled water into a raw water supply immediately upstream of a water treatment plant. Surface water augmentation and groundwater augmentation occur when recycled water is provided for potable purposes using an environmental buffer (lake, reservoir, river, or aquifer) before water is treated at a drinking water treatment plant.[1] Other classifications or applications of potable reuse seek to distinguish between direct and indirect use, with treated and raw water augmentation being direct potable reuse (DPR) and groundwater and reservoir water augmentation being indirect potable reuse (IPR).

Municipal water reuse offers significant untapped water supplies in areas experiencing population growth, uncertainty in availability of water supplies, and water shortages. While the majority of municipal water reuse relies on centralized facilities, decentralized NPR treatment systems are an emerging approach for collecting, treating, and reusing water within the fenceline of a building or campus or among adjacent buildings. Fit-for-purpose treatment approaches for municipal water reuse have the potential to save water, reduce production costs, and decrease energy demands.[15] This is due to both the introduction of new technologies to provide water at specific quality standards for each reuse objective or end-user application and also new water and wastewater infrastructure system configurations that eliminate unnecessary treatment and long-range distribution and conveyance.

In the U.S., there are over 40 IPR facilities and a handful of DRP facilities under study, in design, undergoing approval, or already in operation.[16] In California, there are currently nine permitted groundwater augmentation facilities, with existing production estimated at 207,500 acre-feet per year (AFY). There are plans for 24 more groundwater augmentation facilities (an additional 310,500 AFY), five more reservoir water augmentation facilities (119,000 AFY), and three more raw water augmentation facilities (~91,000 AFY). In total, California's planned potable reuse capacity could reach an estimated 728,000 AFY, serving ~5.8 million people, or more than ~1/8 of the 2020 population.[17]

Municipal reuse can supply water for nonmunicipal purposes as well, including power plants. Using alternative water in power plants can bring a reliable source of sufficient water quality to power plants, reduce water-related risks, and potentially provide regulatory or reputational benefits.[18] Power plants require water for cooling, boiler feedwater, scrubber solutions, wastewater treatment, and dilution, among other processes. Power plants use a variety of alternative water sources to reduce pressure on freshwater or groundwater resources.[19−23] In 2015, a reported 203.2 million gallons per day (MGD) (227,600 AFY) of recycled water was used for thermoelectric power generation.[24] Due to limitations in how reuse was reported, this may be an underestimate.

In 2005 and 2015, the thermoelectric power sector accounted for 49% and 41% of total water withdrawals, respectively, with several case studies emerging as national best practices of municipal reuse at electric utilities.[24,25] This decline is expected to continue with higher penetrations of less water-intensive renewable electricity.[26] At the same time, the economic cost of building or retrofitting existing treatment facilities, either at the power plant or wastewater treatment plant (WWTP), can be a key determinant in the potential for reuse in power plants. Geographic proximity of municipal reuse sources to power plants is an important factor in a power plant's use of municipal recycled water for cooling and other processes. An estimate of 81% of power plants proposed for construction have the potential for use of a municipal effluent

Table 1. Relevant Regulatory and Planning Considerations That Influence Municipal Reuse Decisions

		Municipal reuse			
		Favorable	Neutral	Unfavorable	Reason
Federal	Safe Drinking Water Act	x			Avoided effluent discharge
	Clean Water Act		x		No issue
	National Environmental Production Act	x			Reduces raw water withdrawals
	Endangered Species Act	x			Does not incur environmental review
State	Ocean protection	x			Avoids effluent discharge
	GW management	x			Reduces GW withdrawals
	Restrictions on reuse			x	Limits applications
	Reuse quality standards		x		Could raise or lower costs
	Water rights			x	May be complicated if return flows are committed to downstream users
Local	Conservation/Efficiency			x	Decreases in flows
	Cost recovery		x		Aligns most closely with existing operations
	Conveyance costs			x	Requires dual piping for NPR
	Drought proofing		x	?	Reuse supply will decrease during droughts but may be less impacted than surface water sources
	Local control	x			Locally owned and operated, often in collaboration with wastewater utility or regional water district
	Public acceptance		x		Initial poor image improving

supply within a 10-mile radius of the plants.[27,28] When considering geographical proximity, the cost difference between recycled water and conventional freshwater supplies for power plants can vary. Often, further treatment at the power plant is required to reduce nutrient, microbial, or contaminant levels to minimize scaling, corrosion, and biofouling that could otherwise occur.[29] One of the main drivers for use of municipal effluent in power plants is the regulatory requirement for certain levels of water quality.[6] Constituents of potential concern for power plant operations include Na, Ca, Mg, alkalinity, Cl, SO_4, SiO_2, pH, B, NO_3, Ba, Sr, and total organic carbon.[18,30] A joint workshop with wastewater and electric utility experts described key characteristics of successful recycled water use in power plants that included active collaboration, clearly defined water quality and flow rates, optimal and adaptable system design and regulatory compliance, and outreach.[25] Case study reviews of municipal recycled water use in power plants found that benefits include reduction of permitted discharges, elimination of stormwater discharge, increased revenue, facilitation of wastewater treatment plant siting, cost reduction, and improving watershed stewardship.[18]

1.2. Current Status, Emerging Trends, and Principal Drivers in Municipal Reuse. U.S. municipal wastewater treatment plants (WWTPs) currently treat an estimated 33 billion gallons per day (BGD); only an estimated 1.8 BGD (or 6.6%) is recovered for reuse (Figure 1).[31] The amount of recycled water in the U.S. has been growing at about 5% annually from 2013.[32] With about half of U.S. cities expected to be water stressed by 2050, a municipal reuse rate of 50% may represent an upper limit on future reuse. Globally, nearly 1000 cubic kilometers of wastewater (724 BGD) is generated annually, with an estimated $50 billion dollars spent to treat only a fraction of wastewater.[33] A recent study estimated that globally only 1.7% of municipal wastewater is reused.[34] The estimated breakdown of municipal reuse after advanced treatment includes 32% to agricultural end uses, 20% to landscaping end uses, 19.3% to industrial uses, 8.3% to municipal nonpotable uses, 8.0% to environmental uses, 6.4% to recreational uses, 2.3% to IPR, 2.1% to groundwater recharge, and 1.6% to other water uses.[35]

Reuse has been developed primarily in regions where new freshwater supplies are highly constrained. In some water-stressed countries, over 80% of wastewater is reused for agricultural irrigation.[36] In Israel, where freshwater resources are expected to decline in the future, about 90% of wastewater effluent is currently treated for reuse in the agricultural sector.[37] In Singapore, the densely populated and land-scarce city-state aims to reach 100% municipal reuse for all possible uses. Currently, their NEWater scheme supplies up to 40% of Singapore's water use.[15,38,39] The longest running DPR facility is in Windhoek, Namibia, where it has been operating since 1968 and now provides over a quarter of the city's total supply from treatment of secondary treated sewage effluent for reuse as raw water.[40] In 2007, the Australian federal government responded to their extensive drought by mandating 30% reuse by 2015. In a review of the implementation of reuse projects in Australia, Kunz et al.[41] found the deployment of reuse to be highly uneven, with individual utilities recycling anywhere from 0 to close to 100% of wastewater.

Relative to other alternative water sources, a unique feature of municipal reuse is that it ties together water and wastewater systems that are often owned, operated, and regulated by separate entities. Water providers are generally responsible for water supply planning and wastewater facilities for the environmental impact of wastewater outflows. Survey data from the United States show three primary drivers of reuse projects: water scarcity, environmental constraints on wastewater effluent, and state-level mandates to develop and implement integrated water resource plans (IWRPs).[44−46] Depending on the motivation, reuse projects may be initiated by either party. Obstacles to reuse include energy requirements, cost effectiveness,[47−50] lack of consistent regulatory frameworks,[51] and legal restrictions.[52]

Municipal reuse in the United States is still largely nonpotable, occurring primarily in California, Florida, and Texas. In all three states, experience with drought and groundwater depletion have led to guideline development

https://doi.org/10.1021/acsestengg.1c00351
ACS EST Engg. XXXX, XXX, XXX−XXX

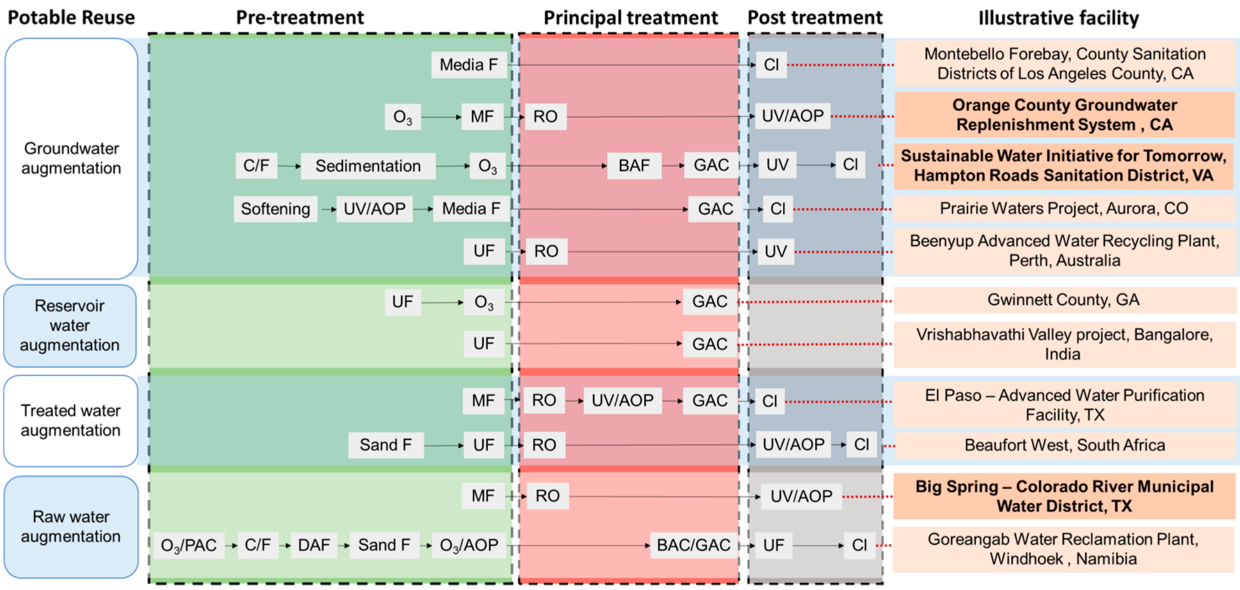


Figure 2. Treatment trains used for municipal wastewater potable reuse: O3, ozone; MF, microfiltration; UF, ultrafiltration; Sand F, sand filtration; Media F, media filtration; C/F, coagulation/flocculation; RO, reverse osmosis; GAC, granular activated carbon; BAC, bioactivated carbon; UV, ultraviolet; AOP, advanced oxidation process; Cl, chlorination; DAF, dissolved air flotation; PAC, polyaluminum chloride; GW, groundwater; SW, surface water. Illustrative facilities in bold are case studies examined in this work.

and implementation of potable reuse.[53] When considering any water supply project, water districts consider a number of factors that may vary by state and by region (Table 1). State-level environmental regulations may create more stringent requirements than the federal statute; for example, the California Ocean Plan sets water quality requirements for ocean waters and mandates that, in case of conflict with other statutes, the more stringent provision shall apply.[54] Water rights are also managed at the state level. Depending on the way water rights are allocated, users downstream of a wastewater treatment plant discharging into a stream or river may have rights to that "return flow" water, which can complicate the development of municipal reuse projects. The circularity of municipal reuse creates challenges in correctly accounting for its role in water supply, particularly when used for groundwater recharge.

Table 1 provides a summary of regulatory and planning considerations that influence water supply project decisions along with an indication of whether these are overall favorable, unfavorable, or neutral for municipal reuse. One of the biggest advantages of municipal reuse is that its overall perception is as a net environmental benefit. Generally, the municipal wastewater system is already part of the built environment, so reuse projects do not require the burdensome level of environmental review that accompanies other new supply options. Water districts also place a high value on local control of supply, which favors reuse.

Cost control and cost recovery are challenges for the water industry in general. Municipal reuse projects have the advantage of offsetting known capital and operating costs associated with effluent treatment and disposal and related permitting. They also have the possibility of generating additional revenues through the sale of recycled water. However, current utility practices do not always provide for costs to be allocated to specific projects and recovered from the beneficiaries of these projects in a coherent way. The American Water Works Association (AWWA) recommends the use of "cost-based rates that generate revenue from each class of customer in proportion to the cost to serve each class of customer"; these are considered fair and equitable and lead to sustainable financial management.[55] Methodologies have been developed for conventional supply but are not well developed for alternative sources, including reuse. A project may be cost effective, but if not all utility customers benefit from the project, then cost recovery may not be equitable. Onsite municipal reuse faces an additional challenge because wastewater bills are often charged as a fraction of the water volume supplied on the assumption that a percentage of that delivered water ends up in the wastewater collection system. Onsite reuse makes the percentage assumed invalid and can leave fewer customers to pay for the costs of maintaining the collection system. In a recent AWWA survey of 19 utilities that had implemented NPR, only two reported definitively that revenues from the sale of recycled water covered the costs of production.[56]

1.3. Current Treatment Practices for Municipal Reuse.

Current treatment for potable reuse is based on five main objectives: removal of suspended solids, reduction of dissolved chemicals, disinfection, water stabilization, and treated water aesthetics (Table S1, Supporting Information). Representative treatment trains and illustrative facilities for each are provided in Figure 2. Media and membrane filtration have been used for removing suspended solids in the effluent from conventional wastewater treatment processes. Processes that include reverse osmosis (RO), electrodialysis (ED), electrodialysis reversal (EDR), nanofiltration (NF), granular activated carbon (GAC), ion exchange (IX), and biologically active filtration (BAF) are used to remove trace organic compounds, pathogens, dissolved chemicals, and total dissolved solids (TDS). Each unit process is unique in its capability for removing subgroups of chemicals within the different categories of dissolved chemicals in the treated wastewater effluent. Without stabilization, the water produced from membrane filtration processes of RO and NF can be highly corrosive toward metallic plumbing or concrete

https://doi.org/10.1021/acsestengg.1c00351
ACS EST Engg. XXXX, XXX, XXX−XXX

storage tanks. Disinfection technologies include ultraviolet (UV) irradiation, chlorination, peracetic acid disinfection, pasteurization, chlorine dioxide, ozone, and advanced oxidation processes (AOPs) for potable reuse treatment to inactivate pathogenic microbes or degrade chemical contaminants via oxidation. Aesthetics of the treated water plays a crucial role in public perception and acceptance of recycled water, especially for DPR. Each treatment process for the five treatment objectives has been discussed in detail in the potable reuse compendium.[1]

1.4. Pipe Parity Framework for Municipal Water Planning and Wastewater Reuse. Pipe parity, a concept proposed by the U.S. Department of Energy, defines the state where a set of new technologies is competitive with conventional solutions.[57] A water source may be considered to have achieved pipe parity when a decision-making body considers it to be the next best option (i.e., their marginal water source) when compared to sources they might have relied on in the past. While a key pipe parity metric is the levelized cost of water (LCOW), metrics of pipe parity can also include electricity use, renewable energy integration, and indicators of resilience and environmental impacts. For example, a water user may pay more for a water source that is more reliable during droughts or that they expect to be more consistently available over the long term, given the expected regulatory regime, climate conditions, and/or competition from other users.

Pipe parity can inform municipal water planning by providing a range of metrics that utilities may use in their decision-making process and a framework for prioritizing them. Many utilities use some form of integrated water resource plan (IWRP) to craft these long-term strategies. These IWRPs are one of the drivers for increased interest in municipal reuse. Central to many IWRPs are stakeholder-based weighting of quantitative and qualitative factors (e.g., cost, reliability, environmental impact) since cost is an important but insufficient metric for making a decision. We propose a framework for evaluating pipe parity to rate, compare, and identify technology solutions that are competitive with existing water sources and end-use applications. We present this framework initially using two metrics: LCOW and energy use. Going forward, we anticipate that the metrics generated by the pipe parity framework will map closely to typical factors commonly used in IWRPs. It may also provide a basis for more utilities to adopt integrated regional water management planning at a lower cost.

1.5. Regulatory Framework. In the U.S., responsibility for water resource planning and environmental management lies primarily with the state governments. Although the U.S. Environmental Protection Agency is ultimately responsible for drinking water and wastewater effluent regulatory standards, responsibility for their implementation is delegated to the states. We review the laws governing water planning and potable reuse in California, Texas, and Virginia. In all cases, state regulations mandate the development of a state-wide water plan with required input from local water districts. The core of this exercise is to project future demand and assess the sufficiency of future supplies, including under possible drought scenarios. In cases where traditional freshwater supplies are forecast to be insufficient or unsustainable, the state may make recommendations on which water management strategies are preferred. In general, these recommendations are not binding, and local water districts are free to decide on which projects they implement. However, financial and other support may be available to incentivize the implementation of preferred strategies.

The responsibility for monitoring and enforcing these regulations is generally delegated to various state agencies, including departments of public health, environmental protection, and fish and wildlife management. States may also impose additional requirements. For example, California has enacted regulations governing NPR and IPR, with rules for groundwater and surface water augmentation effective in 2014 and 2018, respectively. DPR is still being reviewed with a statutory deadline for regulating raw water augmentation in 2023. No timeline exists yet for regulating treated water augmentation. Another important state-level function is groundwater basin management. Municipal reuse can be used to offset groundwater depletion through augmentation. The existence of a state-level legal requirement to manage groundwater levels (e.g., California's Sustainable Groundwater Management Act) can indirectly incentivize reuse.

1.6. Study Scope and Objectives. This study focused on quantifying and analyzing data associated with the current status of technology for treated municipal wastewater as a nontraditional source of potable municipal water supply and building-scale reuse. For building-scale reuse, we focused on systems that treat mixed wastewater (or black water) as opposed to gray water systems. Centralized municipal reuse for nonpotable uses (e.g., landscape irrigation) or in the agricultural sector was beyond the scope of this study. A set of focused case studies was developed that is representative of these end uses and that includes a range of treatment trains. We used the case studies and additional review of the literature to quantify the current range of cost and energy metrics.

Examination and analysis of the data sought to synthesize and build on previous research, while also making novel contributions through the use of the newly developed Water Techno-economic Assessment Pipe-Parity Platform (WaterTAP3). Through the analysis of case studies, application of WaterTAP3, and review of previous literature we aimed to (a) identify the impacts of treatment train selection and facility size on pipe parity metrics, (b) compare the pipe parity metrics from WaterTAP3 with the data assets and metrics currently used by reuse facilities to validate the model and identify needs for model refinement, and (c) compare pipe parity metrics for potable reuse from different alternative source waters using a common analysis platform. As novel contributions initiated as part of this work, our objectives were to (1) assess the sensitivity of cost and energy metrics to specific input variables for the facilities, (2) perform a robust TEA for building-scale NPR, and (3) evaluate the cost and energy of implementing deep well injection or zero liquid discharge, options that might be required for an inland RO-based facility. The outputs of this baseline study can be used to identify opportunities for improving costs and performance that can be addressed through early stage research so municipal reuse can achieve pipe parity more broadly.

2. METHODS

2.1. Case Study Selection. Baseline case studies were down selected from a list of candidate case studies curated based on the location, history, size of facility, data available on influent water to facility, treatment trains, and their unique aspects for municipal reuse. A total of four U.S. case studies were chosen where readily available data could be collected for

https://doi.org/10.1021/acsestengg.1c00351
ACS EST Engg. XXXX, XXX, XXX−XXX

TEA, modeling, and metric benchmarking. Data were collected and analyzed to understand variations in the contexts of reuse for four case studies (Table 2). The Orange County Water District-Groundwater Replenishment System (OCWD-GWRS) in California and the Hampton Roads Sanitation District–Sustainable Water Initiative for Tomorrow (HRSD-SWIFT) in Virginia are representative cases of RO-based and O_3/BAF/GAC-based treatment trains, respectively, the two dominant categories of treatment trains used for potable reuse. The Colorado River Municipal Water District Raw Water Production Facility (RWPF) in Big Spring, Texas, is a raw water augmentation facility with an RO-based treatment train that is the only currently operating DPR facility in the U.S. Finally, the Solaire in-building water reuse system in Battery Park City, New York, is an example of a decentralized nonpotable reuse facility. Two additional case studies of municipal reuse for electric power applications were profiled but not examined with TEA due to the main focus of this study on reuse in the municipal sector. These are Alliant Energy's Emery Generating Station in Iowa and the Palo Verde Nuclear Generating Facility in Arizona (Section S1, Supporting Information).

2.2. Techno-Economic Analysis. WaterTAP3 simulates steady-state water treatment train performance and costs including flow and constituent mass balance across unit processes, based on source water conditions, configurations of treatment technologies, and system-level techno-economic assumptions.[58] Case study performance was evaluated using the LCOW (cost per unit of treated water, $\$/m^3$), energy intensity (energy consumption per unit of treated water, kWh/m^3), and water recovery (percentage of water recovered for beneficial use relative to the source water). Costs estimated by the model include capital investment and annual operating and maintenance costs, consisting of variable (e.g., energy, chemical) and fixed (e.g., labor, maintenance) operating costs. These costs are represented at the unit-process level (i.e., per treatment technology within the train) and aggregated to the system level. The results from WaterTAP3 can identify trade-offs among the different system performance metrics and provide insight into how particular technologies or systems promote pipe parity.

We used WaterTAP3 to simulate four treatment trains that are representative of the OCWD, HRSD, Big Spring, and Solaire case studies. Details of unit-specific configurations and system-level techno-economic assumptions for each train are discussed below and provided in Tables S3 and S4 of the Supporting Information. We simulated an additional five scenarios for the Big Spring treatment train to provide insight into deep well injection (DWI) and zero liquid discharge (ZLD) costs and impacts on system performance for an RO-based treatment trains in a semiarid inland context.

3. RESULTS AND DISCUSSION

3.1. Municipal Reuse Case Studies. *3.1.1. Hampton Roads Sanitation District.* HRSD is an independent political subdivision of the Commonwealth of Virginia that operates nine major and seven smaller WWTPs in southeastern Virginia, serving a population of more than 1.7 million residents with a total capacity of about 250 MGD. Given the sensitivity of the Chesapeake Bay ecosystem, HRSD has faced challenges with nutrient discharges and sanitary sewer overflow management. To address these challenges, HRSD initiated the Sustainable Water Initiative for Tomorrow (SWIFT).

Table 2. Summary of Key Aspects of Municipal Reuse Facilities Chosen as Case Studies

	Facility	RWPF, Big Spring	GWRS, Orange County	SWIFT, Hampton Roads	Solaire, Battery Park City
Facility information	State	Texas	California	Virginia	New York
	Online date	2013	2008	2026	2002–2010
	Capacity (MGD)	1.9	70 in 2008 100 in 2020 130 in 2023	up to 120	multiple systems 0.015–0.04
	Function	Direct potable water supply	Groundwater augmentation	Groundwater augmentation	On-site NPR
	Facility owner	Colorado River MWD	Orange County WD	Hampton Roads Sanitation District	Local building owners
Water agency information	Service population	600,000	2,500,000	1,700,000	10,000 residents
	Supplies to	36 counties	23 member and 11 nonmember agencies	17 cities and counties	~1 M square feet of building space
	Regional planning entity	TWDB Region F	MWDOC, Orange County government	Hampton Roads Planning District	Battery Park City Authority
	Drought prone	Yes	Yes	No	No
	Drivers	GW depletion; Colorado river drought; surface water salinity	Drought; saltwater intrusion; GW depletion	GW depletion; land subsidence; saltwater intrusion; effluent limits	Minimize water footprint in high density urban area; mitigate wastewater CSOs

https://doi.org/10.1021/acsestengg.1c00351
ACS EST Engg. XXXX, XXX, XXX−XXX

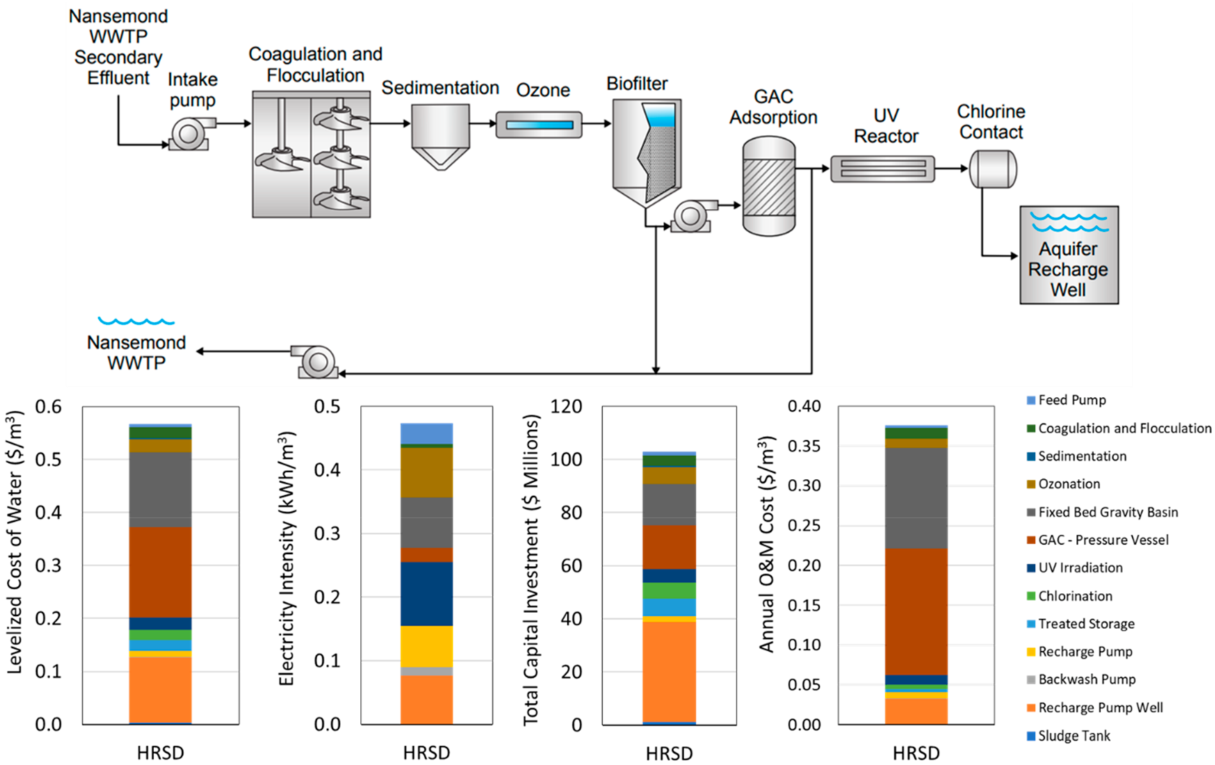


Figure 3. Process flow diagram for a SWIFT advanced treatment plant of HRSD with cost and energy intensity estimates for a 14.5 MGD facility predicted by WaterTAP3.

Supported by an ongoing research and development program, HRSD's ultimate goal with SWIFT is to apply advanced water treatment to up to 100 MGD of its already highly treated wastewater. The resulting SWIFT water meets drinking water standards and is used to replenish the overdrawn Potomac aquifer. SWIFT is a unique example of IPR in a region with abundant surface water supply.

The Hampton Roads metropolitan region is part of the Eastern Virginia Groundwater Management Area (EV-GWMA). Upon passage of the Ground Water Management Act in 1992, the Virginia Department of Environmental Quality (VDEQ) began regulating groundwater withdrawals in designated GWMAs to address the long-term decline of groundwater levels and potential saltwater intrusion. The Virginia Water Control Law was amended in 2000 to promote the reclamation and reuse of wastewater. Legislation enacted in 2003 for state entities, and 2005 for local entities, requires the development of long-term water supply plans incorporating demand projections, assessment of supply adequacy, and drought response plans. In this context, the Hampton Roads Planning District Commission published a regional water supply plan in 2011 that identified potential problems with overuse of groundwater in the Coastal Plain Region and underlying Potomac Aquifer, including land subsidence and tightening of permitted withdrawals by the VDEQ due to falling groundwater levels.

HRSD established a 1 MGD demonstration facility in 2018 that is co-located with the 30 MGD Nansemond Treatment Plant. The demonstration facility, known as the SWIFT Research Center (SRC), consists of advanced water treatment processes that produce water that meets drinking water standards.[59] A network of monitoring wells monitor the progress of the SWIFT water through the aquifer.[60]

SWIFT started out with a pilot-scale facility at the York River Treatment Plant in 2016. At pilot scale, a side-by-side comparison of carbon-based (Ozone/BAF/GAC) and membrane-based (MF/RO/AOP) treatment trains was conducted for 7 months.[61] Both treatment trains met all primary maximum contaminant levels (MCLs) and most secondary MCLs of the Safe Drinking Water Act, as well as additional total nitrogen (TN; 5 mg/L-N) and total organic carbon (TOC; 4 mg/L) limits.[61] The carbon-based train does not remove total dissolved solids (TDS), resulting in a TDS of 500−600 mg/L, which is above the secondary MCL. However, a high TDS is favorable for compatibility with the Potomac aquifer because it avoids metal mobilization and clay dispersion in the aquifer that could potentially clog the recharge wells. While both treatment trains met HRSD's water quality goals, the carbon-based system had benefits of potential capital and operating cost savings and the elimination of a brine stream. On the basis of these advantages, HRSD selected to move forward with the carbon-based system for the SRC. A higher TDS influent or different effluent standards could have resulted in a different choice of treatment train. The full SRC advanced treatment process consists of coagulation, flocculation and sedimentation, ozone oxidation, biologically active filtration (BAF), granular active carbon (GAC) adsorption, ultraviolet disinfection, and pH adjustment (Figure 3).[59] The figure includes the WaterTAP3 cost and energy estimates for each component of the HRSD SWIFT system, and those results are discussed further in a subsequent section. As of October 2020, the aquifer has been recharged with 300 million gallons of water since the SRC's opening in May 18, 2018. The groundwater hydraulic response and the effect on land subsidence are monitored by an extensometer installed by the U.S. Geological Survey.

https://doi.org/10.1021/acsestengg.1c00351
ACS EST Engg. XXXX, XXX, XXX−XXX

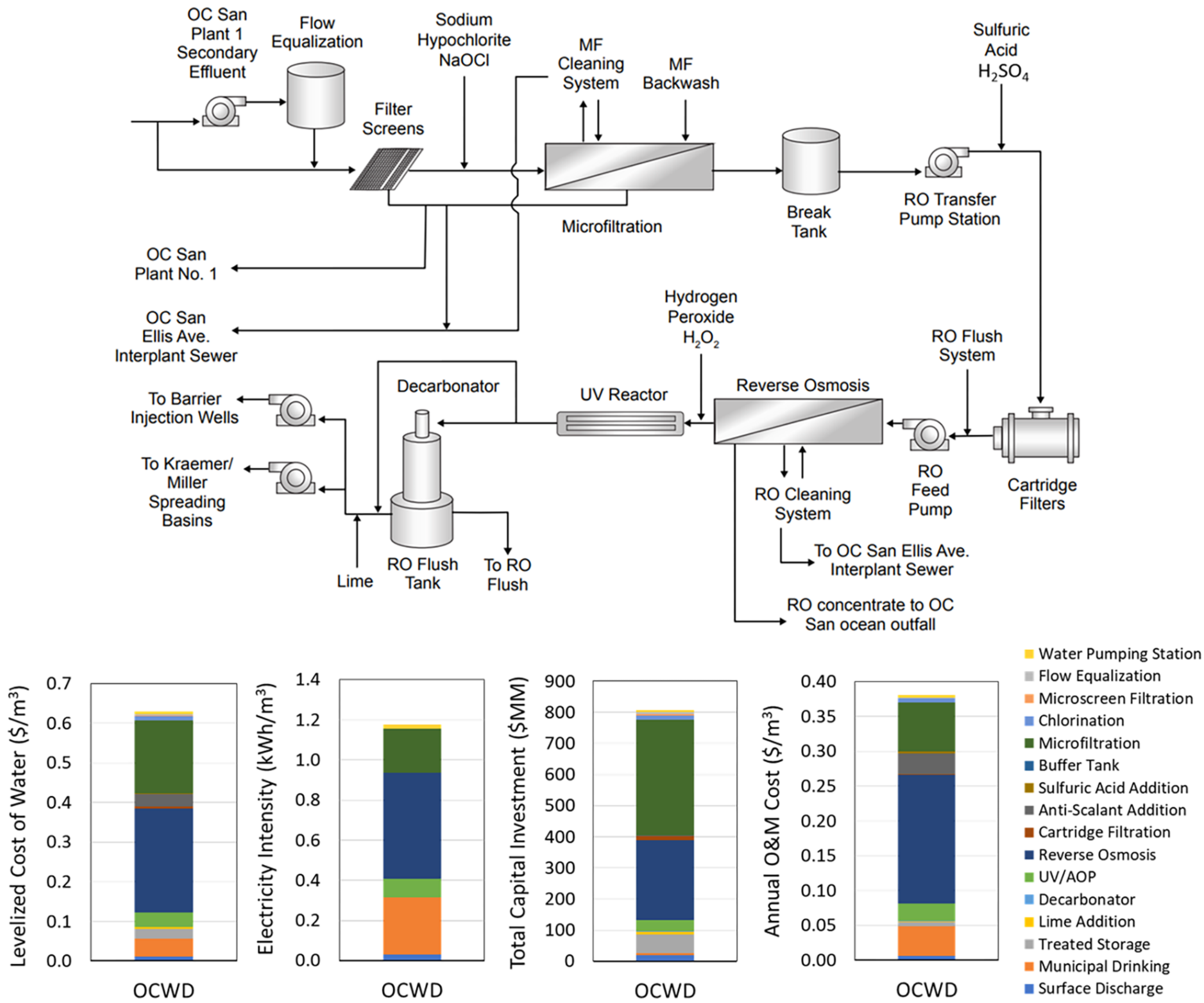


Figure 4. Process flow diagram of the Advanced Water Purification Facility of the OCWD Groundwater Replenishment System with cost and energy estimates for the 100 MGD facility predicted by WaterTAP3.

HRSD plans to install up to 100 MGD of SWIFT water capacity by adding full-scale SWIFT treatment facilities at up to five wastewater treatment plants by 2032. The funding for the full-scale program is supported by funds from the Water Infrastructure Finance and Innovation Act. HRSD is collaborating with federal, state, and regional entities by sharing research and operational data to mitigate challenges for the implementation of the program.

3.1.2. Orange County Water District: Groundwater Replenishment System. The Orange County Water District (OCWD) is a wholesale water agency responsible for sustainable management of the Orange County Groundwater Basin. OCWD provides groundwater to cities and water districts that serve drinking water to 2.5 million residents of north and central Orange County. To replenish and maintain the groundwater supply, OCWD conducts managed aquifer recharge using local Santa Ana River water, purified (recycled) water, and imported water. The advanced treatment facilities and related recharge infrastructure are known as the Groundwater Replenishment System (GWRS), a joint project with the Orange County Sanitation District (OC San). This project was conceived in the mid-1990s when OC San was faced with the costly need to build a second ocean outfall to discharge treated wastewater and OCWD needed to expand Water Factory 21 (GWRS's predecessor) and address challenges with seawater intrusion. Given that drought conditions, in general, are expected to worsen in California, the decision was made to collaborate to build the state-of-the-art Advanced Water Purification Facility (AWPF) to purify OC San wastewater and send it to OCWD recharge basins.

The California Water Code requires urban water suppliers to prepare an Urban Water Management Plan (UWMP) every five years. The UWMP for the OCWD service area is prepared by the Metropolitan Water District of Orange County (MWDOC). In the latest plan, MWDOC notes that groundwater supplies 45% of Orange County water needs in a normal year, approximately 200,000 acre-feet in 2020.[62] The GWRS facility, when operated at its current full capacity (100 MGD), supplies approximately 35% of the OCWD service area's groundwater replenishment needs.

On January 10, 2008, OCWD commissioned the initial 70 MGD GWRS that replaced the 5 MGD Water Factory 21 that had begun service in October 1976. The facility was expanded in 2015 to 100 MGD, and a final expansion to 130 MGD is to be completed in 2023. It is currently the largest potable reuse facility in the world. The treated water from the AWPF is directly injected into a seawater intrusion barrier as well as gravity percolated for groundwater recharge. The treatment train is based on MF, RO, and advanced oxidation with UV/

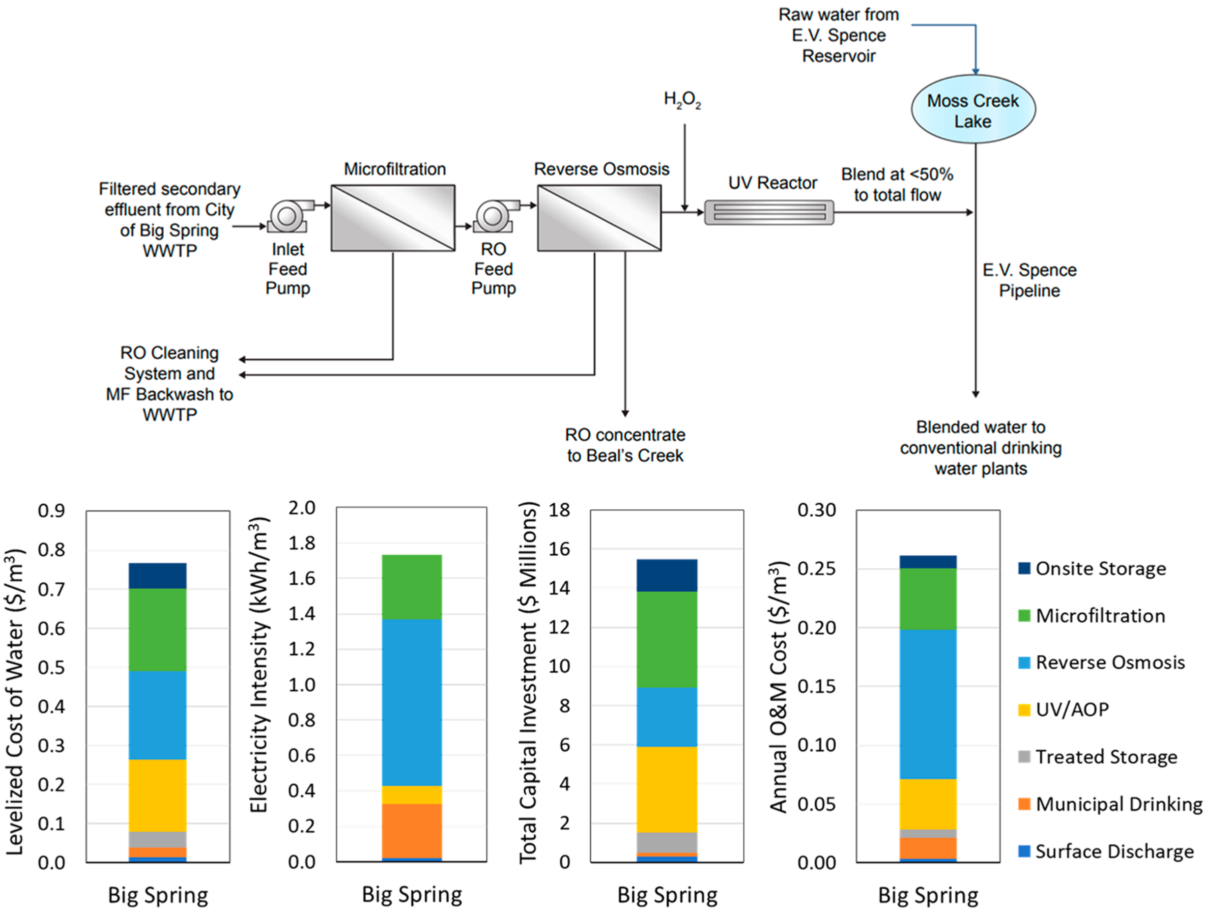


Figure 5. Process flow diagram of the Raw Water Production Facility in Big Spring, Texas, together with cost and energy estimates predicted by WaterTAP3.

H_2O_2 (Figure 4), and the cost and energy estimates presented in Figure 4 are discussed further in the next section.

3.1.3. Colorado River Municipal Water District's Raw Water Production Facility in Big Spring, Texas. The Colorado River Municipal Water District (CRMWD) was formed in 1946 to manage the construction and operation of a reservoir on Texas' Colorado River to meet the water needs of West Texas.[63] In subsequent years, additional surface storage was constructed along with a number of smaller side storage and evaporation reservoirs. The latter were needed to help deal with increasing salinity levels in local surface and groundwater. The district currently provides water to 600,000 users across 36 counties. CRMWD is a member of "Region F", one of 21 designated water planning groups that contribute to the development of the Texas State Water Plan. Within this region, the largest sectoral demand is for irrigation; municipal demand represents about 20% of total demand.[64]

Coincident with a severe drought in West Texas from 2008 to 2012, CRWMD initiated the construction of the Big Spring Raw Water Production Facility (RWPF), the first DPR facility in the U.S. In May 2013, CRMWD began augmenting raw water supplies with 2 MGD of advanced treated water from its $14 million RWPF in Big Spring, Texas. Water produced from this facility is blended with CRMWD's surface water and distributed to five drinking water treatment plants.[65] The Big Spring RWPF capacity represents about 1.5% of municipal demand; although this is a small number, it continuously provides critical local supplies, even under drought conditions.

At the RWPF, filtered secondary effluent is treated with MF, RO, and UV-AOP (Figure 5). The advanced treated water derived from the wastewater effluent is then added to a raw water pipeline that is transmitting water from a source water lake. The cost and energy estimates from WaterTAP3 presented in Figure 5 are discussed further in the next section. The treated water is blended with raw water in a transmission line. The blended water is then treated in one of several drinking water treatment facilities before distribution.[66,67]

3.1.4. Solaire Building. The Solaire building system was the first high-rise residential decentralized NPR project in the U.S.; the building itself received LEED Gold certification. The many water-saving design features qualified the project for a 25% reduction in water and sewer rates from New York City as well as tax credits from the state.[68] Since beginning operation in 2003−2004, it has demonstrated consistent performance in reducing potable water demand by 50% and reducing wastewater flows 60%.

The Solaire water treatment system handles an average daily flow of 25,000 gallons per day (0.025 MGD) of blackwater and graywater. Blackwater and graywater are blended and have anticipated loads typical of domestic wastewater: biochemical oxygen demand 250−280 mg/L, total suspended solids 220−250 mg/L, and total N 40−50 mg/L. This water is collected in an aerated feed tank where it is held for processing. Any excess wastewater is discharged by gravity to sewers. Principal treatment is via a membrane bioreactor (MBR), which includes an anoxic reactor to reduce nitrate and nitrite,

https://doi.org/10.1021/acsestengg.1c00351
ACS EST Engg. XXXX, XXX, XXX−XXX

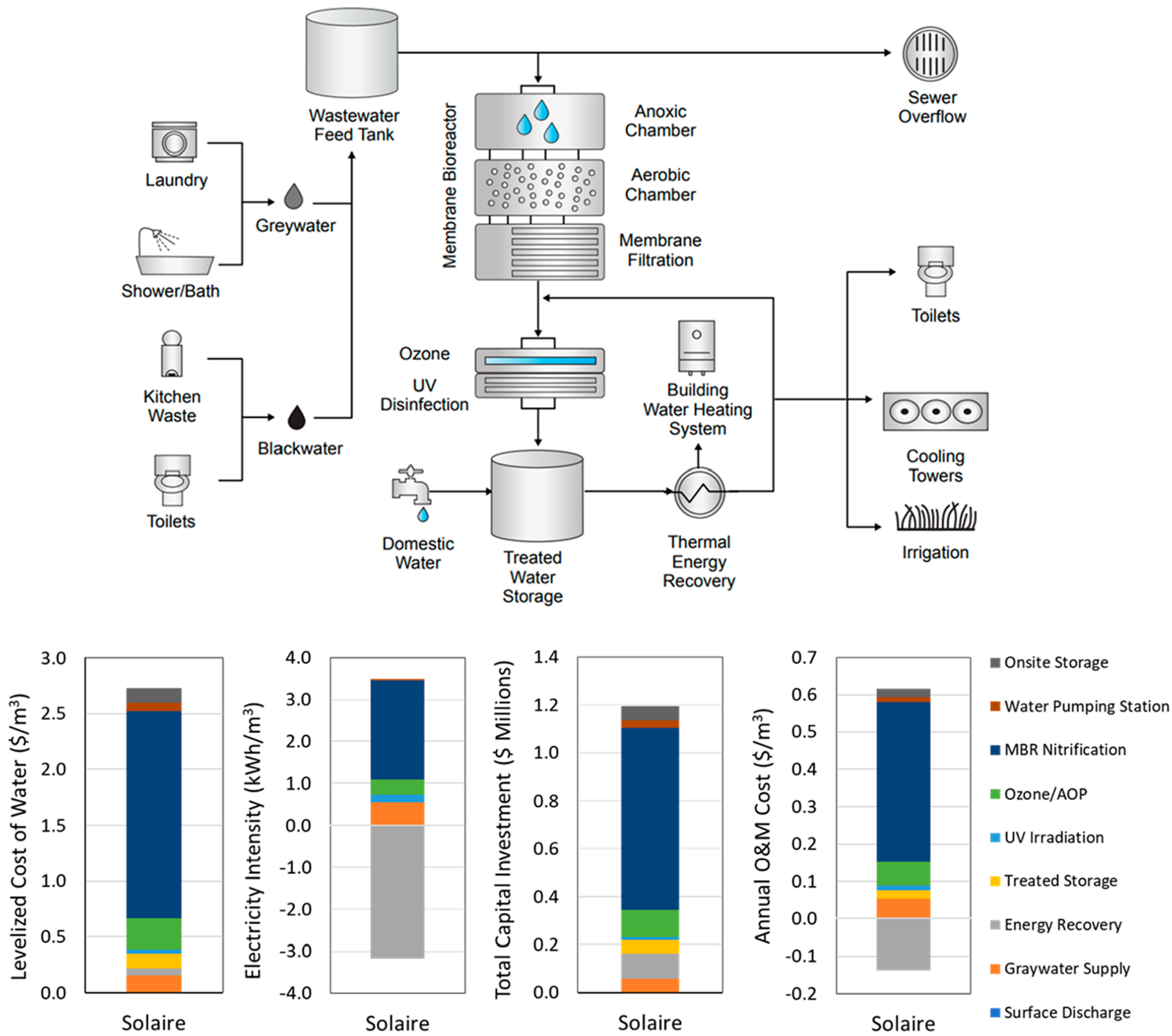


Figure 6. Process flow diagram of the on-site water treatment system at Solaire together with cost and energy estimates for the facility predicted by WaterTAP3.

followed by an aerobic reactor for carbonaceous oxidation and nitrification, and a hollow-fiber filter membrane for 0.04 μm ultrafiltration. The MBR is followed by UV and ozone oxidation. Treated water is stored, passes through a heat recovery system, and then reused for toilets, cooling towers, and irrigation. A separate rooftop system collects rainwater through a media filter and then uses it for irrigation; this rainwater system is not included in the modeled results. The energy recovery system provides the equivalent of up to ~400 kWh/day of domestic water heating and thus can completely offset the ~350 kWh/day energy needs of the treatment system, resulting in a payback of 3−10 years for the energy system depending on the building energy source. The treatment process is illustrated in Figure 6 together with cost and energy estimates for the process that are discussed further in a later section.

Solaire has demonstrated the technical and economic viability of decentralized NPR in multiple ways: (1) Wastewater is treated to the specific level needed for the selected reuse options. (2) Energy costs of pumping water to and from the site are avoided. (3) Heat recovery from the wastewater has offset overall building energy use for producing hot water. The modeled overall LCOW of the system at just over \$2.73/m^3 also compares favorably to the current combined rate of \$3.65/m^3 for water and wastewater in New York.

3.2. Comparison of Model Outputs with Facility Data. The comparison of model output and facility data is a means of identifying areas of the model that could benefit from future refinement. The energy intensity data for OCWD are very close for the model output (1.18 kWh/m^3) and 2019 facility data (1.17 kWh/m^3). The electricity intensity of specific unit processes are also very close for the model output and facility data (Table S5). For comparison of modeled and actual costs, we focused on operating and maintenance costs since the levelization of capital costs is subject to numerous assumptions that may not align perfectly between the model and the facility (e.g., land costs). For the OCWD GWRS, the total operating and maintenance cost in 2019 of \$68.3 million is about 50% higher than the model output of \$48.6 million. However, if the debt service is removed from actual operating and maintenance costs, then the facility data are \$44.0 million. The annual operating and maintenance costs of OCWD from WaterTAP3 and from the facility are compared in Table S6. WaterTAP3 estimates a higher cost associated with electricity (\$0.17/m^3) than is reported for the facility (\$0.13/m^3). Chemical costs are quite similar between the facility and the model.

https://doi.org/10.1021/acsestengg.1c00351
ACS EST Engg. XXXX, XXX, XXX−XXX

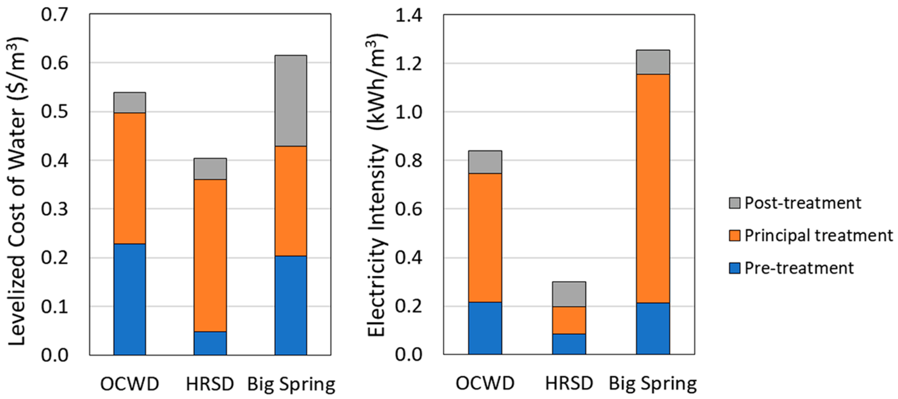


Figure 7. WaterTAP3 estimated cost and electricity intensity breakdown by treatment category type for three potable reuse case studies. These values do not include costs or energy associated with acquisition, storage, and distribution of water or of management of byproducts.

Because the HRSD SWIFT full-scale facilities have not yet been constructed, there are no facility data for comparison, but electricity and operating and maintenance cost estimates from engineers involved in the design of the full-scale facilities were available. The estimated electricity demand for the facility is 85% higher than the calculated output from WaterTAP[3] (Table S7). This difference is largest for UV treatment, which is estimated to require much more electricity (0.30 kWh/m^3) than is modeled in WaterTAP[3] (0.10 kWh/m^3). The facility estimate is also much higher than the reported facility value for OCWD (0.07 kWh/m^3) (Table S5), which may either indicate greater electricity demand for the properties of the HRSD water than for OCWD or that the facility value for HRSD is overestimated. Facility estimates of operating and maintenance costs are also higher ($\$0.50/m^3$) than modeled in WaterTAP3 ($\$0.38/m^3$) (Table S8). The biggest differences are for coagulation/flocculation, ozone, and chlorination, which are higher for facility estimates, and for biofiltration, which is lower for facility estimates.

For Big Spring, the facility value (1.4 kWh/m^3) is about 30% lower than the model value (1.73 kWh/m^3), which may be due to facility electricity costs being less than assumed in the model. The Big Spring facility has not reported operating and maintenance costs, so a comparison of modeled and actual costs was not possible.

Before accounting for energy recovery, the energy intensity reported for Solaire of 3.67 kWh/m^3 is 5% larger than the model value of 3.50 kWh/m^3. Solaire reported annual operating and maintenance costs of $\$2.84/m^3$, while the model output was $\$0.62/m^3$; this underestimate of the model appears to be due at least in part to the small scale of the Solaire system. While the Solaire system treats 25,000 gallons per day, the Water-TAP3 model was built using flows on the order of millions of gallons per day. A separate set of cost curves tailored to the small Solaire flows was generated for the model to address this issue of scale. However, cost data at this scale are limited, and the discrepancy was not fully resolved for this study.

3.3. Discussion and Analysis of Pipe Parity Results.

3.3.1. Comparison of Pipe Parity Metrics for RO-Based and BAF/O_3/GAC-Based Treatment Trains. Energy and cost factors from WaterTAP3 can be broadly grouped into two groups: those stemming from acquisition, distribution, and storage and those from treatment. Cost factors for acquisition and distribution can be influenced by pumping efficiency and the specific geographic context of the facility relative to the municipal wastewater source and the final distribution locations. On the basis of the results already presented for the three case studies (Figures 3–5), acquisition, storage, and distribution contribute from 14.4% to 28.9% of the total LCOW and from 20.7% to 36.9% of the electricity demand. Because the energy requirements and costs of conveyance can be specific to a given location, we focused just on the components of treatment when comparing the treatment trains of the three cases studies.

When focusing on treatment, principal treatment is the largest cost for all three case studies (Figure 7). The overall LCOW of treatment is lowest for the O_3/BAF/GAC-based treatment train of HRSD at $\$0.40/m^3$. The two RO-based treatment trains are higher, $\$0.54/m^3$ for OCWD and $\$0.61/m^3$ for Big Spring; the higher LCOW for Big Spring is likely due to its smaller scale such that it does not benefit as much from the economy of scale as the OCWD facility does. For water reuse facilities, the choice of treatment train will be influenced by factors beyond those of cost and electricity demand. For systems with influents that will require removal of TDS, an RO-based treatment train will be required, and RO also provides an effluent of overall higher quality. The Solaire onsite NPR system has a higher LCOW (about $\$2.73/m^3$) than the three centralized potable reuse systems. This higher LCOW is expected due to the absence of economies of scale and because the cost of wastewater treatment upstream of the potable reuse facilities was not included in their LCOW values. The Solaire's MBR is the largest cost factor for both capital and operating expenses.

For the three potable reuse facilities, the total capital investment is the largest piece of the LCOW when broken down by type of cost (Figure 8). Membrane processes drive both the capital costs and operating and maintenance costs of the OCWD and Big Spring facilities. Reverse osmosis is the single largest capital cost for those two facilities, and it is followed by MF. At HRSD, where there are no RO or MF membranes, the capital costs are more evenly distributed among the various unit operations. Of the operating and maintenance costs, electricity is the largest portion for OCWD. HRSD has more operating costs for chemicals due to the replacement of activated carbon for the GAC process. At HRSD, the dominant operating and maintenance costs are associated with BAF and GAC treatment; however, the BAF costs predicted by WaterTAP3 are 25 times higher than estimates made by personnel associated with the facility. This identifies BAF as a unit process in need of further refinement

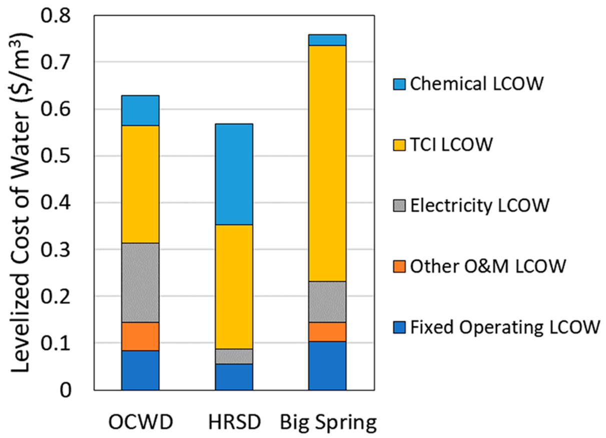


Figure 8. WaterTAP3 estimated cost and electricity intensity breakdown by cost type for the overall production of water, which includes treatment as well as acquisition, storage, and distribution of water and management of byproducts.

in future versions of WaterTAP3. All three facilities have UV irradiation as either part of an AOP process or for disinfection. Only at Big Spring is the UV cost among the top three most expensive unit processes.

The two RO-based facilities (OCWD and Big Spring) have total electricity demands (i.e., not just treatment) of 1.18 and 1.73 kWh/m^3, which are substantially higher than that of HRSD (0.47 kWh/m^3) (Figures 3–5). When focusing just on the electricity demand of treatment, HRSD has an electricity demand of 0.30 kWh/m^3 that is less than half that of the two RO-based facilities (0.84 kWh/m^3 for OCWD and 1.26 kWh/m^3 for Big Spring) (Figure 7). For OCWD and Big Spring, the largest component of electricity use is principal treatment, which includes RO and MF. For HRSD, both principal treatment (includes BAF and GAC) and post-treatment (includes UV and chlorination) are substantial electricity uses.

Reverse osmosis can be used to remove TDS concentration in a range from 1000 to 45,000 mg/L to concentrations below 500 mg/L. Electrical energy spent in this process varies between 0.4 and 7 kWh/m^3 depending on the volume and quality of water being treated.[69] The pressure applied in RO for brackish and seawater desalination varies between 15 and 80 bar depending on the TDS. For municipal water desalination, pressure applied is lower than 15 bar due to the relatively low TDS concentration. RO can efficiently remove most of the colloidal material, including bacteria, viruses, proteins, and smaller compounds, along with dissolved salts from water.

O_3/BAC is less expensive than RO in terms of initial capital and operations and maintenance costs because of the reduced energy requirements, elimination of concentrate and waste management costs, and higher water recovery. For example, in the study by Herman et al.,[70] the initial capital cost (for 20-year plant life with 25 MGD capacity) for RO was higher by 60 MM$ than that for O_3/BAC. Similarly, the operating and maintenance cost for RO was higher by 6 MM$/yr than that for O_3/BAC. However, the equipment replacement costs for O_3/BAC are higher (by 40 MM$) due to the higher cost UV system and replacement cost of O_3 equipment.[4] The combination of O_3 and BAC can significantly transform or biodegrade effluent organic matter,[71] trace organic contaminants oxidation,[72] microbial pathogens, and indicators.[48,73] The primary limitations of O_3/BAC include potential formation of bromate and N-nitroso-dimethylamine during ozonation, the inability to reduce TDS, and practical limits on TOC removal.[74]

GAC can remove TOC, pathogens, and contaminants of emerging concerns. The capital, operation and maintenance, and environmental costs for RO and other membrane-based treatment are generally higher than that of the carbon-based treatment. Even with ocean discharge of the RO concentrate, the membrane-based treatment has higher capital and maintenance costs compared with those of the carbon-based treatment.[75] In addition, the concentrated brine solution generated by RO needs further treatment in inland locations where direct discharge to the sea is not feasible. In a study by Schimmoller et al.,[76] the triple bottom line cost was compared for treatment trains with RO and GAC. The capital cost incurred for the GAC train was lowest (90 MM$ for 20 MGD), and the capital costs for trains with RO producing 20 MGD varied from 120 to 300 MM$ depending on the concentrate handling techniques. With increasing capacity, the cost incurred for GAC became proportionately less expensive than RO. The annual operating and maintenance cost varied in a similar pattern as capital cost. For a 20 MGD plant capacity, an average of 3.6 MM$ was incurred for a GAC-based train

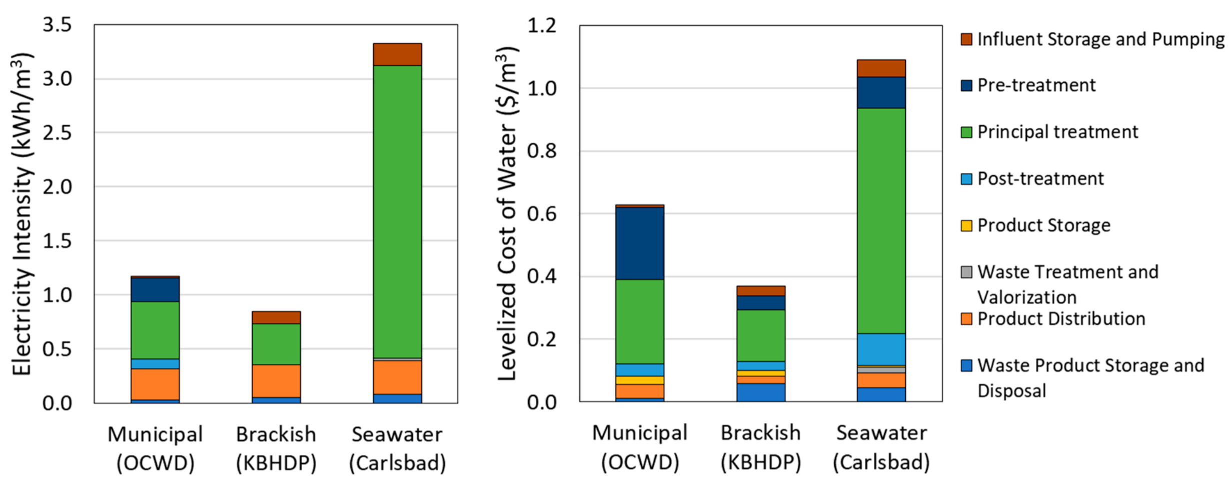


Figure 9. WaterTAP3 estimated cost and electricity intensity breakdown across different components of the overall production of water for facilities producing water from municipal supply from municipal wastewater, brackish water, and seawater.

https://doi.org/10.1021/acsestengg.1c00351
ACS EST Engg. XXXX, XXX, XXX−XXX

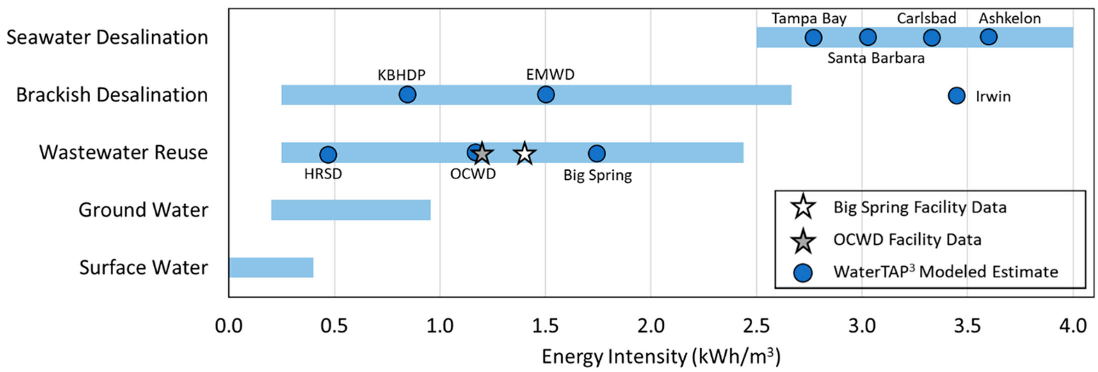


Figure 10. Energy intensity of production of potable water from treatment of different source water options including the model estimates from WaterTAP[3] and specific values for two water reuse facilities.

and 6.0−10.8 MM$ for an RO-based train. When considering just the treatment train, BAF/O_3/GAC-based treatment is less expensive and less energy intensive than RO-based treatment, but additional considerations of needs for removal of specific constituents, including TDS, and options for concentrate management can factor heavily into the choice of treatment train for a given location.

3.3.2. Comparison of Pipe Parity Metrics for Potable Supply from Municipal Reuse, Brackish Water, and Seawater. A comparison of pipe parity metrics was made using the same WaterTAP3 platform for the three largest U.S. facilities practicing RO-based treatment of municipal wastewater, brackish water, and seawater for potable water supply. The OCWD GWRS already described here is the largest plant practicing municipal reuse with a current production capacity of 100 MGD. Supply from a brackish water treatment plant was modeled based on the Kay Bailey Hutchinson Desalination Plant (KBHDP) in El Paso, Texas, which has a production capacity of 27.5 MGD and uses RO to produce potable water from brackish water with a TDS of approximately 2500 mg/L. The largest seawater desalination plant is the Carlsbad Plant in California, which has a production capacity of 50 MGD using RO. For this comparison, brackish water has the lowest LCOW and seawater desalination the highest (Figure 9). These differences are consistent with the literature.[49,77−80] Individual facility ranges depend on a variety of localized factors, including labor and electricity costs, composition of source water quality (e.g., higher TDS, more complex contaminants); acceptance, siting, and permitting for new projects; and willingness to invest in emerging technologies, processes, or systems upgrades (e.g., energy efficiency/demand response, energy recovery/generation, efficient membranes).[81] These results are in line with other existing literature for energy or electricity intensity per m^3 of water treated. Despite brackish water having a higher TDS (∼2500 mg/L) than the treated wastewater that is the influent to the municipal reuse facility (∼990 mg/L), the LCOW was lower for brackish water treatment, which is probably due to differences in the pretreatment processes prior to RO for the facilities. KBHDP uses 15 μm cartridge filters,[82] and OCWD uses membrane microfiltration (<1 μm pore sizes) because of differences in the concentrations and nature of the suspended solids in brackish groundwater and treated municipal wastewater effluent. Membrane microfiltration is both more expensive and more energy intensive than the use of cartridge filters. Another finding was that pretreatment for municipal reuse is a significantly larger contribution in terms of LCOW relative to brackish and seawater.

Figure 10 presents a synthesis of the WaterTAP[3] results, specific facility values, and estimated ranges of the electricity intensity of potable water production from different sources in the U.S. The estimated ranges from previous studies for seawater[83] and for the other sources shown in Figure 10[84] encompass the values generated by WaterTAP[3]. For wastewater reuse, they are also consistent with facility comparisons across the U.S.,[8,85] including for the OCWD GWRS, Big Spring CRMWD, and West Basin, CA.[8,86] Comparisons of the electricity intensity for treatment of different source water options in California noted a kWh/m^3 range; the energy requirements for seawater desalination could be at least two to three times greater than municipal reuse,[87] and up to 25% higher in terms of costs, with both being significantly more cost and energy intensive than traditional surface water treatment. Some forecasts are anticipating roughly half these intensity levels within 20 years, and perhaps faster rates of change are possible.[1,79,86]

3.3.3. Semi-Arid Inland RO-Based Treatment Concentrate Management Scenarios. ZLD uses advanced water treatment technologies to eliminate liquid waste from produced treated water and to increase water recovery. To achieve high water recoveries of greater than 99%, some ZLD systems use membrane technologies to manage the wastewater effluent, and this leads to high energy consumption and high costs.[88] In a pilot-scale study of ZLD (100 L/h) to achieve high recovery (>99%), surface water was treated sequentially with a fluidized weak acid cation exchange resin, UF, NF, and GAC combined with marble filtration. In the same study, the treatment train for groundwater included precipitation at high pH followed by sedimentation, weak acid cation exchange, and NF. These trains were designed to increase the recovery rate of membrane installations such as NF or RO by removing the scaling components from the feedwater.[89]

Management of high salinity residual streams is often the limiting factor for municipal reuse in semiarid inland settings where discharge to the ocean is not an option. The deployment of water reuse in Big Spring was largely possible because of the ability to discharge RO concentrate to Beals Creek, which is naturally brackish due to the local geology. The most cost-effective method of managing concentrated brine is to discharge it to surface water as seen in the case of Big Spring. In the absence of such a naturally brackish surface water for discharge, DWI, evaporation in large pond systems, or ZLD systems can be considered. Five such scenarios, two with DWI

https://doi.org/10.1021/acsestengg.1c00351
ACS EST Engg. XXXX, XXX, XXX−XXX

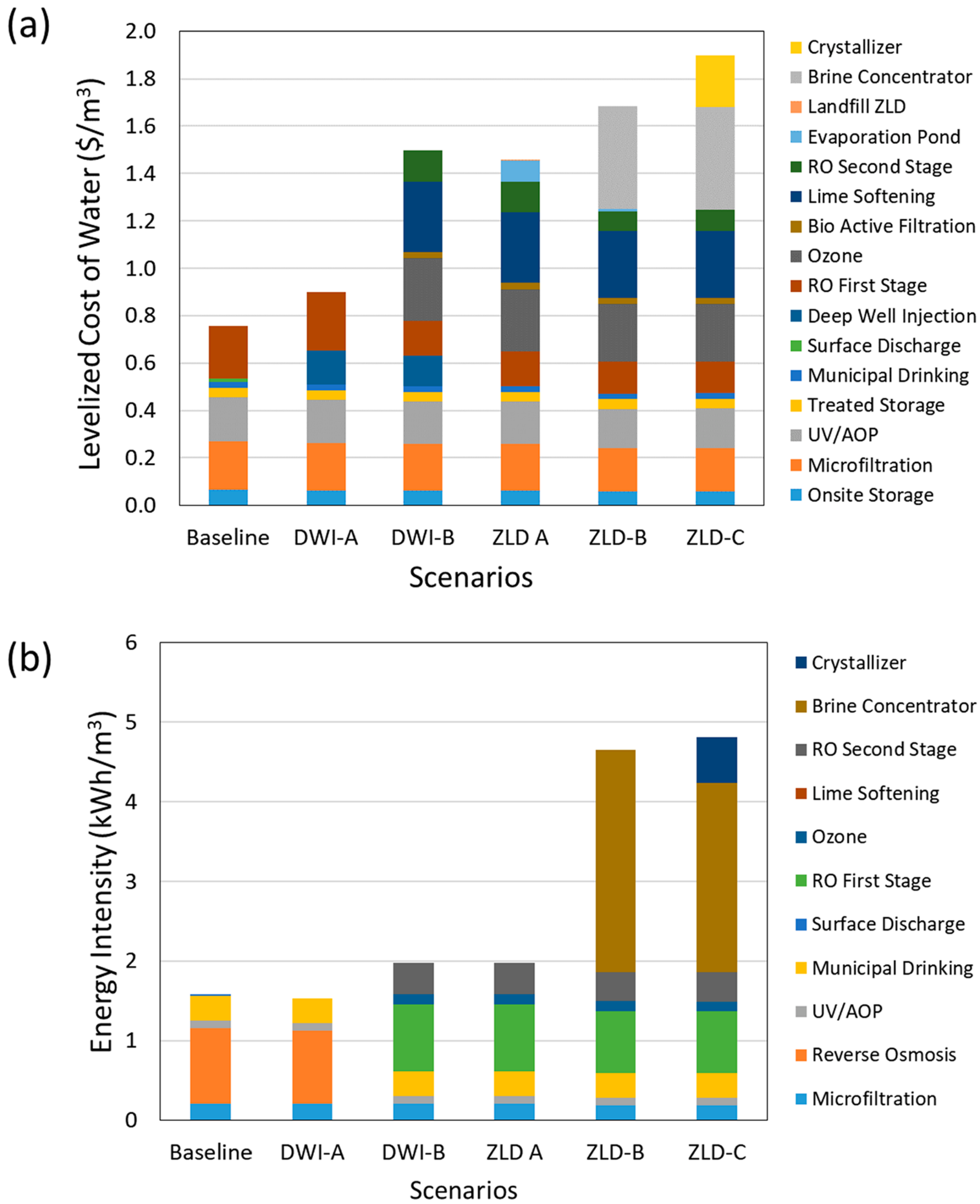


Figure 11. WaterTAP3 estimated (a) cost and (b) energy intensity for zero liquid discharge scenarios for semiarid inland settings. The sizes of the facility and baseline treatment train are those of the Big Spring Raw Water Production Facility.

and three with ZLD, are presented below with results for the cost, energy intensity, and water recovery. These scenarios were implemented in WaterTAP3 for a facility with the production capacity of Big Spring (2 MGD) as well as its influent from treated wastewater and its inland context. Scenarios DWI-A and DWI-B are deep well injection. DWI-B included ozonation, BAF, lime softening, and a second stage of RO to recover additional water prior to injection. The three ZLD scenarios all include ozonation, BAF, lime softening, and a second stage of RO. ZLD-A involves an evaporation pond and landfill. ZLD-B involves a brine concentrator prior to the evaporation pond. ZLD-C has a brine concentrator and crystallizer prior to the landfill.

The deep well injection unit model in WaterTAP3 assumes the water is transported via pipeline. The capital costs are scaled to those for a deep well injection site used for the Kay Bailey Hutchison Desalination Plant located in El Paso, Texas. Capital costs are a function of the piping distance ($35,000 per mile) and the well pump construction. Unless otherwise specified, the pipe distance from the treatment facility to the deep well injection site is assumed to be 10 miles. If the brine were to be trucked from the treatment facility, transportation in Texas is less expensive (up to $5.2/m^3) than in other states like Pennsylvania (up to $31.4/m^3) due to the higher number of injection sites and thus closer proximity to a suitable site according to an estimate for trucking costs of produced water.[90] Electricity costs are a function of the total dynamic head (TDH) of the well pump that is assumed to be 400 ft if not otherwise specified. A full description of the costing method for deep well injection in WaterTAP3 is available in the model documentation.[58]

The two DWI scenarios have a lower LCOW than the three ZLD scenarios (Figure 11). The two-stage RO system used in ZLD-B concentrates the brine in the waste stream further, is

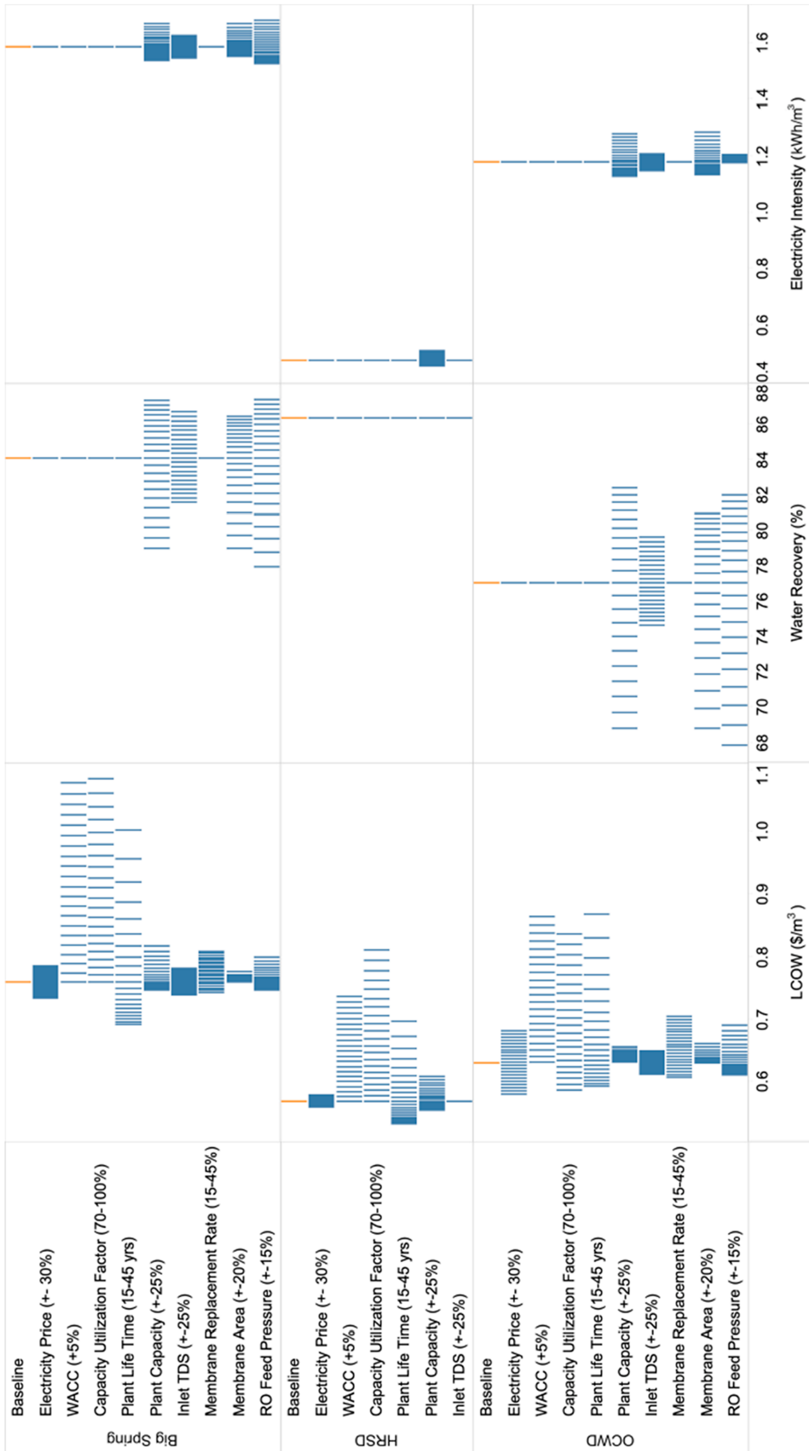


Figure 12. Sensitivity analysis of LCOW, water recovery, and electricity intensity for three potable reuse facilities. Values are shown for uniform increments in variation of a specified input parameter within the range shown in parentheses in the right-hand column. Analyses were performed in WaterTAP3.

more energy intensive, and increases the LCOW, despite an increase in the system's recovered water from the second stage RO. The disadvantages of DWI are lower overall water recovery relative to ZLD, an increase in the salinity of groundwater if the aquifer is not well isolated, and potential contamination of the aquifer due to lack of a post-treatment step as in DWI-A.

Scenarios ZLD-B and ZLD-C use thermal systems that include pretreatment of wastewater that reduces its scaling potential and then goes through a brine concentrator and brine crystallizer or an evaporation pond. The most common technology used for brine concentration is mechanical vapor compression (MVC). This technology has a high capital cost due to the use of materials such as titanium or stainless steel that prevents corrosion. MVC is also energy intensive and can consume 20−25 kWh/m^3 of treated water to reach TDS below 10 mg/L in finished product water and maintain a high-water recovery rate of greater than 98%. The brine concentrator

https://doi.org/10.1021/acsestengg.1c00351
ACS EST Engg. XXXX, XXX, XXX−XXX

consequently represents more than half of the electricity intensity for the ZLD-B and ZLD-C scenarios (Figure 11). The LCOW values in ZLD-B and ZLD-C are higher than in ZLD-A due to the presence of a brine concentrator before the evaporation pond. With brine concentrators, the distillate generated can be reused, whereas the water evaporated in an evaporation pond cannot be reused, and the evaporation pond also has a relatively high capital cost. The evaporation ponds simulated in this train use natural solar energy, with no electricity consumption.

3.3.5. Sensitivity Analysis. The sensitivities of LCOW, energy intensity, and water recovery to factors such as capacity, weighted average cost of capital (WACC), plant life, and on-stream time were assessed (Figure 12). This sensitivity analysis suggests that the LCOW for these systems is dominated by capital costs. For OCWD, Big Spring, and HRSD, capital costs drive the LCOW, with the top three sensitivities being either capital related or a function of capacity (WACC, plant life, and capacity utilization). Results indicate the greatest opportunity across these three systems to reduce LCOW may be through financing and WACC, whereas plant downtime is the greatest risk to increasing LCOW. In almost all cases, operational strategies (including electricity cost) show small potential returns, with the key exception being OCWD, which shows a much higher sensitivity to electricity costs than the other two plants due to the higher baseline cost of electricity in Southern California.

3.3.6. Implications for Use of Renewable Energy. The current analysis has implications for the use of renewable energy in municipal reuse. These treatment facilities are often considered potentially attractive locations for siting of renewable energy installations because they are nodes in regional infrastructure, may have available resources (land for solar photovoltaics or wind, biogas from anaerobic digesters, or hydropower), and may be operated by organizations with decarbonization goals. Given the current findings that these systems are dominated by capital costs and show minimal sensitivity to electricity cost, LCOW would show limited impact from using more (or less) expensive electricity from renewables. Therefore, among the various factors that might contribute to a decision to deploy renewables at a facility, including the cost of electricity, concerns about the impact on LCOW would likely be only a minor factor—neither significantly positive or negative. The current finding that the LCOW is very sensitive to capacity factors suggests that running treatment plants intermittently is unlikely to be cost effective; therefore, any use of renewable energy would require sufficient on-site storage or a grid connection so treatment facility operations would not be dependent on the availability of renewables.

3.4. Future of Treatment for Municipal Reuse. The examination of the pipe parity metrics for the case studies and other relevant data highlight opportunities for research that can enable greater municipal reuse for different end uses in geographically distinct regions using a variety of treatment trains to meet future water demands. These research opportunities align with recently published technology roadmaps for the municipal and power end-use sectors.[91,92] For systems involving RO and membrane filtration, these operations are both the most expensive and energy intensive; consequently, research that enables the development of processes with longer lifetimes, lower production costs, and that are more resilient to fluctuations in influent water quality can have major benefits. Research that advances the modularity, autonomy, and electrification (e.g., substitution of electricity for chemicals) of treatment trains has the potential to make potable reuse of municipal wastewater a viable option for small systems as well as for the large systems where they are currently deployed. These features can also be central to greater development of building- and district-scale municipal reuse for nonpotable uses as well as upgrading that water for potable use. It appears likely that RO-based treatment trains are both the present and future of municipal reuse in regions where salinity management is an inherent challenge or where it is required by regulations. In contrast, a more diverse range of treatment trains will be deployed in low salinity regions with the final selection based on a range of driving factors, as illustrated by HRSD. The Big Spring facility is an anomaly of an inland facility where RO concentrate can be discharged to surface water, and technologies that improve intensified brine management will be critical to increasing municipal reuse in these regions. Technologies that can lower the cost and electricity intensity of brine concentrators and crystallizers for zero liquid discharge could enable broader deployment of water reuse in semiarid inland contexts.

Treatment technologies that enable municipal reuse for thermoelectric power plants have already enabled the decoupling of electricity demand and water resource availability in the siting of power plants. Reuse of municipal wastewater and ZLD operations have allowed the nation's largest nuclear power plant to operate in arid central Arizona. Municipal reuse has also expanded potential locations for the construction of new natural gas combined cycle plants. These trends are anticipated to continue. Research that enables lower cost ZLD operations has the potential to substantially lower pipe parity metrics for municipal reuse, especially in inland areas.

4. CONCLUSIONS

The four case studies represent different treatment trains and different contexts with region-specific drivers of reuse and regulatory frameworks. The WaterTAP3 TEA tool enabled the determination of cost and energy metrics for these facilities using a common platform. Principal treatment is the component of overall water supply with the greatest contribution to LCOW. Overall treatment processes contribute significantly more to LCOW than do acquisition, storage, and distribution. The total capital investment is the largest single cost type. The treatment trains based on O_3/BAF/GAC has a significantly lower LCOW than RO-based treatment trains, and the electricity demand O_3/BAF/GAC is less than half that of the RO-based treatment trains. When using WaterTAP3 to compare the production of potable municipal water from different alternative sources by RO-based processes, municipal reuse has both a lower LCOW and electricity demand than desalination of seawater. However, production from the largest brackish desalination facility in the U.S. has an even lower LCOW and electricity intensity than the largest municipal reuse facility. The management of RO concentration for inland reuse facilities poses substantial cost and energy barriers.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsestengg.1c00351.

https://doi.org/10.1021/acsestengg.1c00351
ACS EST Engg. XXXX, XXX, XXX−XXX

Case study descriptions of two thermoelectric power plants that practice municipal reuse are presented. Tables with typical ranges of influent water quality to reuse facilities, water quality requirements for different end uses, financial and operational inputs for case studies, and summary of case study data and WaterTAP3 results. (PDF)

AUTHOR INFORMATION

Corresponding Author

Daniel E. Giammar − *Washington University in St. Louis, St. Louis, Missouri 63130, United States*; orcid.org/0000-0002-4634-5640; Email: giammar@wustl.edu

Authors

David M. Greene − *National Renewable Energy Laboratory, Golden, Colorado 80401, United States*

Anushka Mishrra − *Washington University in St. Louis, St. Louis, Missouri 63130, United States*; orcid.org/0000-0002-6443-0101

Nalini Rao − *Electric Power Research Institute, Palo Alto, California 94304, United States*

Joshua B. Sperling − *National Renewable Energy Laboratory, Golden, Colorado 80401, United States*

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

Alana Wilson − *National Renewable Energy Laboratory, Golden, Colorado 80401, United States*

Sertac Akar − *National Renewable Energy Laboratory, Golden, Colorado 80401, United States*

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

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

Katie Coughlin − *Lawrence Berkeley National Laboratory, Berkeley, California 94720, United States*

Complete contact information is available at:
https://pubs.acs.org/10.1021/acsestengg.1c00351

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This material is based upon work supported by the National Alliance for Water Innovation (NAWI), funded by the U.S. Department of Energy, Energy Efficiency and Renewable Energy Office, Advanced Manufacturing Office under Funding Opportunity Announcement DE-FOA-0001905. This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. We are grateful to people associated with the case studies who provided data and input to our technoeconomic analysis. Charles Bott of HRSD and Tyler Nading of Jacobs were valuable points of contact for the SWIFT facilities. Megan Plumlee and Han Gu of OCWD provided helpful information and perspectives. David Sloan of Freese and Nichols was a key point of contact regarding the Big Spring RWPF. Tim Harden and William Skalitzky of Alliant Energy provided helpful information about Alliant Energy's Emery Generating Station in Iowa. Ed Clerico, Sheng Chu, and Zach Gallagher of Natural Systems Utilities provided valuable data, references, and feedback on the Solaire case study. We appreciate the critical inputs of two anonymous reviewers that helped us improve the interpretation and presentation of the results. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

REFERENCES

(1) *Potable Reuse Compendium*; U.S. Environmental Protection Agency, 2017.

(2) *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment*, Vol. *II*; U.S. Global Climate Change Research Program: Washington, DC, 2018.

(3) Brown, T. C.; Mahat, V.; Ramirez, J. A. Adaptation to future water shortages in the United States caused by population growth and climate change. *Earth's Future* **2019**, 7 (3), 219−234.

(4) Current State of Water Reuse. In *Water Reuse: Potential for Expanding the Nation's Water Supply through Reuse of Municipal Wastewater*; National Research Council, 2012; Chapter 2.

(5) Basic Information about Water Reuse. *U.S. Environmental Protection Agency*.https://www.epa.gov/waterreuse/basic-information-about-water-reuse (August 10, 2021).

(6) Cherchi, C.; Kesaano, M.; Badruzzaman, M.; Schwab, K.; Jacangelo, J. G. Municipal reclaimed water for multi-purpose applications in the power sector: A review. *J. Environ. Manage.* **2019**, *236*, 561−570.

(7) Veil, J. A. *Use of Reclaimed Water for Power Plant Cooling*; Argonne National Laboratory: Argonne, IL, 2007.

(8) Sim, A.; Mauter, M. S. Cost and energy intensity of US potable water reuse systems. *Environ. Sci.: Water Res. Technol.* **2021**, 7 (4), 748−761.

(9) Jones, C. H.; Meyer, J.; Cornejo, P. K.; Hogrewe, W.; Seidel, C. J.; Cook, S. M. A new framework for small drinking water plant sustainability support and decision-making. *Sci. Total Environ.* **2019**, *695*, 133899.

(10) Cornejo, P. K.; Becker, J.; Pagilla, K.; Mo, W.; Zhang, Q.; Mihelcic, J. R.; Chandran, K.; Sturm, B.; Yeh, D.; Rosso, D. Sustainability metrics for assessing water resource recovery facilities of the future. *Water Environ. Res.* **2019**, *91* (1), 45−53.

(11) Mihelcic, J. R.; Ren, Z. J.; Cornejo, P. K.; Fisher, A.; Simon, A. J.; Snyder, S. W.; Zhang, Q.; Rosso, D.; Huggins, T. M.; Cooper, W.; Moeller, J.; Rose, B.; Schottel, B. L.; Turgeon, J. Accelerating innovation that enhances resource recovery in the wastewater sector: advancing a national testbed network. *Environ. Sci. Technol.* **2017**, *51* (14), 7749−7758.

(12) Rice, J.; Westerhoff, P. Spatial and temporal variation in de facto wastewater reuse in drinking water systems across the USA. *Environ. Sci. Technol.* **2015**, *49* (2), 982−989.

(13) Mancha, E. Water Reuse in Texas Webinar. *Texas Water Development Board*. https://www.nctcog.org/nctcg/media/Environment-and-Development/Documents/Natural%20Resources/Water%20Quality/WaterReuseWebinar-06-18-2019.pdf (November 20, 2020).

(14) Recycled Water—Expert Panel to Advise on Developing Uniform Recycling Criteria for Indirect Potable Reuse via Surface Water Augmentation and on the Feasibility of Developing Such Criteria for Direct Potable Reuse. *California Water Boards*. www.

waterboards.ca.gov/drinking_water/certlic/drinkingwater/RW_SWA_DPRexpertpanel.shtml (August 24, 2021).
(15) Capodaglio, A. G. Fit-for-purpose urban wastewater reuse: Analysis of issues and available technologies for sustainable multiple barrier approaches. *Crit. Rev. Environ. Sci. Technol.* **2021**, *51*, 1619−1666.
(16) Wetterau, G.; Zornes, G. End-of-Cycle: Water Reuse.*SIWI Stockholm World Water Week*, 2020.
(17) California Potable Reuse Map of California. *WateReuse*. https://watereuse.org/sections/watereuse-california/potable-reuse-map-of-california/ (November 12, 2021).
(18) *Alternative Water Supplies for Power Generation*; 3002012045; Electric Power Research Institute: Palo Alto, CA, 2017.
(19) Macknick, J.; Newmark, R.; Heath, G.; Hallett, K. *Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies*; National Renewable Energy Laboratory: Golden, CO, 2011.
(20) Woldeyesus, T. A. *Electric Portfolio Modeling with Stochastic Water-Climate Interactions: Implications for Co-Management of Water and Electric Utilities*. Ph.D. Thesis, University of Colorado at Denver, 2012.
(21) Cohen, E.; Ramaswami, A. The water withdrawal footprint of energy supply to cities: Conceptual development and application to Denver, Colorado, USA. *J. Ind. Ecol.* **2014**, *18* (1), 26−39.
(22) Macknick, J.; Zhou, E.; O'Connell, M.; Brinkman, G.; Miara, A.; Ibanez, E.; Hummon, M. *Water and Climate Impacts on Power System Operations: The Importance of Cooling Systems and Demand Response Measures*; National Renewable Energy Laboratory: Golden, CO, 2016.
(23) Miara, A.; Barrows, C.; Macknick, J.; Sigler, D.; Liu, Y. The Potential for Water Infrastructure to Provide Power Grid Services, *AGU Fall Meeting Abstracts*, 2019.
(24) Dieter, C. A. *Water Availability and Use Science Program: Estimated Use of Water in the United States in 2015*; U.S. Geological Survey, 2018.
(25) *Municipal Wastewater Reuse by Electric Utilities: Best Practices and Future Decisions. Workshop Report*; Water Environment Federation and American Society of Mechanical Engineers: Alexandria, VA, 2012.
(26) Arent, D.; Pless, J.; Mai, T.; Wiser, R.; Hand, M.; Baldwin, S.; Heath, G.; Macknick, J.; Bazilian, M.; Schlosser, A.; Denholm, P. Implications of high renewable electricity penetration in the US for water use, greenhouse gas emissions, land-use, and materials supply. *Appl. Energy* **2014**, *123*, 368−377.
(27) Barker, Z. A.; Stillwell, A. S. Implications of transitioning from de facto to engineered water reuse for power plant cooling. *Environ. Sci. Technol.* **2016**, *50* (10), 5379−5388.
(28) Munson, R.; Murphy, J.; Walsh, K. *Use of Non-Traditional Water for Power Plant Applications: An Overview of DOE/NETL R&D Efforts*; DOE/NETL-311/040609; National Energy Technology Laboratory, 2009.
(29) Li, H.; Chien, S.-H.; Hsieh, M.-K.; Dzombak, D. A.; Vidic, R. D. Escalating water demand for energy production and the potential for use of treated municipal wastewater. *Environ. Sci. Technol.* **2011**, *45* (10), 4195−4200.
(30) *Use of Degraded Water Sources as Cooling Water in Power Plants*; 1005359; Electric Power Research Institute and California Energy Commission: Palo Alto, CA, 2003.
(31) Best Practices to Consider When Evaluating Water Conservation and Efficiency as an Alternative for Water Supply Expansion. *U.S. Envionmental Protection Agency*. https://www.epa.gov/sites/production/files/2016-12/documents/wc_best_practices_to_avoid_supply_expansion_2016_508.pdf (May 2, 2020).
(32) Cernansky, R. From Drain to Drink: Innovations in Wastewater Reuse, 2013. *GreenBiz*. https://www.greenbiz.com/article/drain-drink-innovations-wastewater-reuse (accessed November 20, 2020).
(33) Ren, Z. J. Editorial Perspectives: the value proposition of resource recovery. *Environ. Sci.: Water Res. Technol.* **2019**, *5* (2), 196−197.
(34) Larsen, T. A.; Hoffmann, S.; Luthi, C.; Truffer, B.; Maurer, M. Emerging solutions to the water challenges of an urbanizing world. *Science* **2016**, *352* (6288), 928−933.
(35) Ryder, G. *The United Nations World Water Development Report, 2017: Wastewater: The Untapped Resource*. UNESCO, 2017.
(36) Voulvoulis, N. Water reuse from a circular economy perspective and potential risks from an unregulated approach. *Current Opinion in Environmental Science & Health* **2018**, *2*, 32−45.
(37) *Master Plan for the National Water Sector*; State of Israel Water Authority, 2012.
(38) Lee, H.; Tan, T. P. Singapore's experience with reclaimed water: NEWater. *Int. J. Water Resource Dev.* **2016**, *32* (4), 611−621.
(39) Ghernaout, D.; Elboughdiri, N.; Alghamdi, A. Direct Potable Reuse: The Singapore NEWater Project as a Role Model. *Open Access Library Journal* **2019**, *06* (12), 1.
(40) Du Pisani, P.; Menge, J. Direct potable reclamation in Windhoek: a critical review of the design philosophy of new Goreangab drinking water reclamation plant. *Water Sci. Technol.: Water Supply* **2013**, *13* (2), 214−226.
(41) Kunz, N. C.; Fischer, M.; Ingold, K.; Hering, J. G. Why do some water utilities recycle more than others? A qualitative comparative analysis in New South Wales, Australia. *Environ. Sci. Technol.* **2015**, *49* (14), 8287−8296.
(42) *National Water Reuse Action Plan: Collaborative Implementation (Version 1)*; EPA-HQ-OW-2019−0174; U.S. Envionmental Protection Agency, 2020.
(43) Bryck, J.; Prasad, R.; Lindley, T.; Davis, S.; Carpenter, G. *National Database of Water Reuse Facilities Summary Report*; WRF-02-004; WaterReuse Foundation: Alexandria, VA, 2008.
(44) Bischel, H. N.; Simon, G. L.; Frisby, T. M.; Luthy, R. G. Management experiences and trends for water reuse implementation in Northern California. *Environ. Sci. Technol.* **2012**, *46* (1), 180−188.
(45) Bui, A.; Burnham, A.; Zieburtz, W. Survey Results Provide Water Reuse Cost Allocations and Pricing Guidance. *J. - Am. Water Works Assoc.* **2019**, *111* (11), 60−63.
(46) Zieburtz, W.; Coopersmith, M.; Burnham, A. *Water Reuse Cost Allocations and Pricing Survey*; TEC Project; American Water Works Association, May 2019.
(47) Po, M.; Nancarrow, B. E.; Kaercher, J. D. *Literature Review of Factors Influencing Public Perceptions of Water Reuse*; Technical Report 54/03; CSIRO Land and Water, 2003.
(48) Gerrity, D.; Pecson, B.; Trussell, R. S.; Trussell, R. R. Potable reuse treatment trains throughout the world. *Aqua* **2013**, *62* (6), 321−338.
(49) Guo, T.; Englehardt, J.; Wu, T. Review of cost versus scale: water and wastewater treatment and reuse processes. *Water Sci. Technol.* **2014**, *69* (2), 223−234.
(50) Tran, Q. K.; Jassby, D.; Schwabe, K. A. The implications of drought and water conservation on the reuse of municipal wastewater: Recognizing impacts and identifying mitigation possibilities. *Water Res.* **2017**, *124*, 472−481.
(51) Harris-Lovett, S. R.; Binz, C.; Sedlak, D. L.; Kiparsky, M.; Truffer, B. Beyond User Acceptance: A Legitimacy Framework for Potable Water Reuse in California. *Environ. Sci. Technol.* **2015**, *49* (13), 7552−61.
(52) Rice, J.; Wutich, A.; White, D. D.; Westerhoff, P. Comparing actual de facto wastewater reuse and its public acceptability: A three city case study. *Sustain. Cities Soc.* **2016**, *27*, 467−474.
(53) Angelakis, A. N.; Snyder, S. A. *Wastewater Treatment and Reuse: Past, Present, and Future*; Multidisciplinary Digital Publishing Institute, 2015.
(54) California Ocean Plan, 2018. *California State Water Resources Control Board*. https://www.waterboards.ca.gov/water_issues/programs/ocean/docs/oceanplan2019.pdf (accessed June 18, 2021).
(55) *Principles of Water Rates, Fees, and Charges*, Seventh ed.; American Water Works Association, 2017; Vol. *M1*.
(56) Water Reuse Cost Allocations and Pricing Survey. *American Water Works Association*. https://www.awwa.org/Portals/0/AWWA/

ETS/Resources/AWWAReuseSurveyReportMay2019_WEBRES.pdf?ver=2019-10-07-151457-847 (July 21, 2021).

(57) Klembara, M. *Energy-Water Desalination Hub: Funding Opportunity Announcement*; DE-FOA-0001905; U.S. Department of Energy, 2019.

(58) Miara, A.; Sitterley, K.; Talmadge, M.; Huang, Z.; Evans, A.; Stokes-Draut, J.; Macknick, J. WaterTAP3 Documentation, version 0.0.1. *GitHub*.https://github.com/NREL/WaterTAP3/blob/2376317686065e089862514a51aec5132e23efa4/watertap3/WaterTAP3_doc_v1.pdf (September 2, 2021).

(59) Hogard, S.; Salazar-Benites, G.; Pearce, R.; Nading, T.; Schimmoller, L.; Wilson, C.; Heisig-Mitchell, J.; Bott, C. Demonstration-scale evaluation of ozone−biofiltration−granular activated carbon advanced water treatment for managed aquifer recharge. *Water Environ. Res.* **2021**, *93*, 1157−1172.

(60) Martinez, M.; Widdowson, M. Development of Analytical Models to Evaluate Transport and Attenuation in a Multi-Layer Aquifer during Managed Aquifer Recharge; *AGU Fall Meeting Abstracts*, 2020.

(61) Vaidya, R.; Buehlmann, P. H.; Salazar-Benites, G.; Schimmoller, L.; Nading, T.; Wilson, C. A.; Bott, C.; Gonzalez, R.; Novak, J. T. Pilot Plant Performance Comparing Carbon-Based and Membrane-Based Potable Reuse Schemes. *Environ. Eng. Sci.* **2019**, *36* (11), 1369−1378.

(62) Heide, A. *2020 Urban Water Management Plan*; Municipal Water District of Orange County, 2021.

(63) CRMWD's History, 2018. *CRMWD*. https://www.crmwd.org/about/history/ (accessed November 2021).

(64) Freeze and Nichols, Inc., LBG - Guyton Associates, Inc. *Region F 2016 Water Plan Vol. 1*; Texas Water Development Board, 2015.

(65) CRMWD Reclaimed Water, 2020. *CRMWD*. https://www.crmwd.org/water-sources/reuse/ (accessed November 2021).

(66) Salveson, A.; Steinle-Darling, E.; Trussell, S.; Trussell, B.; McPherson, L. *Guidelines for Engineered Storage for Direct Potable Reuse*; WateReuse Research Foundation: Alexandria, VA, 2015. .

(67) Livingston, E.; Salveson, A. Village of Cloudcroft, New Mexico's PUReWater Project, unpublished slide presentation, *Water-Smart Innovations Conference and Exposition*, October 8−10, 2008, Las Vegas, NV.

(68) Zavoda, M., NYC High-Rise Reuse Proves Decentralized System Works. *WaterWorld*, 2006.

(69) Fritzmann, C.; Löwenberg, J.; Wintgens, T.; Melin, T. State-of-the-art of reverse osmosis desalination. *Desalination* **2007**, *216* (1−3), 1−76.

(70) Herman, J. G.; Scruggs, C. E.; Thomson, B. M. The costs of direct and indirect potable water reuse in a medium-sized arid inland community. *J. Water Process Eng.* **2017**, *19*, 239−247.

(71) Nanaboina, V.; Korshin, G. V. Evolution of absorbance spectra of ozonated wastewater and its relationship with the degradation of trace-level organic species. *Environ. Sci. Technol.* **2010**, *44* (16), 6130−6137.

(72) Lee, Y.; Gerrity, D.; Lee, M.; Bogeat, A. E.; Salhi, E.; Gamage, S.; Trenholm, R. A.; Wert, E. C.; Snyder, S. A.; Von Gunten, U. Prediction of micropollutant elimination during ozonation of municipal wastewater effluents: use of kinetic and water specific information. *Environ. Sci. Technol.* **2013**, *47* (11), 5872−5881.

(73) Gamage, S.; Gerrity, D.; Pisarenko, A. N.; Wert, E. C.; Snyder, S. A. Evaluation of process control alternatives for the inactivation of Escherichia coli, MS2 bacteriophage, and Bacillus subtilis spores during wastewater ozonation. *Ozone: Sci. Eng.* **2013**, *35* (6), 501−513.

(74) Gerrity, D.; Owens-Bennett, E.; Venezia, T.; Stanford, B. D.; Plumlee, M. H.; Debroux, J.; Trussell, R. S. Applicability of ozone and biological activated carbon for potable reuse. *Ozone: Sci. Eng.* **2014**, *36* (2), 123−137.

(75) Schimmoller, L.; Kealy, M. *Fit for Purpose Water: The Cost of Overtreating Reclaimed*; WateReuse Research Foundation and U.S. Bureau of Reclamation: Alexandria, VA, 2014.

(76) Schimmoller, L.; Kealy, M.; Foster, S. Triple bottom line costs for multiple potable reuse treatment schemes. *Environ. Sci.: Water Res. Technol.* **2015**, *1* (5), 644−658.

(77) Plumlee, M. H.; Stanford, B. D.; Debroux, J.-F.; Hopkins, D. C.; Snyder, S. A. Costs of advanced treatment in water reclamation. *Ozone: Sci. Eng.* **2014**, *36* (5), 485−495.

(78) McGivney, W.; Kawamura, S. *Cost Estimating Manual for Water Treatment Facilities*; Wiley Online Library, 2008.

(79) Voutchkov, N. Desalination − Past, Present, and Future. *International Water Association*. https://iwa-network.org/desalination-past-present-future/ (November 12, 2021).

(80) Estevez-Olea. Life Cycle Assessment of Reclaimed Water for Potable and Nonpotable Reuse in California. Master's Projects and Capstones. The University of San Francisco, 2015.

(81) *Electricity Use and Management in the Municipal Water Supply and Wastewater Industries*; Water Research Foundation and Electric Power Research Institute, 2013.

(82) Shubert, R. A. Overview of the El Paso Kay Bailey Hutchison Desalination Plant. In *El Paso Water Utilities Board, Texas Desal Conference*, 2015.

(83) Voutchkov, N. Energy use for membrane seawater desalination - current status and trends. *Desalination* **2018**, *431*, 2−14.

(84) Cooley, H. Desalination and Energy Use...Should We Pass the Salt? *Pacific Institute*. https://pacinst.org/desal-and-energy-use-should-we-pass-the-salt/ (November 18, 2021).

(85) Stillwell, A. S.; Twomey, K. M.; Osborne, R.; Greene, D. M.; Pedersen, D. W.; Webber, M. E. An integrated energy, carbon, water, and economic analysis of reclaimed water use in urban settings: a case study of Austin, Texas. *J. Water Reuse Desalin.* **2011**, *1* (4), 208−223.

(86) Assessment of Energy Intensity and Greenhouse Emissions of Proposed West Basin Desalination Plant and Water Supply Alternatives. *Powers Engineering*. www.smarterwaterla.org/wp-content/uploads/2018/01/Powers_Engineering_2018_WB_Desal.pdf (November 18, 2020).

(87) Cooley, H.; Gleick, P. H.; Wolff, G. *Desalination, with a Grain of Salt*; Pacific Institute, 2006.

(88) Tong, T.; Elimelech, M. The global rise of zero liquid discharge for wastewater management: drivers, technologies, and future directions. *Environ. Sci. Technol.* **2016**, *50* (13), 6846−6855.

(89) Heijman, S. G. J.; Guo, H.; Li, S.; Van Dijk, J. C.; Wessels, L. P. Zero liquid discharge: Heading for 99% recovery in nanofiltration and reverse osmosis. *Desalination* **2009**, *236* (1−3), 357−362.

(90) McCurdy, R. Underground Injection Wells for Produced Water Disposal. *Chesapeake Energy Corporation*. https://www.epa.gov/sites/default/files/documents/21_McCurdy_-_UIC_Disposal_508.pdf (November 15, 2021).

(91) Giammar, D.; Jiang, S.; Xu, P.; Breckenridge, R.; Macknick, J.; Rao, N.; Sedlak, D.; Stokes-Draut, J. *National Alliance for Water Innovation (NAWI) Technology Roadmap: Municipal Sector*; National Renewable Energy Laboratory: Golden, CO, 2021.

(92) Childress, A.; Giammar, D.; Jiang, S.; Breckenridge, R.; Howell, A.; Macknick, J.; Sedlak, D.; Stokes-Draut, J. *National Alliance for Water Innovation (NAWI) Technology Roadmap: Power Sector*; National Renewable Energy Laboratory: Golden, CO, 2021.