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Cost and Energy Intensity of U.S. Potable Water Reuse Systems

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Abstract

This paper reports on a new and open-source dataset, curated from facility-specific engineering reports, detailing facility features for an aggregated total of 70 operating, demonstration, pilot and unbuilt U.S. potable water reuse systems. The dataset and our following analysis reviews treatment train design, estimated electricity consumption, facility capital and operation and maintenance costs, and air emission externalities of those systems. Despite a wide variety of feedwater qualities and augmentation strategies, we observe remarkable consistency in potable reuse treatment train design. We estimate potable reuse electricity intensity for each facility as a function of feedwater quality and installed unit processes, finding that advanced treatment train electricity intensities fall within the range of 0.23–2.0 kWh/m^3. This range excludes the energy required for conveying water to advanced treatment facilities or pumping the water for supply augmentation. For 25 facilities with capital cost data, we find that potable reuse capital costs normalized by system design capacity fall between 1000 and 5300 $\$m^{-3}d$. Subsequent cost analysis of the subset of full advanced treatment (FAT) systems suggests capacity normalized capital costs between 1800 and 4100 $\$m^3d^{-1}$ and capacity normalized operation and maintenance costs between 100 and 200 $\$m^3d^{-1}$. These ranges validate previously reported bottom-up cost estimates for FAT facilities. Finally, we use the Water AHEAD model to estimate the annual human health, environmental, and climate damages for representative advanced treatment trains. Air emission externalities from U.S. potable reuse facilities fall between 10 and 40 $ per thousand m^3, with the majority of damages associated with electricity consumption at potable reuse facilities.

Water Impact Statement

Increasing water demand and climate change impacts are straining water resources in arid regions of the U.S. Potable water reuse is one approach for enhancing the resiliency of a water supply portfolio. Benchmarks for technical, cost, energy, and climate and health externalities from existing systems will aid evaluation of potable water reuse against other supply alternatives.

1. Introduction

Potable water reuse is a climate-resilient approach for augmenting and securing water supplies.[1,2] Municipalities cite local and regional water shortages, groundwater or surface water withdrawal limits, seasonal surface water contamination, and the high costs of non-potable distribution as common drivers for adoption of potable reuse systems.[3,4] While adoption of potable reuse was slow through the 2000's, the number of potable reuse projects in the U.S. has tripled since 2010 and it is now widely recognized as a key component of urban water security portfolios.[1]

Supporting this expansion of potable reuse is a series of substantial federal, state, local, and philanthropic investments in water reuse research, development, and demonstration. Significant investments in early-stage research have come through federally funded centers, including the Reinventing the National Urban Water Infrastructure (ReNUWit) center and the National Alliance for Water Innovation (NAWI),[5,6] while targeted research programs led by organizations such as the WateReuse Association and potable reuse facility operators have contributed essential support for applied research and development.[7–10] The newly released National Water Reuse Action Plan (WRAP) builds on this history of collaborative investments in water reuse research and champions broader engagement across federal, state, and local governments.[11]

With the opportunity for substantial further investment in potable water reuse comes the need for clear technical, cost, and environmental benchmarks for potable reuse facilities in the U.S. General technology attributes influencing the adoption of potable reuse facilities include capital and infrastructure costs, operations and maintenance (O&M) costs, capacity factors, energy requirements, and climate and health impacts. Several site-specific factors, including public perception of water reuse, conveyance and distribution needs, system capacity limits, feedwater quality, regulatory requirements, and concentrate disposal costs also influence adoption.[4,12,13] For example, the costs of potable water reuse at facilities without costal discharge permits for facile concentrate disposal average between 2.2 to 3.6 times higher, depending on the facility size.[8]

Significant prior work to provide technical, financial, and environmental benchmarks for water reuse has primarily used case-based or process level models, but widespread data-driven validation of these benchmarks is scarce in the peer-reviewed literature. Technical work characterizing the function and sequence of unit processes in potable reuse treatment trains has evaluated a series of direct and indirect potable reuse schemes.[4,14–16] These schemes are generally classified into membrane and non-membrane based systems. Full advanced treatment (FAT), the most common membrane-based treatment train for potable reuse, consists of microfiltration (MF), reverse osmosis (RO), and advanced oxidation processes (AOPs), often using ultraviolet radiation (UV) and hydrogen peroxide (H_2O_2) technology. FAT, required for groundwater injection applications in California,[17,18] has been widely demonstrated to remove bulk organic matter, trace organic carbon, and total dissolved solids (TDS).[4,14,19]

Non-membrane approaches, such as ozone and biologically activated carbon (BAC) or filtration (BAF), degrade trace organic carbon and remove by-products but do not reduce TDS or high concentrations of nitrogen. As a result, additional nanofiltration or RO processes may be required to meet end user water quality requirements or location specific discharge regulations.[7,14,20] While capable of producing high quality effluent in low TDS waters, carcinogenic byproduct (e.g., bromate, NDMA) formation from wastewater ozonation remains a concern in these systems.[21–24]

Finally, an increasing number of treatment configurations hybridize membrane and non-membrane-based treatment trains (e.g., RO combined with BAF). Past technical evaluation of these treatment schema has documented high water quality from direct and indirect potable reuse, but the water treatment community lacks a centralized repository of pilot, demonstration, and full-scale treatment trains that can serve as a benchmark for new projects and future R&D investments.

This diversity of treatment trains, combined with location and time specific factors, also complicates efforts to assess the cost of potable water reuse. Capital costs are subject to fluctuations in the cost of capital, local labor conditions, infrastructure demands for conveying and storing reclaimed water, and regulatory and permitting costs,[25,26] while influent water quality, energy costs, and project scale can lead to significant variations in operational costs.[13] Past work suggests that O&M costs are more consistent across potable reuse projects and are best estimated through standardized annual cost elements, such as energy and chemical usage, labor, and major equipment replacement.[8,27]

Previous studies have collected potable water reuse costs for up to seven operational facilities [4,12,13] or 20 pilot or demonstration facilities,[28] but each study has opted to include or exclude different aspects of project costs. For example, Cooley & Phurisamban (2016) collected cost data for a total of six small (< 34,000 m^3/d or 10,000 AFY) and large (> 34,000 m^3/d or 10,000 AF) operational IPR facilities and found that total costs ranged from \$1.6/m^3 (\$2000/AF) to \$2.1/m^3 (\$2700/AF) for smaller facilities and \$1.3/m^3 (\$1600/AF) to \$1.6/m^3 (\$2000/AF) for larger facilities. Unfortunately, this work did not detail the technologies or facility attributes that might explain the variation within this range. Other studies have alternated between including or excluding infrastructure expansion, IPR injection wells, and concentrate disposal costs in calculations of IPR project costs.[23,24]

This lack of standardized reporting explains variation in capital cost estimates of up to 50% and hinders the development of reliable cost curves for new projects. A complete assessment of costs that is grounded in treatment train design, facility size, and site-specific factors would improve our understanding of the origins of cost variability across projects. It would also make it easier for communities to evaluate potable water reuse relative to the costs of other water supply options, for stakeholders to project the economic impact that potable reuse will have on water resources across the U.S., and for researchers to evaluate alternative process schema against clear cost targets.

Finally, few of these studies have incorporated environmental externalities into their cost framework. Recent work has estimated the human health, environmental, and climate (HEC) damages from direct and indirect emissions of greenhouse gases (GHGs), criteria air pollutants (CAPs), and particulate matter from U.S. water and wastewater treatment facilities to be on the order of \$750 M annually.[29] The majority of these HEC damages are associated with the electricity and chemical consumption during treatment plant operation, and potable reuse facilities often use energy intensive unit processes.[30] Studies specifically evaluating potable reuse energy intensity via surveys, case studies, and analytical tools [25,31–33] have provided valuable insight into operational energy demands, but have rarely translated energy into emissions estimates, accounted for the embedded emissions from chemical consumption, or evaluated tradeoffs between financial and HEC implications as a function of plant design and operational characteristics. Other work has included holistic comparisons of the financial, social and environmental impacts of specific water reuse case studies via life cycle assessments and Triple Bottom Line analyses, but did so for a very limited set of one to two facilities.[8,9,34] Finally, published literature on potable reuse energy consumption and environmental impacts tends to present point estimates rather than ranges that account for variability in unit process electricity consumption as a function of feedwater quality or end use application.[31,32]

While technical, cost, energy, and HEC data are helpful for benchmarking potable reuse projects to other water supply alternatives, public acceptance of the technology is a critical factor that is less readily quantified. Though successfully operating IPR and DPR systems in the U.S. have demonstrated the reliability of potable water reuse technology, public opposition halted several proposed potable reuse projects in Los Angeles and San Diego in the late 1990s.[35] California has since seen growth in potable water reuse capacity, but regions unfamiliar with water reuse may continue to oppose technology adoption. The decade-long education and outreach campaign led by the Orange County Water District Groundwater Replenishment System (GWRS) laid the groundwork for public approval,[35] but not all water districts or cities have resources to direct similar efforts. Given the importance of public acceptance for successful implementation of potable water reuse, past work has used surveys to track stakeholder perceptions and preferences,[36–39] outlined paths for technology legitimization, and detailed strategies for garnering support.[35,40] While we recognize negative public perception as a considerable impediment to the adoption potable water reuse, we lack historical survey data on a facility-by-facility basis that would be necessary to address public perception in this work.

Water reuse is one of several alternatives to augment scarce water supplies. The evaluation of the potential for water reuse vis-a-vis other water sources will depend on a number of factors, including the fidelity between prospective and retrospective analysis of past potable water reuse projects. This work performs a comprehensive review of both literature and publicly available data to deliver benchmarks for current potable water reuse projects in the U.S. through 2020, to investigate common U.S. specific potable reuse treatment trains by source water, and to evaluate electricity intensities of proposed and operating systems as a function of their unit processes. We also apply the Water AHEAD tool[41] to estimate the HEC damages associated with electricity and chemical consumption of common potable reuse treatment trains. Finally, we provide a validation dataset for potable reuse cost estimation tools. By comprehensively cataloging and analyzing past projects, including relating their treatment trains, energy intensity, capital and operational costs, and HEC externalities, we hope to assist future municipalities in evaluating potable reuse as an alternative water source. Additionally, this work aims to provide baselines for researchers pursuing innovations to potable reuse treatment trains, be those in terms of technology or system scale.

2. Methods

We develop a detailed dataset containing general features of 70 potable reuse systems, omitting *de facto* reuse. In addition, we collect facility or total project cost data for a subset of 25 of the analyzed systems and O&M costs for a smaller subset of 7 of the 25 systems. The complete dataset and corresponding references are provided in Table S1-S2 and Supporting Information (SI) Section 1.0. We compare facility data to previously published potable reuse data from a combination of past compendia by the National Research Council (NRC)[13] and the U.S. Environmental Protection Agency (EPA)[4], as well as to data reported in the Safe Drinking Water Information System (SDWIS) (Figure 1).

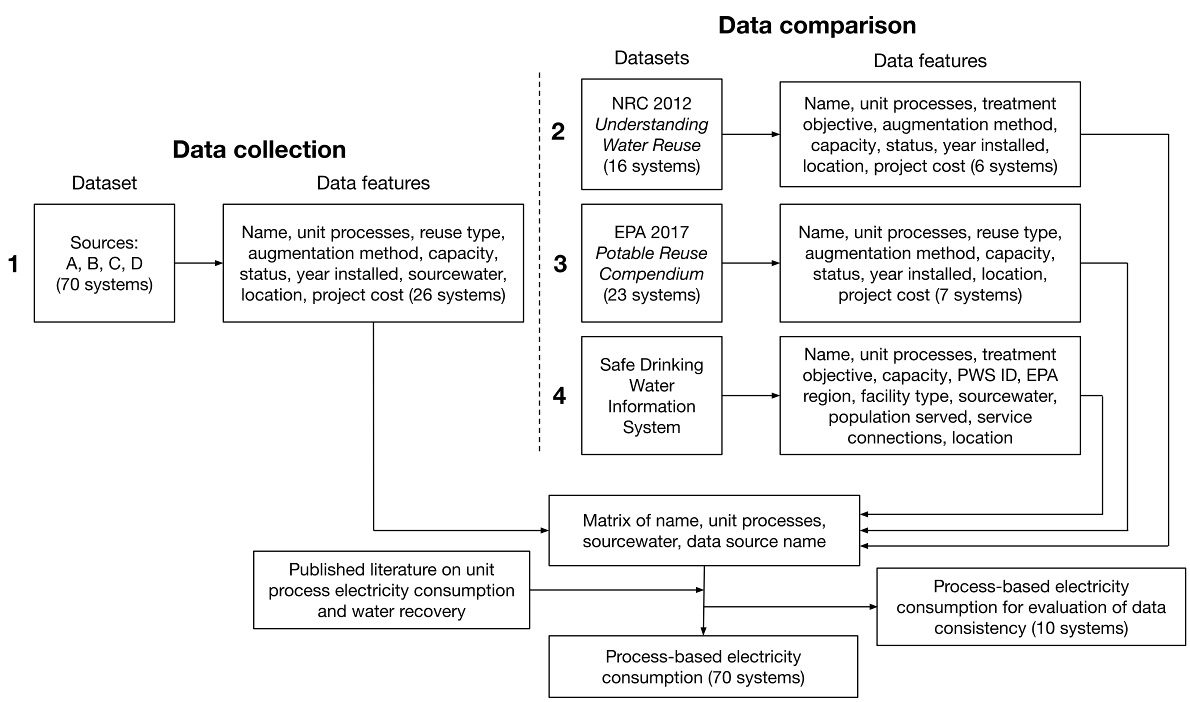


Figure 1. Methods, data sources, and data features used to compare four separate datasets and calculate the process-based electricity consumption for proposed and operational U.S. potable reuse systems. In addition to the *Understanding Water Reuse* report (NRC 2012), *EPA Potable Reuse Compendium* (EPA 2017), and Safe Drinking Water Information System (SDWIS) dataset, we compiled data from (A) government agencies (e.g., US Bureau of Reclamation), (B) national trade associations (e.g., WateReuse), (C) peer reviewed publications, and (D) water and wastewater utility-published engineering reports for 70 systems. We do not use all the data features from datasets 2, 3, and 4 in our analysis. The number in parentheses represents the total number of potable reuse systems extracted from each source, the subset of systems for which we acquired project cost data, or the number of systems for which we calculated process-based electricity intensities. Detailed information on the specific potable reuse system features collected from each source are provided in Section 2.1. The method for matching SDWIS public water systems (PWSs) to potable reuse facilities is provided in SI Section 2.0.

After cleaning and extracting data from each source (or sources) into four separate datasets, we use Python to merge the datasets into a single data frame that is then converted into a matrix with field codes of potable reuse system name, unit processes, source water, and data source. We do not use all the reported data features in dataset 2, 3, and 4. Potable reuse systems that appear in more than one dataset have an equivalent number of rows in the matrix. For example, the matrix has four distinct rows for a system reported in all four datasets, with each row differentiated by the information available in the respective dataset. Potable reuse systems documented in more than one dataset were evaluated for consistency.

2.1. Data aggregation of potable reuse facility features

There is a tremendous amount of facility-level data on potable reuse facilities in engineering reports. We perform a web search to consolidate data from government agencies (i.e., Title XVI Water Reclamation and Reuse feasibility studies),[42] white papers, scientific investigations from national trade organizations (i.e., WateReuse Association), peer-reviewed academic publications, and water and wastewater utility reports (i.e., Title 22 engineering reports) released on utility websites. From these technical documents, we collect and use information on treatment train, reuse type, augmentation method, capacity, operational status, year of installation, source water, and location for 70 potable reuse facilities.

The 2012 NRC *Understanding Water Reuse* report contains information on water quality, human health risks, treatment technologies, costs, social, and regulatory challenges of potable and non-potable reuse.[13] The report documented the name, unit treatment processes, treatment objective of each unit process (i.e., removal of organics or residual salts), augmentation method (i.e., surface water versus groundwater), capacity (MGD), operational status, and year of installation for 16 potable reuse schemes in the U.S., with the data sourced from Drewes and Khan (2010).[16] This report also surveyed responses for a subset of 6 potable reuse facilities (of the 16) for capital, O&M, and total annual costs in units of $/kgal. While this report provides diverse information about U.S. water reuse facilities, many of the facilities have been upgraded since data was collected in 2012. As such, we limit data use from this report to the list of installed unit processes.

The *EPA Potable Reuse Compendium* (EPA 2017) includes discussion on opportunities and obstacles for potable water reuse, chemical constituents in the feed and effluent streams, epidemiological studies, water quality monitoring, ongoing research efforts, and a general review of the benefits and challenges of regulatory-approved potable reuse treatment technologies.[4] The compendium also provides data on the name, location, year of installation, operational status, capacity (MGD), reuse type (i.e., IPR versus DPR), and treatment train for 25 full-scale, demonstration, pilot-study and unbuilt U.S. potable reuse facilities. For a subset of 7 of the 25 plants, it provides capital cost data for each plant and other background information, such as process flow diagrams, construction histories, and water quality. The report has limited information on the methods for data collection of the 25 plants, so we limit data use from this report to the installed list of unit processes and the capital cost estimate for a single plant that could not be obtained elsewhere.

The SDWIS dataset provides name, installed unit processes and treatment objective, capacity, PWS identification numbers, facility type, source water, population served, and location (city, state, and zip code) for all regulated PWS in the U.S. While the coverage of SDWIS data is much broader than the NRC or EPA datasets, past work suggests that SDWIS reporting is highly inconsistent across plants and years.[29] Thus, we limit data use to installed unit processes.

2.2. Process-based estimates of the electricity intensity of potable reuse systems

We define our control volume boundary around advanced water treatment, excluding conventional wastewater treatment processes and post-treatment (Figure 2). Post-treatment includes de- or re-carbonation, pH adjustment, and/or chemical softening processes. In energy calculations, we also exclude energy embedded in wastewater collection, conveyance, treatment, and distribution to end users.[23]

We estimate potable reuse electricity intensity by source water following the calculation methods detailed in Gingerich & Mauter (2017)[29] and using Python for simple matrix multiplication. Electricity intensities of unit processes are adjusted for water recovery and then summed across the treatment train. Gingerich & Mauter (2017) used SDWIS as the sole source of data for unit processes of PWSs, while the present work uses only the unit processes compiled from facility specific reports for each of the 70 systems (Table S1), as we believe those primary sources to be the most reliable. Electricity intensity and water recovery estimates for individual unit processes are in SI Section 3.0.

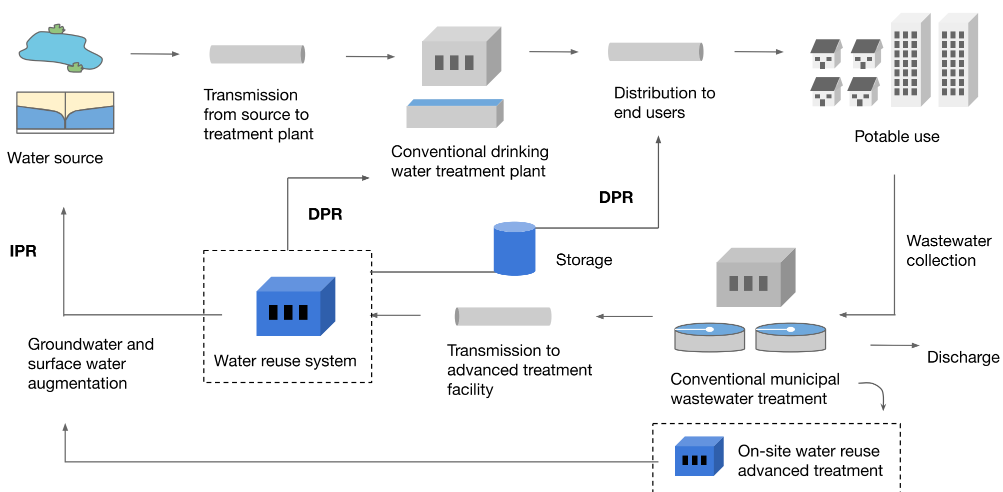


Figure 2. Characterization of indirect (IPR) and direct potable (DPR) reuse schema. Some IPR facilities convey reclaimed water from conventional municipal wastewater treatment plants to offsite advanced water treatment facilities, while other facilities employ their advanced treatment process onsite. The advanced treated water is then directed towards an environmental buffer. DPR pathways include sending advanced treated water to a drinking water plant or storage before distribution for potable use. We calculate the process-based energy intensity using a control volume boundary of advanced water treatment, or treatment of secondary and tertiary

effluent feedwaters, excluding conventional wastewater treatment processes (i.e., aeration or flocculation) but including small-scaled membrane bioreactors (MBRs).

A subset of 10 potable reuse projects were covered by the EPA, NRC, SDWIS, and our dataset. These facilities were used to evaluate the consistency of energy intensity estimates from past assessments and the accuracy of these estimates relative to measured process-based electricity intensities (kWh/m^3), where available. These 10 projects include examples from both membrane- and non-membrane-based systems.

2.3 Capital and operational costs of analyzed facilities

We curated data on capital and operational costs of potable reuse facilities from published presentations and reports from engineering consulting firms, utility and water agency press releases, and peer reviewed and grey literature sources. We use one data point from the EPA (2017) compendium, while the rest of the capital and O&M costs are from utility or engineering firm documentation of specific facilities. For unbuilt facilities, the costs reported in technical documentation are engineering estimates that are subject to change as construction proceeds. For built facilities, we report the actual costs of construction and, when available, routine costs for facility operation and maintenance. Available capital cost breakdowns for a selected number of reuse projects are in Table S2. While robust cost data was not available for each class of treatment train, costs were widely available for potable reuse systems with MF, RO, and UV AOP unit processes. All costs were adjusted to $2020.

2.4. Estimating average air emission externalities using Water-AHEAD

We estimate the air emission externalities of four representative membrane and non-membrane potable reuse treatment trains using the Water-AHEAD tool for estimating human health, environmental, and climate (HEC) externalities associated with water and wastewater treatment trains.[29] We use plant-specific unit processes, average recoveries for unit processes, and national averages for electricity generation and chemical manufacturing. Specific input values and model assumptions are detailed in SI Section 3.0. The output of the model includes the electricity and thermal energy consumed (kWh/m^3), the total chemicals consumed in the treatment train (mg/L), and air emission climate and health damages ($K/year) adjusted in

$2020.

3. Results and Discussion

3.1. General Characteristics of U.S. Potable Reuse Systems

Our analysis identified 70 operational, unbuilt, pilot, demonstration, and decommissioned U.S. potable reuse systems. Over the past 15 years, 14 pilot studies and demonstrations have been implemented, with over 10 potable reuse systems currently in the design or construction phase (Figure S1a). The majority of facilities analyzed in this work were located in California (34%) or Florida (17%), with many facilities sited near the coast for cost effective brine disposal (Figure S3**)**. Another 17% of the facilities were located in TX, though most serve land-locked urban areas. The remaining potable reuse systems were located in Arizona, Colorado, Georgia, New Mexico, Texas, Virginia, and Washington.

The operational facilities in our dataset spanned a wide range of capacities, from less than 10,000 m^3/day to over 350,000 m^3/day, with an average size of 84,600 m^3/day (Figure 3A). Over half of the systems are either unbuilt demonstration projects or pilot studies, with only 38% (27 systems) currently online. The distribution of facility sizes for the 25 operational, unbuilt, pilot, and demonstration with available cost information is representative and reported in Figure 3B. Of the 25 facilities with capital cost information, 12 are operational, 6 are demonstration projects or pilot studies, and 7 are unbuilt. The 7 O&M cost data points represent 2 demonstration projects, 3 operational, and 2 unbuilt facilities.

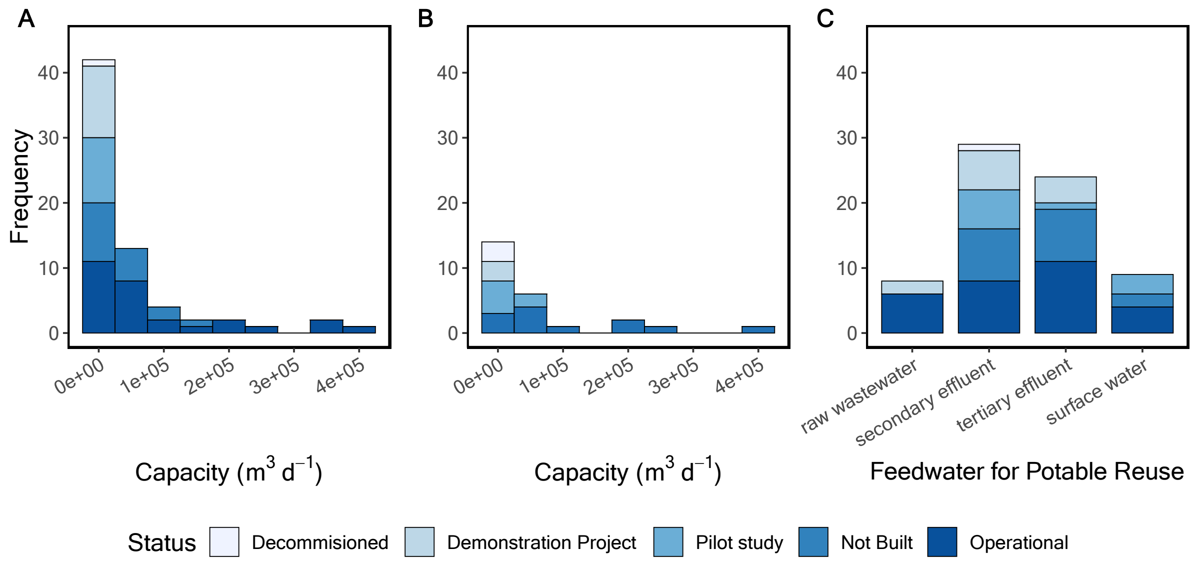
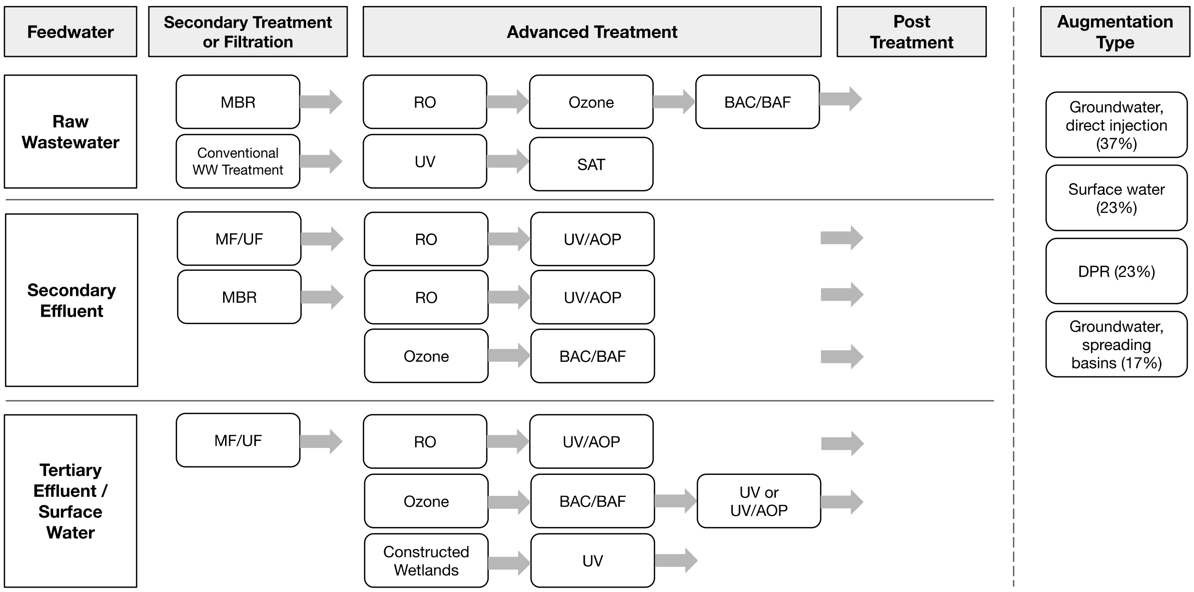


Figure 3. Attributes of U.S. potable water reuse systems. (A) Capacities in m^3/day for all 70 potable reuse systems. (B) Capacities in m^3/day for the subset of 25 potable reuse systems with sufficient cost data to be included in our cost analysis. (C) Feed water type entering IPR facilities.

Feedwaters for potable reuse systems fall into four general categories: raw wastewater, secondary, tertiary, or surface water. We define "raw wastewater" as untreated sewage pumped or gravity-fed to the centralized wastewater treatment plants. "Secondary effluent systems" are systems that intake secondary treated effluent as their feedwater. In our analysis, we assume secondary treated effluent as wastewater that has undergone a biological and/or clarification process. Likewise, "tertiary effluent systems" are systems that intake tertiary treated wastewater, or secondary treated wastewater that has undergone nutrient removal. The category surface water includes non-traditional feedwaters, such as wetland effluent or an imported blend of surface waters. Over 75% of the analyzed systems use secondary (29 systems) and tertiary effluent (25 systems) feed streams (Figure 3C). Raw wastewater is a feedwater for only 6 operational systems, where advanced water treatment occurs immediately after conventional wastewater treatment.

Treatment trains are tailored for feedwater quality, end user, and state discharge standards. Figure 4 presents selected reported treatment trains for both proposed and operational potable reuse treatment trains by feedwater type, with unit processes organized by treatment stage. This figure is not exhaustive in the diversity of the treatment trains for the 70 potable reuse systems. However, most treatment configurations are close variations of one another and deviate by only a few treatment processes.



Frequency in 70 potable reuse treatment trains: BAC/BAF (**16%**), Constructed Wetlands (**13%**), GAC (**21%**), Ozone (**20%**), MF/UF (**71%**), RO (**56%**), SAT (**13%**), UV/AOP (**55%**), UV (**24%**).

Figure 4. Unit processes in potable reuse treatment trains, categorized by treatment purpose and augmentation type for all potable reuse systems. Percentages at the bottom of the figure denote the frequency that the unit process appears in our set of 70 analyzed potable reuse treatment trains. Representative percentages were not calculated for post-treatment since the absence of consistent reporting precluded definition of specific chemicals used in each treatment train or any associated electricity consumption at the plant. (BAC/BAF = biologically active carbon/filtration, GAC = granular activated carbon, DPR = direct potable reuse, MBR = membrane bioreactor, MF/UF = micro/ultrafiltration, RO = reverse osmosis, SAT = soil aquifer treatment, UV/AOP = ultraviolet advanced oxidation process).

Raw wastewater feed streams are universally treated by conventional wastewater treatment processes or membrane bioreactors (MBRs). MBRs combine a suspended biomass reactor with a membrane filtration step to act as a pretreatment step or produce high quality water adequate for water reuse.[49] For example, the City of Abilene Hamby Water Reclamation Facility employs a MBR before RO and ozone-BAF for treatment to potable reuse standards.[43] For raw wastewater feed streams, however, conventional wastewater treatment followed by ultraviolet radiation (UV) and soil aquifer treatment (SAT) is more common than MBRs, with half of the operational systems employing this treatment train.

For secondary and tertiary effluent or blended feed streams, MF and UF is the most common pretreatment method and was present in 71% of the analyzed systems. This percentage is inclusive of the MF and UF membranes that are employed in MBR systems. Over half of the advanced treatment systems use RO with ultraviolet advanced oxidation processes (UV/AOP). Membrane-based RO systems are often followed by post-treatment chemical addition of lime, caustic soda, and/or calcium chloride stabilizers. Inconsistent reporting precluded determination of the frequency of use for different post-treatment chemicals, but we note that most systems use more than one. Membrane-free ozone-BAF/BAC is employed in 16% of the analyzed systems and does not require post treatment other than disinfection.[7,20] GAC not used in ozone-BAC treatment trains was counted separately and was present in 21% of the systems.

Most potable reuse facilities supply water indirectly by discharging into groundwater aquifers (37%) via direct injection and spreading basins or surface waters (23%), such as rivers, ponds, and lakes. A few systems (13%) direct tertiary effluent or blended feed streams into engineered environmental buffers, such as constructed wetlands, for treatment before augmentation back into surface waters. While at least 12 DPR pilot studies and demonstration projects (or 23% of 70 systems) have been installed since 1980, only two operational facilities discharge directly to distribution systems in a direct potable reuse (DPR) scheme. Past work has documented the myriad of regulatory, technological, funding, and public perception barriers to DPR.[9,35,40,44–46]

3.3. Electricity intensity of advanced treatment for potable water reuse

There are few direct reports of energy consumption at operational facilities, and past work often presents point estimate energy intensities for specific facilities or treatment trains without accounting for variability in unit process electricity consumption. We perform a meta-analysis of past studies and compare this distribution of energy intensity estimates to actual energy intensity for operational facilities. We plot the expected range of IPR electricity intensity for individual facilities (Figure 5A), with the range representing the sum of the minimum and maximum electricity intensity values for each of the unit processes and the black triangles representing measured energy intensity values from operational facilities. The process-based approach leads to very broad ranges in estimated energy intensity, while discrepancies in the data sources reporting installed unit processes further broaden this potential range. The greatest discrepancy originates with SDWIS data, which tends to provide an incomplete list of unit processes and results in underestimates of treatment train energy intensity. Since the SDWIS is the only comprehensive database of public drinking water systems in the U.S., we strongly recommend prioritizing reporting consistency and explicit demarcation of potable water reuse facilities.

Our model estimates a range of energy intensities for FAT process trains (e.g., GWRS, West Basin) that spans 0.9–2.2 kWh/m^3, though operational FAT systems typically report electricity intensities of approximately 1.1–1.4 kWh/m^3.[47–49] We estimate a range for non-membrane based BAF systems (e.g., Gwinnett County) of 0.26–0.40 kWh/m^3, which is closer to the reported average electricity intensities of 0.37 kWh/m^3.[8] Treatment trains for the selected potable reuse systems in Figure 5A are further described in Table S1.

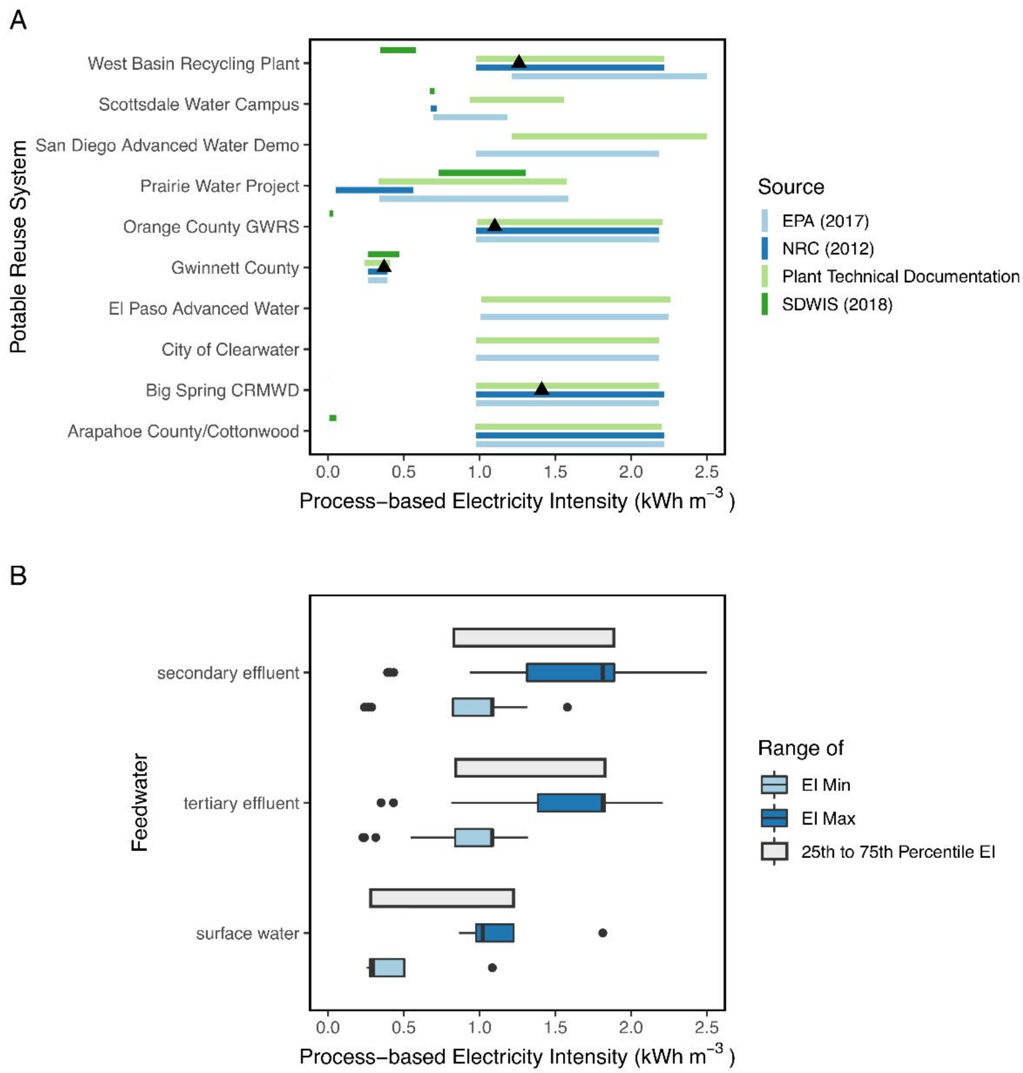


Figure 5. (A) Comparison of the process-based electricity intensities (kWh/m^3) for a subset of 10 potable reuse systems with unit processes reported by more than one source (See Table S4 for treatment trains of selected facilities). The black triangle represents actual electricity consumption at four operational facilities.[42–45] **(B)** Process-based electricity intensities (EIs) by feedwater type. The "EI min" represents the computed electricity intensity of the system using the minimum electricity consumption of all unit processes, while the "EI max" is the computed range using the maximum electricity consumption of all unit processes. The "Full EI Range" represents the processed-based electricity intensity from the 25th percentile of the EI min to the 75th percentile of the EI max.

Despite the data limitations that lead to uncertainty and variability in estimated energy intensity of IPR facilities, we find that our estimated range of energy intensity is inclusive of the documented energy intensity of operational facilities. Operational facility energy intensity for the four facilities is at the far lower end of the estimated range, reflecting judicious selection and operation of unit processes for the feed water quality. While this is an intuitive finding, it is drawn from a very limited dataset of operational facility data and it underscores the importance of generating a larger validation dataset for IPR facilities.

The variation in IPR energy intensity across facilities is readily explained by the feedwater quality and the treatment train configurations, including membrane and non-membrane-based approaches. We plot the estimated electricity intensity ranges for all 70 IPR treatment train configurations and group the results by feedwater source in Figure 5B. We exclude electricity intensity calculation for raw wastewater feedwater sources since many employed unit processes following conventional wastewater treatment are similar to those found in secondary and tertiary treatment trains. The minimum advanced treatment electricity intensity range (EI min) is calculated using the minimum electricity consumption of all unit processes, while the maximum advanced treatment electricity intensity (EI max) range is computed using the maximum electricity consumption of all unit processes. The full electricity intensity range in Figure 5B is defined as the values between the 25th percentile of the minimum electricity intensity and the 75th percentile of the maximum electricity intensity. This is to be inclusive of unit process electricity consumption process uncertainty and variability, but also to omit potential outliers. Regardless of feedwater type, the electricity intensity of these ranges between 0.3–2.0 kWh/m^3.

Since secondary effluent and tertiary feedwaters often share treatment train configurations, the average system electricity intensities are similar with a full electricity intensity range of 0.8–1.8 kWh/m^3 (Figure 5B). A possible explanation for the slightly higher electricity intensity for secondary effluent is the use of energy intensive MBRs consuming 0.5–0.7 kWh/m^3 at full-scale wastewater treatment plants and at least double that in systems with capacities less than 50 m^3/d.[47,48] MBRs are more often used for treatment of direct raw wastewater, but several pilot studies have implemented MBR for secondary effluent feedwaters (Table S1). Besides MBRs, other energy intensive unit processes include RO (0.7 kWh/m^3), UV AOP with H_2O_2 (0.28–1.0 kWh/m^3), and ozone (0.25–0.35 kWh/m^3).[29,50]

The electricity intensity of systems treating surface or blended (tertiary effluent blended with surface water) feedwaters is significantly lower because only a few systems include ozone-BAF/BAC or FAT processes. The vast majority of systems divert the surface water or water blend to constructed wetlands or spreading basins for soil-aquifer treatment (SAT). The greatest consumption from these natural systems originates in the energy intensity required to transmit water to the passive treatment system, which is excluded in our calculation.

3.4. Potable reuse capital and O&M costs

Potable reuse capital and O&M costs are important evaluating water reuse relative to other water supplies. Unfortunately, the lack of standardized cost reporting in past publications has resulted in large variations in capital cost estimates and complicated efforts to develop reliable cost curves.[12,26,27] We curated a dataset of reported capital and O&M costs for a select number of potable reuse systems for a simple cost analysis and for validation of past cost estimation curve estimates for MF, RO, and UV/AOP treatment trains.

Total capital costs of a project include costs for engineering and construction, permitting, land purchase and development, offsite waste product management and water transmission.[4,13] In this work, we exclude the costs of additional infrastructure (i.e., piping for distribution, brine disposal wells, or equipment replacement), scientific studies, and public outreach for potable water reuse, whenever possible. The coarse resolution of cost data, however, precludes us from definitively differentiating between facility specific and total capital costs for some projects. Total capital costs generally include costs for distribution infrastructure, which are often the next most costly component of a potable reuse system.

In Figure 6, we plot system capital costs normalized by capacity and categorized by unit processes and status. The 12 operational plants are labeled by number and are listed in Table S2. Costs for operational plants are encompassed by a transparent grey “envelope.” The maximum normalized cost of the operating systems is approximately \$5300 per cubic meter per day (m^3d^{-1}) and the minimum is approximately \$1000 m^3d^{-1}. A majority of capital costs are below \$4500 m^3d^{-1}. Cost data on facilities larger than 100,000 m^3d^{-1} is limited, so there is greater uncertainty on the bounds of the envelope for large-scale facilities. Some of the variation in this plot is explained by variability in installed unit processes at the treatment facilities, while other variation is likely explained by facility scale, location specific costs, and other factors described above. Generally, smaller RO-based systems (i.e., 19,000 m^3d^{-1}) are cost competitive with non-membrane treatment trains (Ozone-GAC) where inexpensive ocean or sewer disposal is accessible.[8] However, past work suggests that RO-based systems with capacities greater than 19,000 m^3/day or with less readily available concentrate disposal have higher capital, O&M, and environmental costs than non-membrane systems.[8]

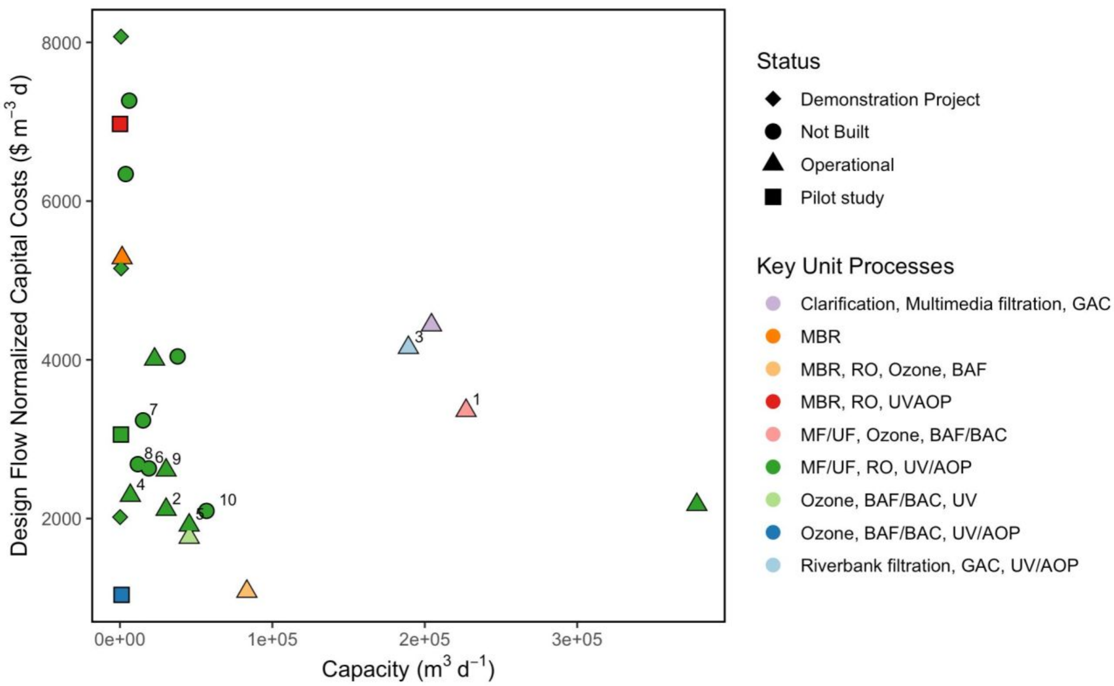


Figure 6. System design capacity normalized capital costs for 25 potable reuse facilities by status and treatment train. The costs for the unbuilt facilities are engineering estimates and may be subject to change upon construction. The operational status of the facility is differentiated by color, while treatment trains are differentiated by symbol. Facility capital cost data are labeled by number corresponding to system names in Table S2. Facilities that did not differentiate between capital costs for water treatment infrastructure and those for conveyance or other infrastructure upgrades are unlabeled and less reliable. The grey envelope represents the cost range for operational plants with high data reliability.

The coarse resolution of cost data and inclusion of unbuilt, demonstration and pilot studies also contribute to the scatter of cost data points in Figure 6. Distribution infrastructure is often included in total project cost estimates and can account for up to 20% of the facility cost in the 25 systems we analyzed. Since cost estimates for some systems did not distinguish between total and facility costs, some of the data points presented in the plot inflate the facility specific costs. In Figure 6, facility capital costs are labeled by number, while total capital costs are unlabeled. The corresponding system names are in Table S2. Additionally, the costs for demonstration projects and pilot studies, which fall between \$1000 and \$7000 m^3d^{-1}, may not be reflective of full-scale facility costs since they may temporarily implement certain treatment processes that are not going to be used in the full-scale facility. Finally, cost estimates for unbuilt facilities are subject to change as construction proceeds.

The flow normalized treatment plant capital and O&M costs for a subset of potable reuse systems with MF, RO, and UV/AOP processes are plotted in Figure 7. We also plot capital and O&M cost-estimation curves developed by Plumlee et al (2014) for MF, RO, and UV AOP facilities with capacities greater than 100,000 m^3d^{-1} and 300,000 m^3d^{-1} that were built from a combination of models, engineering experience, and vendor quotes.[18] The cost curves, adjusted to \$2020, follows a power function of the form $y = Ax^b$, where y is the cost in $\$/m^{-3}$ d, x is the capacity in m^{-3} d, and A and b are constants. For capital costs, A equals 18740 and b equals -0.21, while for O&M costs, A equals 386.9 and b equals -0.095.

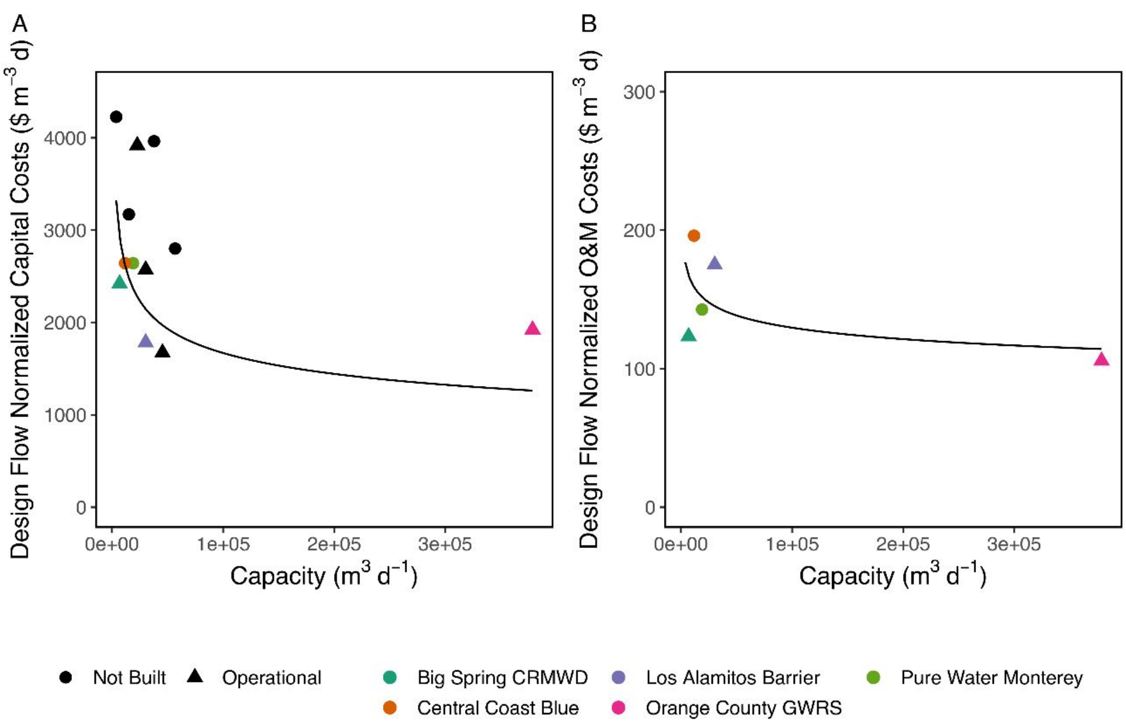


Figure 7. (A) Comparison of flow normalized capital costs of the microfiltration (MF), reverse osmosis (RO), and ultraviolet advanced oxidation (UV/AOP) treatment train to cost estimation

curves of the same treatment train. The triangle symbol represents costs for operating systems, while the dot symbol represents cost estimates for systems that have not yet been built. The solid black line matches cost curve estimates by Plumlee et al (2014). **(B)** Operation and management (O&M) costs of the MF, RO, and UV AOP process train.

We observe reasonable agreement between past cost estimation curves and the actual facility costs of FAT treatment trains in our dataset, though the lack of standardization for cost reporting complicates this comparison. For example, the Plumlee et al (2014) capital cost curve excludes consideration of special land access, backup power, and water storage, but includes a 30% construction contingency cost. Multi-stage construction and expansions further complicate the cost analysis, as information reported on the intermediate phases may be unpublished or inaccessible. While published O&M costs are scarce, there is less variability and less economy of scale due to better standardization of annual cost elements, such as energy and chemical usage, labor, and major equipment replacement.

3.5. Potable reuse air emission externalities

Quantifying the risk-tradeoffs of increased human health, environmental, and climate (HEC) impacts from electricity and chemical consumption during treatment plant operation can assist in selection of a water source and treatment technologies. In this work, we use the water-AHEAD model that estimates embedded emissions of greenhouse gases (GHG), NO_x, SO_2, CO_2, and $PM_{2.5}$ from drinking water unit processes. The model then calculates the associated human health and environmental damages of treatment trains using AP2, EASIUR, and the social cost of carbon.[29] Additional methodological details and underlying assumptions of the model are detailed in Gingerich & Mauter (2017).[29]

The median air emission externalities in dollars per thousand m^3 ($/1000 m^3) for four representative advanced treatment trains from pilot, demonstration and operating systems are plotted in Figure 8. For the set of analyzed treatment trains, the total HEC impacts are between 10 and 48 $/1000$m^3$. A representative FAT treatment train has HEC externalities of 48 $/1000$m^3$, nearly four times greater than that of a representative ozone-BAF/BAC treatment train 12 $/1000$m^3$. An average size treatment facility of 84,600 m^3d^{-1} that employs FAT is expected to generate annual climate and health impacts of approximately US$4000. We also emphasize that lifecycle emissions are just one of many criteria for treatment train selection, and the reliability and high water quality produced by FAT systems may deliver yet-unquantified health benefits.[14,36,38] For all systems, the total damages from electricity consumption during operation are greater than those for chemical consumption. Environmental externalities, or air pollution damages to crops and timber, are included in the "Total" column and constitute less than 5% of total damages.

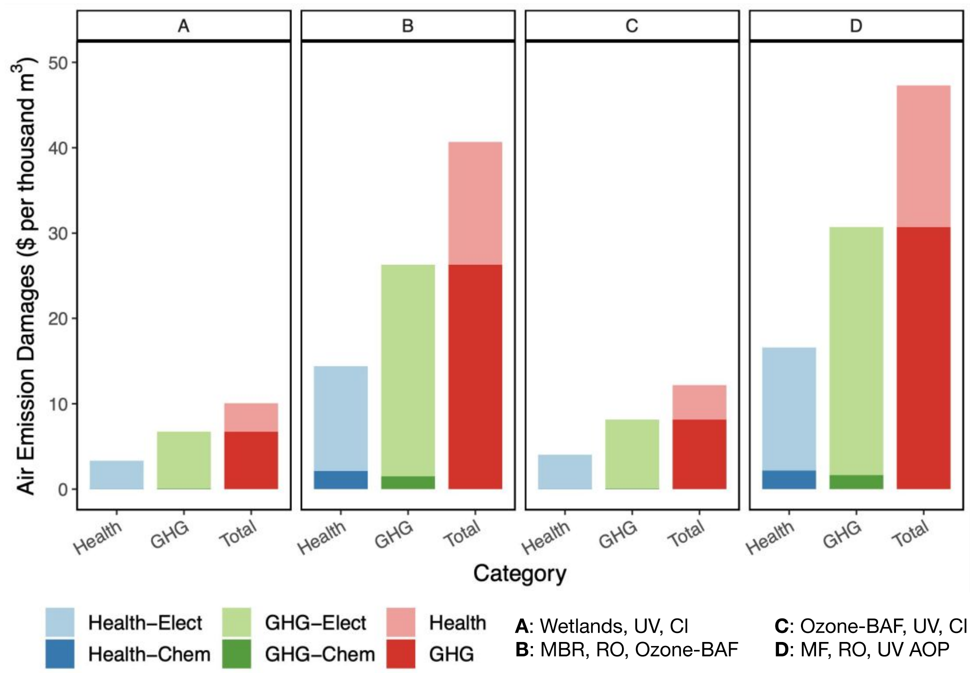


Figure 8. Bar graph of median annual air emission externalities ($ m^{-3}) of treatment trains from Figure 4 representing each feedwater type. "Health-Elect" and "Health-Chem" distinguish relative electricity and chemical consumption contributions to health damages. "GHG-Elect" and GHG-Chem" are relative electricity and chemical contributions to climate damages. The total annual air emission damages consist of "GHG" (climate), "Health," and environmental externalities (not color coded). Costs are in $2020.

Finally, while energy production and treatment chemicals dominate life-cycle emissions in the treatment phase of water reuse, other contributions not within our project scope, such as conveyance and distribution of water may be more significant than the treatment phase depending on the friction loss, elevation, and grid mix in a specific location.[51]

4. CONCLUSION

Water users have a myriad of options for meeting demand, including water efficiency investments, water conservation programs, inland brackish and coastal seawater desalination, and water reuse. Quantitatively evaluating water supply options necessitates good baseline values for site-specific capital and operation costs, energy intensity, and greenhouse gas and criteria air pollutant emission externalities. This study provides a summary of these features for an aggregated total of over 70 operating, demonstration, pilot and unbuilt U.S. potable water reuse systems as of 2020.

The cost, energy, and HEC analysis presented herein will benefit from extension in several areas. This work reports the electricity intensity of advanced water treatment processes, but future work should consider the total system energy intensity, including the conveyance and distribution electricity intensity of water. In our cost analysis, the coarse resolution of cost data makes it difficult to differentiate between total and facility capital costs. Collaboration with municipalities and consulting engineering firms to obtain specific capital cost breakdowns and data on larger capacity and non-FAT systems would enhance understanding of the relative minimum and maximum capital and O&M cost bounds for operational facilities. We also find that advanced treatment trains are typically constructed as separate facilities, rather than integrated into an existing wastewater treatment plant. On-site advanced treatment would reduce the need for costly distribution infrastructure to deliver the secondary or tertiary treated water but could introduce space constraints and retrofitting costs required at the existing plant. Future studies comparing the retrofitting costs of an existing wastewater treatment plant, a separate advanced treatment facility with distribution infrastructure, and a new wastewater treatment plant with advanced treatment integrated will aid the evaluation of potable water reuse relative to other supply alternatives. Additionally, retrospective assessments of the difference between projected and actual built costs, including identifying the source of any cost-overages will improve project cost estimates for future potable reuse systems.

Finally, we provide air emissions for a select number of advanced treatment trains, but future work should also consider projections of the HEC damages under future electricity grid mixes and opportunities for energy intensive treatment systems to provide energy services to the grid. Finally, we recommend better SDWIS data collection for the continuous monitoring of potable water reuse capacity across the U.S.

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