

## Modeling the energy consumption of potable water reuse schemes

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### ARTICLE INFO

#### Keywords:

Potable reuse  
Energy consumption  
Water recycling  
Reclaimed water  
Desalination  
Advanced water treatment  
Energy modeling

### ABSTRACT

Potable reuse of municipal wastewater is often the lowest-energy option for increasing the availability of fresh water. However, limited data are available on the energy consumption of potable reuse facilities and schemes, and the many variables affecting energy consumption obscure the process of estimating energy requirements. By synthesizing available data and developing a simple model for the energy consumption of centralized potable reuse schemes, this study provides a framework for understanding when potable reuse is the lowest-energy option for augmenting water supply. The model is evaluated to determine a representative range for the specific electrical energy consumption of direct and indirect potable reuse schemes and compare potable reuse to other water supply augmentation options, such as seawater desalination. Finally, the model is used to identify the most promising avenues for further reducing the energy consumption of potable reuse, including encouraging direct potable reuse without additional drinking water treatment, avoiding reverse osmosis in indirect potable reuse when effluent quality allows it, updating pipe networks, or using more permeable membranes. Potable reuse already requires far less energy than seawater desalination and, with a few investments in energy efficiency, entire potable reuse schemes could operate with a specific electrical energy consumption of less than 1 kWh/m<sup>3</sup>, showing the promise of potable reuse as a low-energy option for augmenting water supply.

### 1. Introduction

Freshwater scarcity is a widespread issue that only gains urgency as Earth's human population grows and its climate changes under their influence (Vörösmarty et al., 2000). Several technologies exist for upgrading more plentiful non-potable water to potable quality, but all require some energy input (Plappally and Lienhard, 2012). All energy sources—and particularly fossil energy sources—have a significant environmental impact (Pehl et al., 2017), as does most freshwater consumption (Pfister et al., 2009). Therefore, identifying and optimizing water treatment technologies that use minimal freshwater and energy is essential for sustainable water security. Potable reuse (of wastewater) is

one water regeneration paradigm that has the potential to supply people with safe, potable water almost anywhere wastewater is created (World Health Organization, 2017).

Although the efficacy of potable reuse processes in producing clean water has been demonstrated (Drewes et al., 2003), estimating the energy consumption associated with potable reuse is not straightforward. Energy requirements vary with location and water quality as well as the treatment processes selected (Gerrity et al., 2013). It is generally accepted that the energy consumption of potable reuse is below that of seawater desalination, but it is less clear how potable reuse compares to other water procurement methods such as brackish water desalination or long-distance water transfer (Leverenz et al., 2011). In contrast, methods of modeling the energy consumption of seawater desalination

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<https://doi.org/10.1016/j.wroa.2021.100126>

Received 11 August 2021; Received in revised form 30 October 2021; Accepted 17 November 2021

Available online 21 November 2021

2589-9147/© 2021 The Authors.

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Nomenclature		p	Permeate
A	Membrane permeability, m/(Pa·s)	SBRO	Semi-batch reverse osmosis
$\eta$	Efficiency	tr	Local water conveyance
$E_{EO}$	Electrical efficiency per order, kWh/m <sup>3</sup>	<i>Abbreviations</i>	
$J_w$	Water flux, m/s	AOP	Advanced oxidation process
LR	Log removal	AWT	Advanced water treatment
N	Number of inter-stage pumps	DOC	Dissolved organic carbon
$\pi$	Osmotic pressure, Pa	DPR	Direct potable reuse
V	Volume, m <sup>3</sup>	DWT	Drinking water treatment
w	Specific electrical energy consumption, J/m <sup>3</sup> or kWh/m <sup>3</sup>	ERD	Energy recovery device
<i>Subscripts</i>		IPR	Indirect potable reuse
AO	Advanced oxidation	MF	Microfiltration
BRO	Batch reverse osmosis	RO	Reverse osmosis
CRO	Continuous reverse osmosis	RR	Recovery ratio
E	Energy recovery device	SAT	Soil aquifer treatment
f	Feed	SEEC	Specific electrical energy consumption
P	High pressure pump	TDS	Total dissolved solids
m	Membrane	UF	Ultrafiltration
		WWTP	Wastewater treatment plant

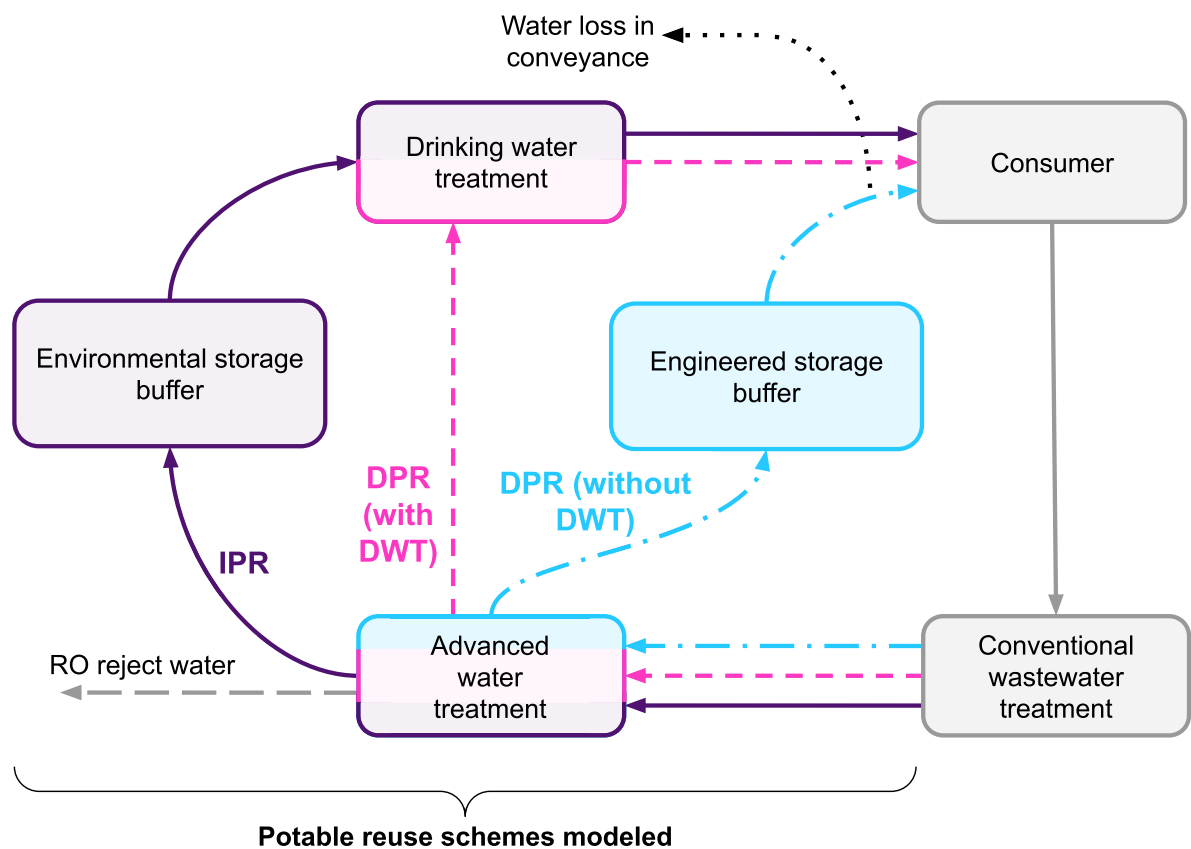


Fig. 1. Flow diagram adapted from Gerrity et al. (2013) to show the three potable reuse schemes modeled in this study, including the water losses considered in modeling. IPR = indirect potable reuse; DPR = direct potable reuse; DWT = drinking water treatment.

has been considered extensively (Altmann et al., 2019; Elimelech and Phillip, 2011; Mistry et al., 2011), and we endeavor here to give the same attention to potable reuse.

Sim and Mauter (2021) used data and modeling to quantify the energy intensity of potable reuse in their review of 70 U.S. water reuse facilities. They found four facilities with published energy consumption data, which spanned the range 0.4–1.4 kWh/m<sup>3</sup>. Based on a wider dataset

of treatment train processes and a model for treatment train energy consumption, they also Sim and Mauter (2021) estimated that advanced treatment trains in the U.S. have energy consumption levels in the wide range of 0.23–2.5 kWh/m<sup>3</sup> and acknowledge that real facilities are more likely to fall on the lower end of that spectrum. They also analyzed costs and air emissions externalities for these plants. Their study illustrates the high degree of variability in reuse processes, costs, and energy

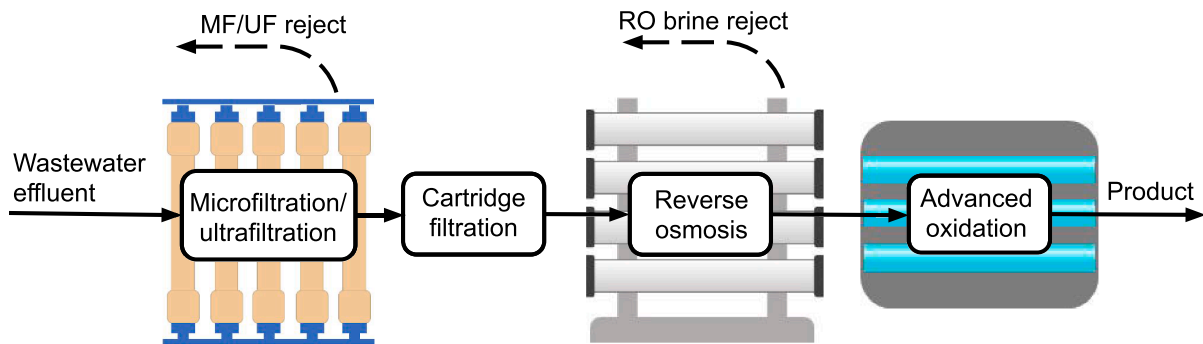


Fig. 2. Schematic diagram of key processes in full advanced treatment. MF = microfiltration; UF = ultrafiltration.

Table 1

Table of parameters used in model evaluation.

Parameter	Default value	SEEC sensitivity
Osmotic pressure	0.7 bar <sup>a</sup>	0.06
Membrane permeability	8.3e-12 m/s-Pa <sup>b</sup>	- 0.26
Flux	8.3e-6 m/s	0.26
Pump efficiency	0.75	- 0.33
ERD efficiency	0	- 0.05 <sup>c</sup>
Number of RO stages	2	n/a
Number of inter-stage pumps	1	n/a
RO recovery ratio	0.8	- 0.31
Water transport recovery ratio <sup>b</sup>	0.85	- 0.94
MF/UF SEEC	0.2 kWh/m <sup>3</sup>	0.14
UV-AOP SEEC	0.11 kWh/m <sup>3</sup>	0.06
GAC-based AWT SEEC	0.37 kWh/m <sup>3</sup>	0.31 <sup>d</sup>
GMF-based AWT SEEC	0.22 kWh/m <sup>3</sup>	0.21 <sup>d</sup>
SAT-related SEEC	0.48 kWh/m <sup>3e</sup>	0.27
DWT SEEC	0.23 kWh/m <sup>3</sup>	0.13
Local water conveyance SEEC	0.14 kWh/m <sup>3</sup>	0.07

<sup>a</sup> For explanation of and sources for chosen values, see Section 2.

<sup>b</sup> Equivalent to 3 L/m<sup>2</sup>-hr-bar.

<sup>c</sup> Based on a 70%-efficient ERD.

<sup>d</sup> Based on IPR with GAC or GMF.

<sup>e</sup> 0.2 kWh/m<sup>3</sup> for SAT itself plus 0.28 kWh/m<sup>3</sup> for transport to and from aquifer.

requirements and calls for more widespread reporting of reuse facility energy consumption in the future. While it shares the aim to quantify the energy consumption of potable water reuse with the review by Sim and Mauter (2021), the present paper takes a different approach to quantifying the energy consumption of potable water reuse at the scheme level by modeling entire reuse schemes and examining the effects of hypothetical variations within reuse processes. Scheme-level modeling includes processes that use energy or lose water beyond the advanced treatment plant, such as soil aquifer treatment and pipe network losses, and enables comparison of direct and indirect reuse schemes. The present analysis aims both to fairly compare hypothetical water reuse schemes and to provide a tool for estimation of specific reuse schemes' energy needs by incorporating case-specific data, such as the energy intensity of an existing drinking water treatment plant.

This study synthesizes information about the paths, processes, and choices involved in centralized potable water reuse to create and validate a simple model for estimating the energy consumption of both direct and indirect potable reuse schemes. Using the model, the energy consumption of potable reuse is then compared to other methods of securing water, including seawater and groundwater desalination and long-distance water transfer. Finally, we explore how design choices and future developments may affect the energy requirements of potable reuse. In doing so, we hope to enhance understanding of the energy consumption of potable reuse and identify influential directions for research and future practice.

### 1.1. Background: Potable water reuse

Potable water reuse is the treatment and reintroduction of wastewater into the potable (drinkable) water supply. It holds promise as a relatively low-energy way to augment the potable water supply in water-scarce regions (Tang et al., 2018). In addition, potable reuse meets the need to safely reintroduce treated wastewater effluent to the water cycle. Although engineered potable reuse has occurred for decades, it is just beginning to be adopted outside of severely drought-ridden areas due to negative public perception and inconsistent legislation (Warsing et al., 2018a). Wastewater is also reused in non-potable applications (e.g., for irrigation), but we limit the scope of this study to potable reuse.

Engineered potable reuse is classified as direct or indirect depending on the path of water beyond the advanced treatment plant. Direct potable reuse (DPR), though rare in current practice (Sim and Mauter, 2021), describes a system where purified wastewater effluents are sent directly from an advanced treatment plant back into the water supply network, typically passing through an engineered storage buffer and/or a drinking water treatment plant on the way. In indirect potable reuse (IPR), water is transferred from the advanced treatment plant to a natural buffer, such as an aquifer or body of surface water, which ultimately provides source water for drinking water treatment and subsequent potable use. Figure 1 illustrates the direct and indirect potable reuse schemes modeled in this paper.

Planned potable reuse typically begins with conventional wastewater treatment, and the effluent of that process then undergoes advanced water treatment processes in a reuse facility, which may or may not be co-located with the conventional wastewater treatment plant. Two previous studies provide an overview of the major steps in advanced water treatment (AWT): Gerrity et al. (2013), who review the AWT trains in use worldwide, and Sim and Mauter (2021), who review the processes used at AWT facilities in the U.S. to analyze energy consumption, cost, and environmental impact. Most advanced water treatment (AWT) processes (Fig. 2) begin with microfiltration (MF) or ultrafiltration (UF) to remove suspended matter, including most microbes (Sim and Mauter, 2021). The MF/UF permeate is passed through a cartridge filter and then usually treated with reverse osmosis (RO) to remove nearly all dissolved material (Gerrity et al., 2013). The final major energy-consuming step in advanced treatment is an advanced oxidation process (AOP) to degrade remaining dissolved organics and inactivate any persisting viruses. Low-energy post-treatments such as remineralization may follow (Sim and Mauter, 2021). Each major step in the reuse process plays a role in preparing water for drinking, but each step consumes energy; given the required pressure, RO tends to be one of the more energy-intensive steps. Although the combination of MF/UF, RO, and AOP is relatively common (see Table D.1 for a few examples or a more comprehensive list in Office of Ground Water and Drinking Water (2017)), some reuse plants forgo RO in favor of biologically active filtration if desalination is not necessary (Gerrity et al., 2013).

In large-scale, centralized reuse schemes, a relatively small amount of reused water is blended with a larger stream from a conventional drinking water source before delivery to the consumer. For example, in the DPR scheme in Big Spring, Texas, USA, the advanced treatment plant product stream is blended in a ratio less than 1:4 with surface water before conventional drinking water treatment, despite the fact that the advanced-treated water is of higher quality than the surface water (Steinle-Darling et al., 2016). In IPR, blending occurs when advanced-treated water is returned to the environment through a natural buffer, where it can mix with natural groundwater, as well as when water drawn from an environmental buffer is combined with water from other sources, such as reservoirs. The use of blending limits the size of advanced treatment plants, particularly for small-blending-ratio DPR installations, which tends to raise the cost of recycled water (Guo et al., 2013) and can limit the efficiency of critical components, such as RO pumps. Alternatively, although they are beyond the scope of this study, decentralized reuse schemes that minimize blending represent a promising approach to achieving “net-zero water” by treating wastewater where it is created, avoiding potential quality losses associated with blending, and retaining thermal energy (Englehardt et al., 2016; Wu and Englehardt, 2016).

## 2. Contributors to energy consumption in potable reuse

In this section, common centralized potable reuse schemes are broken down into energy-consuming processes to create a model for the total energy consumption associated with potable water reuse at the scheme level. Individual treatment processes are modeled using simple equations that allow for manipulation of variables that significantly affect energy consumption. These process-level models are combined at the treatment train and reuse scheme levels to provide a straightforward, validated, and replicable framework for estimating the energy consumption of potable reuse.

### 2.1. Energy consumption of advanced treatment processes

This section reviews plant data and simple models for unit processes used in advanced water treatment. It also specifies how unit processes will be modeled in analyzing the energy consumption of reuse schemes in Section 4.

#### 2.1.1. Microfiltration and ultrafiltration

MF and UF are porous membrane filtration methods that have become the primary choice for RO pretreatment and are used in 71% of U.S. reuse facilities (Sim and Mauter, 2021). Although energy consumption varies somewhat, the typical energy consumption of an MF system is approximately 0.18 kWh/m<sup>3</sup> and that of a UF system is approximately 0.2 kWh/m<sup>3</sup> (based on reported energy data compiled in Appendix A, Table A.1). MF energy consumption varies primarily in proportion to transmembrane flux (Tangsubkul et al., 2006), with higher flux and thus energy consumption potentially being tolerated to reduce the number of membrane modules and thus minimize water cost; however, the data in Table A.1 suggest that the variations in MF/UF energy consumption are small relative to the total SEEC of a potable reuse scheme. Rather than modeling these relatively low-energy filtration processes in detail, a default value of specific electrical energy consumption for MF/UF of 0.2 kWh/m<sup>3</sup> of MF/UF permeate was used in evaluating the present model, and the sensitivity of scheme-level SEEC to changes in MF/UF energy consumption is reported in Table 1.

Because the downstream RO step has a significant reject stream, not all of the MF/UF permeate will ultimately become potable water. Therefore, the total energy consumption (per unit volume of RO permeate) of the MF/UF step will slightly exceed the MF/UF process SEEC reported above, which will be accounted for in the treatment train model (Eq. (8)).

#### 2.1.2. Reverse osmosis

To achieve target water quality, most water reclamation plants have implemented RO in their water treatment process (Lahnsteiner et al., 2018; Sim and Mauter, 2021). While RO processes require pumping water to high pressures (typically more than 10 bar) that exceed the osmotic pressure of the concentrated feedwater<sup>1</sup>, the advantage of using RO is that its membranes reject most solutes and produce nearly-pure water (Baker, 2004). Several innovations in RO system design have served to reduce the energy consumption of RO, and thus the SEEC of an RO system varies depending on the system design as well as the osmotic pressure of the source water and the way the system is operated.

Almost all large-scale RO plants operate in a continuous mode, where water passes through the membranes continuously and the system operates near steady state. Although water recovery in a single stage of RO is generally limited to approximately 50% (Stover, 2013), potable reuse systems tend to operate at much higher recovery by using a multi-stage continuous RO system with two or three stages. In a simple multi-stage RO system, the concentrate from each stage becomes the feed to the subsequent stage. This design has the advantage of low capital cost due to the simplicity of the design, but it requires more energy than designs involving inter-stage pumps and energy recovery. A multi-stage RO system may use inter-stage pumping to reduce energy consumption: booster pumps may be added to the concentrate line between any two stages so that a lower pressure can be used in the earlier stage, where the osmotic pressure is lower (Wei et al., 2017). Energy consumption may also be reduced by adding an energy recovery device (ERD) to the reject stream from the final stage. We also consider emerging semi-batch and batch RO configurations due to their capabilities for high water recovery.

Approaches to modeling energy consumption in RO systems vary widely in complexity (see, e.g.: Gude, 2011; Li, 2012; Li, 2017; Li and Noh, 2012; Qiu and Davies, 2012; Warsinger et al., 2016; Zhu et al., 2009). Given that RO is just one of many energy-consuming steps in potable reuse, this paper will utilize a basic model for RO energy consumption. We assume that all RO stages operate with a given pressure pinch (the minimum difference between hydraulic pressure and osmotic pressure). We treat solutions as ideal because of the low salinity of municipal wastewater. We assume fixed pump and energy recovery device efficiencies. We neglect hydraulic pressure drop through the modules due to friction. We assume each stage has an equal recovery ratio; i.e., an equal fraction of the feed to each stage is produced as permeate. Membrane permeability decline over time due to fouling is not captured by the model, but could be accounted for by changing the permeability input to the model; the effect of permeability on reuse scheme SEEC is included in Table 1. Using these assumptions, we combined the equations of Werber et al. (2017) and Qiu and Davies (2012) and added a term corresponding to a fixed pressure pinch as did Warsinger et al. (2016) to approximate the specific (i.e., per unit permeate volume) electrical energy consumption of continuous RO,  $w_{\text{CRO}}$ :

$$w_{\text{CRO}} = \frac{1}{\eta_p \text{RR}} \left( \pi_f \left( \frac{N}{(1 - \text{RR})^{1/N}} + 1 - N - \eta_E \right) + \frac{J_w}{A_m} \left( 1 - \eta_E (1 - \text{RR}) \right) \right) \quad (1)$$

where RR is the total water recovery,  $\eta_p$  is the pump efficiency,  $\pi_f$  is the feed osmotic pressure,  $N$  is the number of stages separated by inter-stage pumps,  $\eta_E$  is the energy recovery device (ERD) efficiency,  $J_w$  is the water flux and  $A_m$  is the membranes water permeability. This equation enables estimation of the energy consumption of many possible continuous RO configurations with or without inter-stage pumping (if no inter-stage

<sup>1</sup> Typical total dissolved solids of secondary effluents fed to potable reuse plants is 600–1700 mg/L with an osmotic pressure of approximately 0.3 to 1.1 bar (see Appendix D).

pumps are present, use  $N = 1$ , regardless of the number of stages) and with or without an ERD (if no ERD, use  $\eta_E = 0$ ).

In potable reuse scenarios, this model finds the energy requirement of the RO step is typically on the order of 0.6 kWh/m<sup>3</sup> of permeate—far less energy than required for RO desalination of seawater, which has a much higher osmotic pressure and thus requires higher applied pressure (Tow et al., 2015).

*Semi-batch and batch RO* Batch RO processes are emerging desalination processes in which a volume of feed is concentrated by RO until reaching a desired salinity and then discharged. Batch RO configurations are promising techniques for wastewater reuse because they have been shown to have the potential for lower energy consumption at high water recovery (Cordoba et al., 2021; Efraty, 2012; Warsinger et al., 2016; Wei et al., 2020) and higher resistance to inorganic scaling (Warsinger et al., 2018b). This study models the energy consumption of batch RO assuming a pressurized tank design, which was demonstrated at laboratory scale with an internal bladder by Wei et al. (2020). Semi-batch RO is a commercially-available process in which retentate is constantly mixed with fresh feed before recirculation through the RO module (Efraty, 2012). Semi-batch RO (Desalitech's closed-circuit RO system) was demonstrated to increase water recovery in RO for potable reuse from 85% to 92% through a 2-year pilot test at the Orange County Water District Groundwater Replenishment System (OCWD GWRS) (Gu et al., 2021). Batch and semi-batch RO may also be combined to reduce energy consumption and cost at high water recovery (Park and Davies, 2021), although the combination is not modeled in this study.

Batch and semi-batch RO have been modeled in prior studies (Swaminathan et al., 2019; Warsinger et al., 2016; Werber et al., 2017). In this work, we utilize a simplified model to estimate the energy consumption of batch and semi-batch RO that is consistent with the assumptions used in the continuous RO model (Eq. (1)). While both batch and semi-batch RO are susceptible to feed osmotic pressure elevation due to salt retention between cycles (Wei et al., 2020), this effect is neglected by the simple model recommended here; the (low) sensitivity of reuse scheme SEEC to feed osmotic pressure elevation is given in Table 1. As explained in Appendix B, the SEEC of batch and semi-batch RO can be estimated with the following equations:

$$w_{\text{BRO}} = \frac{1}{\eta_p} \left( \frac{J_w}{A_m} + \frac{\pi_f}{\text{RR}} \ln \left( \frac{1}{1 - \text{RR}} \right) \right) \quad (2)$$

$$w_{\text{SBRO}} = \frac{1}{\eta_p} \left( \frac{J_w}{A_m} + \pi_f \left( 1 + \frac{\text{RR}}{2(1 - \text{RR})} \right) \right) \quad (3)$$

where  $\eta_p$  is high-pressure pump efficiency.

*RO concentrate management* In addition to nearly-pure water, all types of RO create a concentrated reject stream that must be discharged appropriately. The choice of method for managing the concentrate is a function of the local environment, concentrate composition, concentrate volume, and local regulations (Younos, 2005). Large-scale concentrate management methods include surface water disposal, municipal sewer disposal, deep-well injection, evaporation ponds, and energy-intensive brine minimization technologies (Subramani and Jacangelo, 2014).

In the US, surface discharge was utilized for concentrate disposal by 50% of municipal brackish water reverse osmosis plants, followed by sewer discharge and deep well injection at 22% and 18%, respectively (Mickley, 2012). Given that the majority of plants utilize surface or sewer discharge, disposal-related energy consumption will be neglected in evaluation of the model in Section 4. However, it is possible that future regulations may increasingly prohibit surface or sewer discharge of concentrates. In situations where surface and sewer discharge are not possible, the considerable and highly variable energy consumption associated with other concentrate management methods, such as deep well injection, would need to be taken into account (Sim and Mauter, 2021).

### 2.1.3. Advanced oxidation processes

Advanced oxidation processes (AOPs) are based on the in situ generation of strong oxidants, primarily hydroxyl radicals, for the oxidation of organic compounds and disinfection. These processes are critical for wastewater treatment, as wastewater contains microorganisms, pharmaceutical residues, disinfection byproducts, and other compounds that must be degraded due to their potential effects on human health when these treated waters are used as drinking water. In ultraviolet-based AOPs, the relevant reactions are initiated by absorption of ultraviolet (UV) photons by target molecules such as nucleic acids (DNA, RNA) and trace organic chemicals (TOCs). An AOP is often one of the last treatment steps in an advanced treatment train, as it can eliminate trace contaminants not removed by prior processes.

Energy requirements for UV-based AOPs depend on reactor design, water quality, treatment objectives (e.g., log removal of specific contaminants such as the carcinogenic disinfection byproduct *N*-nitrosodimethylamine (NDMA)), lamp type, number of lamps, and the choice of promoter molecule (Miklos et al., 2018). As such, reported values of energy consumption in AOP systems demonstrate some variability. The electrical efficiency per order ( $E_{\text{EO}}$ ), which is discussed in Appendix C, is defined as the energy (in kWh) needed to reduce the concentration of a target molecule by one order of magnitude in one cubic meter of water (James et al., 2014). In most municipal-scale applications, UV is applied in a continuous-flow mode and as such the SEEC  $w_{\text{AO}}$  can be calculated from  $E_{\text{EO}}$  and the desired log removal (LR) for a given contaminant:

$$w_{\text{AO}} = E_{\text{EO}} \text{LR} \quad (4)$$

We direct the reader to Appendix C for further discussion of AOP energy consumption modeling,  $E_{\text{EO}}$ , and the derivation of Eq. (4).

Ozone-based AOPs are also common (Miklos et al., 2018). When ozone is used in wastewater tertiary treatment, between 0.5-1.5 mg ozone is typically applied per mg dissolved organic matter. The energy consumption for ozone production is between 6 to 18 kWh/kg O<sub>3</sub><sup>2</sup>, depending on the scale and feed gas characteristics (Bixio and Wintgens, 2006).

There is little published data on the energy consumption of advanced oxidation in potable water reuse plants, but a case study on the West Basin Water Recycling Facility, an IPR plant in CA, shows that UV-H<sub>2</sub>O<sub>2</sub> advanced oxidation uses approximately 0.15 kWh/m<sup>3</sup>, depending on the current plant flowrate and the number of reactors in use (Chang et al., 2008). The OCWD GWRS reported a UV SEEC of 0.07 kWh/m<sup>3</sup> in 2019 (Burris, 2019). Sim and Mauter's analysis (Sim and Mauter, 2021) of reuse facility data found a higher typical range of 0.28-1.0 kWh/m<sup>3</sup> for UV-AOPs, but acknowledged that the lower end of the range is more often reflected in real plants due to energy-conscious process design. In this paper, the SEEC of advanced oxidation is modeled as 0.11 kWh/m<sup>3</sup>, the average SEEC of the West Basin and Orange County facilities' UV energy consumption data (Burris, 2019; Chang et al., 2008; Kawczynski, 2020). In practice, case-specific effluent quality and the choice of other treatment steps will influence the LR required by the AOP process and thus the SEEC of the AOP.

### 2.2. Biologically active filtration

Biologically active filtration (BAF) is a type of granular media filtration (GMF) using the biofilm that naturally occurs on most media filters to biodegrade dissolved organic contaminants (Khan, 2013; Office of Ground Water and Drinking Water, 2017; Schimmoller, 2014). BAF alone is inadequate for high salinity applications due to its inability to remove TDS (Office of Ground Water and Drinking Water, 2017).

<sup>2</sup> The source gives these values in kW/kg, but we assume units of kWh/kg were intended, which falls within the range of case studies for ozone production in drinking water treatment plants (Chang et al., 2008).

Most BAF-based potable water reuse treatment trains in the U.S. use granular activated carbon (GAC) as a filter medium (Schimmoller, 2014). GAC is absorptive and highly porous allowing for more microbial growth than other media such as sand and anthracite (Office of Ground Water and Drinking Water, 2017). The energy consumption of GAC-based advanced treatment plants in the US (including complementary treatment processes such as ozonation) is approximately 0.37 kWh/m<sup>3</sup> (Office of Ground Water and Drinking Water, 2017).

Many other BAF treatment trains use GMF without GAC (Office of Ground Water and Drinking Water, 2017). GMF is also commonly used in non-potable water reuse and as a pretreatment in potable reuse treatment schemes utilizing soil aquifer treatment (SAT), as will be discussed in Section 2.3.1. The energy consumption of GMF-based advanced treatment in the US ranges from 0.16 - 0.32 kWh/m<sup>3</sup> (Office of Ground Water and Drinking Water, 2017).

### 2.3. Energy consumption of complementary processes

In centralized potable reuse schemes, complementary processes both precede and follow advanced water treatment, as shown earlier in Fig. 1. These processes include conventional wastewater treatment prior to advanced water treatment, buffering (environmental or engineered), drinking water treatment, and conveyance between treatment facilities and to end users. Each process involves energy consumption and/or water loss, both of which affect the overall energy consumption of the reuse scheme per unit volume delivered to the consumer. The following sections summarize the energy consumption and, when applicable, water loss of these complementary processes and identify values that will be used in modeling reuse schemes' energy consumption in Section 4. Conventional wastewater treatment is not included in the present model because it is required whether or not wastewater reuse occurs, but it is discussed in Appendix E.

#### 2.3.1. Buffering

Managed aquifer recharge is a water management method by which an aquifer is recharged with treated wastewater or stormwater, which is ultimately used to bolster water supply or protect depleted aquifers. The two aquifer replenishment schemes generally employed are direct injection into suitable aquifers through injection wells and surface infiltration into aquifers through ponds and basins. In the latter approach—also known as soil aquifer treatment (SAT)—infiltration facilitates nutrient and pathogen removal from the reclaimed water in combined biological and physiochemical processes during infiltration (Amy and Drewes, 2007), reducing the need for additional post-treatment steps (Page et al., 2018). For example, at the major reclamation-reuse project in Israel (Shafdan), over 80% removal of dissolved organic carbon (from 10–12 mg/L to 1–2 mg/L DOC) from secondary effluents occurs following a long hydraulic retention time of 6–12 months in the aquifer that enables effective biodegradation of organic matter (Ickson-Tal et al., 2013). The typical water withdrawal after SAT processes exceeds the volume of infiltrated water (i.e., it includes some native groundwater) to avoid contamination of neighboring pristine aquifers with recycled water (Negev et al., 2017). Therefore, the SAT process is modeled here as having a 100% recovery ratio with respect to the infiltrated water.

The energy consumption associated with a natural buffering treatment can vary widely due to the range of possible distances over which water must be transported, and limited data is currently available. Energy consumption is mostly associated with water transfer to and from the replenishment zone, injection, and reclamation (i.e., pumping out) through wells from the aquifer. For instance, the energy consumption associated with SAT in Israel's Shafdan Reclamation System is estimated as 0.63 kWh/m<sup>3</sup> of recovered water (Elkayam et al., 2020). This consumption includes energy for pumping effluent to the recharge basin at 0.14 kWh/m<sup>3</sup> and for recovering the water from the aquifer and transporting it approximately 30 km to the customer at 0.49 kWh/m<sup>3</sup>.

Similarly, at the OCWD GWRS, 0.3 kWh/m<sup>3</sup> is used to pump to recharge basins and approximately another 0.3 kWh/m<sup>3</sup> is required for subsequent product water extraction and distribution. Due to the scarcity of SAT SEEC data, the total SEEC associated with SAT (including transport between the water use area and the aquifer, but not including local conveyance to water users) has been modeled as the average energy consumption at Shafdan and OCWD (0.62 kWh/m<sup>3</sup>) minus the average energy consumption of potable water distribution (0.14 kWh/m<sup>3</sup>) (Cooley et al., 2012): 0.48 kWh/m<sup>3</sup>. Of this 0.48 kWh/m<sup>3</sup>, 0.28 kWh/m<sup>3</sup> (twice the local transport SEEC) is modeled as being attributed to water conveyance to and from the aquifer, and 0.2 kWh/m<sup>3</sup> (e.g., for pumping up 37 m at 50% efficiency) is attributed to SAT itself, for which the primary energy requirement is for pumping water out of the aquifer against gravity.

The energy consumption associated with an engineered storage buffer such as might be used in direct potable reuse is assumed to be negligible because it would ideally be placed near the reuse plant.

#### 2.3.2. Conventional drinking water treatment

Both DPR and IPR typically blend treated water with other potable water sources and send the mixture through conventional drinking water treatment (DWT), which is aimed at removing dissolved organics and pathogens from water, before supplying it for potable use. Energy consumption is affected by quality of raw water, technologies used and guidelines for product quality (Wakeel et al., 2016b). From a range of water treatment plants from several countries (Plappally and Lienhard, 2012), a typical range of 0.11 kWh/m<sup>3</sup> to 0.91 kWh/m<sup>3</sup> was found; we use the median energy consumption of 0.23 kWh/m<sup>3</sup> for a conventional water treatment plant as a representative value in the following analysis.

#### 2.3.3. Local water conveyance

Local water conveyance occurs between the wastewater treatment plant and the end user, and may involve several stop at facilities along the way. The energy cost of this transfer varies widely between municipalities and largely depends on distance, but it is also sensitive to changes in elevation, pump efficiency and pipeline properties (Plappally and Lienhard, 2012). At longer distances, energy cost is typically between 0.004 to 0.007 kWh/(km·m<sup>3</sup>), but municipal pipelines delivering water to end users are usually of smaller diameter, resulting in a total energy cost for water transfer of approximately 0.14 kWh/m<sup>3</sup> (Cooley et al., 2012). Most potable reuse treatment facilities are located at or near wastewater treatment facilities, and so the only energy consumption of local water conveyance associated with potable reuse in this model is the average energy consumed in transporting water from the advanced treatment plant to end users, which we treat as a constant 0.14 kWh/m<sup>3</sup> when evaluating reuse scheme energy requirements in Section 4. However, users wishing to evaluate the model for specific reuse scenarios may wish to use a different constant value based on published data for their region; alternatively, they may choose to model the local water conveyance energy consumption as proportional to distance traveled using a constant of proportionality derived for data in their region.

In modeling IPR, additional energy is required to transport water to and from the environmental buffer, as discussed in Section 2.3.1.

Due to aging, municipal piping systems are subject to water losses through leakage, which are commonly around 10–20% in the U.S. and can be over 50% in developing countries (Hennigar, 1984; Hunaidi et al., 2012; Wakeel et al., 2016b). A 15% water loss in conveyance is assumed in the model based on typical water losses in the U.S.; this loss influences the SEEC of reused water because more water must be produced by the reuse plant than is received by the end user.

### 2.4. Energy consumption of alternative water procurement methods

The following sections briefly summarize the energy requirements of seawater and groundwater desalination and long-distance water

transfer, which are alternative methods of augmenting water supply that will be compared with potable reuse in Section 4.

#### 2.4.1. Desalination

Desalination of natural saline water—usually seawater or brackish groundwater—is an increasingly common way to supplement freshwater supply. RO is currently the most energy-efficient process for seawater desalination (Altmann et al., 2019), with the total energy consumption of large RO plants in the range of 3.5–4.5 kWh/m<sup>3</sup> (DesalData, accessed 2016; Tow et al., 2015). Where lower-salinity brackish groundwater or surface water is available, it can be desalinated by RO or electrodialysis for less energy than required by seawater RO; for example, the Wadi Main, Jordan RO plant treats water with 2000 ppm total dissolved solids (TDS) for 0.8 kWh/m<sup>3</sup> (DesalData, accessed 2016), which is in the typical range for groundwater desalination (Ahdab and Lienhard, 2021).

#### 2.4.2. Long-distance water transfer

Water may be transferred between regions when water is scarce where it is needed (e.g., in a city or agricultural area) but plentiful some distance away. Energy costs for this transfer depend on distance, elevation gain, pump efficiency, and evaporation/leakage rates. For instance, in the case of the Hetch Hetchy supply system, water travels over 100 miles across California's Central Valley using the force of gravity at an energy consumption of just  $5.3 \times 10^{-4}$  kWh/m<sup>3</sup> (Cooley et al., 2012). In contrast, the energy cost for importing raw water from the Colorado River and Sacramento-San Joaquin Delta to San Diego is 2 kWh/m<sup>3</sup> (Cooley et al., 2012). Typical energy costs for transfer of imported water are 0.5 to 1.4 kWh/m<sup>3</sup> (Cooley et al., 2012).

### 3. Modeling energy consumption of potable reuse schemes

In this section, we present a model that describes the three potable reuse schemes shown in Fig. 1, including two DPR schemes (one with and one without drinking water treatment) and one IPR scheme. All scheme models explored in this study consider municipal wastewater effluent as their feedwater, begin with advanced treatment, and include the energy consumption and water loss associated with water conveyance. Energy consumption in domestic use, sewage conveyance, and at the conventional wastewater treatment plant (see Appendix E) are excluded from the modeling based on the assumption that these processes would not be affected by the choice of reuse scheme.

As shown in Fig. 1, the water's path from the advanced water treatment plant to the consumers depends on the reuse scheme. In the DPR scheme without drinking water treatment, water moves from the advanced treatment facility to an engineered storage buffer, whose energy consumption is assumed to be negligible compared to the other processes, before being returned to consumers. In the DPR scheme with drinking water treatment, water moves from the advanced treatment facility through a drinking water treatment plant before being returned to consumers. In the IPR scheme, water leaving the advanced treatment plant is assumed to undergo soil aquifer treatment and then drinking water treatment, and we assume no water is lost in soil aquifer treatment.

All reuse schemes involve the potential to lose water through leakage during conveyance, and we model this leakage as occurring shortly before return to the consumer, as indicated in Fig. 1. The model reflects this assumption by dividing the SEEC of all treatment processes by the recovery ratio of conveyance ( $RR_{tr}$ ), defined as the fraction of advanced-treated water that is not lost to leakage. The scheme-level SEEC of DPR without drinking water treatment ( $w_{DPR}$ ), DPR with drinking water treatment ( $w_{DPR+D}$ ), and IPR ( $w_{IPR}$ ) are shown in Eqs. (5), (6), and (7):

$$w_{DPR} = \frac{w_{AWT}}{RR_{tr}} + w_{tr} \quad (5)$$

$$w_{DPR+D} = \frac{w_{AWT} + w_{DWT}}{RR_{tr}} + w_{tr} \quad (6)$$

$$w_{IPR} = \frac{w_{AWT} + w_{SAT} + w_{DWT}}{RR_{tr}} + w_{tr} \quad (7)$$

where  $w_{AWT}$  is the energy consumption of AWT,  $w_{DWT}$  is the energy consumption of drinking water treatment,  $w_{SAT}$  is the energy consumption of soil aquifer treatment, and  $w_{tr}$  is the energy consumption of transporting water locally.

Some IPR schemes (23% in the U.S. Sim and Mauter, 2021) avoid the long-distance water transfer often associated with aquifer recharge by discharging advanced-treated effluent to nearby surface water. Neglecting any surface discharge-associated water losses, such an IPR scheme could be modeled as DPR with drinking water treatment.

#### 3.1. The full advanced treatment train

The most common AWT train, known as “full advanced treatment,” consists of MF followed by RO and advanced oxidation. For the three U. S. reuse facilities using full advanced treatment reviewed by Sim and Mauter (2021), train energy consumption spanned 1.1–1.4 kWh/m<sup>3</sup>. The SEEC of the treatment train is approximately the sum of the SEECs of the individual processes, except that some water is removed as concentrate in the RO step. Because SEEC is calculated per unit product (equal to the RO permeate volume), the MF energy consumption (per unit MF permeate) is modified by the RO recovery ratio,  $RR_{RO}$ , as shown previously by Sim and Mauter (2021). Thus, the overall SEEC of the full advanced treatment train,  $w_{FAT}$ , can be estimated with Eq. (8) (Sim and Mauter, 2021):

$$w_{FAT} = \frac{w_{MF}}{RR_{RO}} + w_{RO} + w_{AO} \quad (8)$$

At the OCWD GWRS, MF, RO, and UV treatment comprise 98% of the plant's energy consumption (excluding pumping to storage and injection sites)<sup>3</sup>, validating the focus on these three processes when estimating a full advanced treatment plant's SEEC.

If the energy consumption associated with RO concentrate disposal is significant, that additional energy consumption per unit RO concentrate ( $w_{disposal}$ ) can be incorporated into the reuse plant's SEEC (per unit permeate,  $w_{FAT+disposal}$ ) as follows:

$$w_{FAT+disposal} = \frac{w_{MF}}{RR_{RO}} + w_{RO} + w_{AO} + w_{disposal} \left( \frac{1}{RR_{RO}} - 1 \right) \quad (9)$$

The final term incorporates the fact that the ratio of concentrate volume to permeate volume is  $1/RR_{RO} - 1$ .

#### 3.2. Model evaluation

In evaluating the model for analysis of scheme-level potable reuse SEEC in the following sections, the SEEC of RO (if used in the reuse scheme) is first estimated, then the SEEC of full advanced treatment (if used) is estimated, and finally the SEEC of the reuse scheme is estimated, as described below. Significant variability exists within many of the processes involved in potable reuse; however, accuracy can be improved by using case-specific values and more complex process models such as the Water Application Value Engine (WAVE) (Dupont Water Solutions, 2021).

The energy consumption of RO (continuous, batch, and/or semi-batch) was estimated with Eqs. (1), (2), and (3), respectively using default parameters from Table 1 (except where noted).

<sup>3</sup> Calculated from internal data from 2020 provided by Mehul Patel (OCWD).

Energy consumption of the full advanced treatment train is estimated with Eq. (8) (or Eq. (8), if accounting for concentrate disposal) using the previously calculated RO SEEC and default parameters from Table 1, below (except where noted). The energy consumption associated with RO concentrate disposal (per unit volume of permeate) was assumed to be negligible in the analysis that follows.

The energy consumption of advanced treatment, whether full advanced treatment or another type (for example, SEECs for GAC-based and GMF-based AWT are listed in Table 1) was used as an input to Eqs. (5)–(7) along with default parameters from Table 1 (except where noted) to estimate scheme-level SEEC.

Other researchers may estimate the SEEC of a reuse scheme of interest by following the procedure above, making use of as many case-specific values (such as local water transport energy consumption or feed osmotic pressure) as possible. For examples of using case-specific values in the estimation of SEEC, see Section 3.4. They may also choose to integrate other models for processes (e.g., modeling UF and/or RO with WAVE (Dupont Water Solutions, 2021) or modeling the advanced treatment train with the Water Associated Health and Environmental Air Damages (Water AHEAD) model (Gingerich and Mauter, 2012)). The Supplementary Information contains a MATLAB script to facilitate evaluation of this model with default and/or user-specified values.

### 3.3. Model inputs and sensitivity

A summary of default parameters, chosen based on the literature review (Section 2), that are used in evaluating the model for energy consumption of reuse processes and schemes in Section 4 is provided in Table 1.

Table 1 also includes results of a one-at-a-time sensitivity analysis, in which the effects of 1% changes in each input to the model were evaluated (as described in Section 3.2) individually to determine the resulting change in the model output for the default scheme, which was chosen to be IPR with RO, with other relevant parameters equal to the default parameters in Table 1. The “SEEC sensitivity” is reported as the fractional increase in scheme SEEC per fractional increase in the input parameter. For example, the SEEC sensitivity to osmotic pressure of 0.06 means that if the osmotic pressure of wastewater effluent increased by 10% (from 0.7 to 0.77 bar), the SEEC of the default IPR scheme would increase by approximately 0.6% (from 2.078 to 2.091 kWh/m<sup>3</sup>).

### 3.4. Model validation

Although the model is based on plant data to the extent possible, published energy consumption data for potable reuse processes is limited, and some theoretical modeling was required. Therefore, this section aims to validate the model by comparing model-produced estimates to available data.

To validate the RO portion of the model, the model output was compared with data from an internal report from the OCWD GWRS, which showed that the SEEC for a set of seven 5 million gallon per day (MGD) RO units with no inter-stage pumping or energy recovery ranged from 0.54–0.64 kWh/m<sup>3</sup> in 2019, and with plant-provided data for the GWRS overall, which found an RO SEEC of 0.54 kWh/m<sup>3</sup>. For an RO system treating feedwater with an osmotic pressure of 0.61 bar (the middle of the plant’s typical range; see Table D.1) that is otherwise modeled using default system values (one ISP, etc.; see Table 1), the model-estimated SEEC is 0.56 kWh/m<sup>3</sup>, in close agreement with the reported SEECs.

Internal OCWD GWRS data for energy consumption of unit processes (provided by Mehul Patel, OCWD’s Executive Director of Operations) also lends confidence to the full advanced treatment model: the total energy consumed by MF, RO, and UV as well as the less energy-intensive flow equalization, screenings, lime post-treatment, and decarbonation during the reported period (January to November 2020) was 0.908

kWh/m<sup>3</sup>.<sup>4</sup> Using a feed osmotic pressure of 0.61 bar, as described above, and default values for other parameters, Eq. (8) estimates an SEEC for the full advanced treatment system of 0.92 kWh/m<sup>3</sup>, 1.3% higher than reported.

To further validate the full advanced treatment train model (Eq. (8)) and the choice of relevant default values, the model output was compared to published data from the Leo J. Vander Lans water treatment facility in Long Beach, California (Schimmoller, 2014), which treats wastewater effluent with a TDS<sup>5</sup> of 703 mg/kg (Fu, 2014). Utilizing an MF-RO-UV train with continuous three stage RO without either inter-stage pumping or energy recovery at a recovery ratio of 92%, this train requires 0.97 kWh/m<sup>3</sup> (Schimmoller, 2014). The model-predicted SEEC of this train, using the known system parameters above and otherwise assuming default values from Table 1, is 0.94 kWh/m<sup>3</sup> (3% lower than actual).

Scheme-level energy data is not commonly reported, but to validate the DPR model across the entire reuse scheme, the predicted energy consumption has been compared to published data from the Colorado River Municipal Water District’s Big Spring, Texas DPR scheme (MF-RO-UV/AOP and drinking water treatment) (Office of Ground Water and Drinking Water, 2017), which includes in its energy figure the pumping energy used for product water conveyance, but does not account for water loss in pipe networks or drinking water treatment. The energy consumption of the Big Spring DPR scheme was reported as 1.41 kWh/m<sup>3</sup> (Office of Ground Water and Drinking Water, 2017). The modeled energy consumption of a DPR scheme without drinking water treatment, using Big Spring’s mid-range osmotic pressure (1.21 bar; see Table D.1) and otherwise using default values (Table 1) and neglecting water loss in transport, is 1.34 kWh/m<sup>3</sup>, 5% lower than the published data.

The consistent agreement between data and model outputs for energy consumption of RO, full advanced treatment, and DPR suggest that these models are capable of estimating the energy requirements of potable reuse processes, facilities, and schemes with reasonable accuracy, even when relying on some default values for unknowns such as membrane permeability. Agreement of the full advanced treatment model is also reasonably good in comparison to reuse plant data reviewed by Sim and Mauter (2021), which found full advanced treatment plant energy consumption to vary between 1.1 kWh/m<sup>3</sup> (the GWRS, likely including water conveyance to an injection site) and 1.4 kWh/m<sup>3</sup> (the Big Spring facility, including local conveyance), and the range identified by their process-based model (0.9–2.2 kWh/m<sup>3</sup>). Given the agreement between model outputs and treatment facility data, the model described in this section (and, except where noted, the default values provided in Table D.1) will be used in the analysis that follows.

## 4. Analysis: energy consumption of reuse schemes

In this section, the model described in Section 3 is evaluated to estimate the energy consumption of several potable reuse schemes, compare reuse schemes to alternative water procurement methods, and evaluate the effects of design changes on reuse scheme energy consumption.

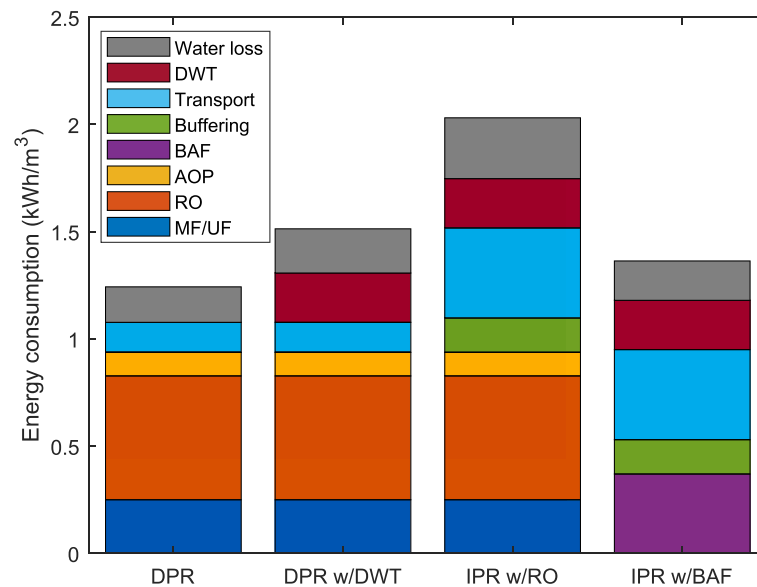
### 4.1. Energy consumption breakdown of potable reuse schemes

Figure 3 shows how various parts of the reuse process contribute to

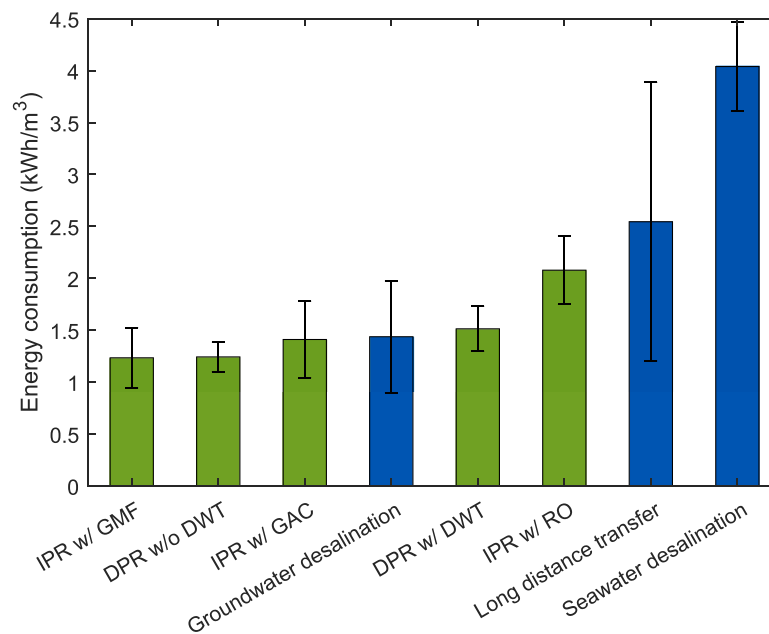
<sup>4</sup> While this SEEC is lower than that reported for the GWRS previously (Hutchinson, 2017), the GWRS also supplies energy (0.17 kWh/m<sup>3</sup> to seawater barrier well sites or 0.30 kWh/m<sup>3</sup> to recharge basins), which was likely included in the previously-published figure for GWRS SEEC (1.12 kWh/m<sup>3</sup>).

<sup>5</sup> Given its proximity to the OCWD GWRS, we use the GWRS’s TDS-to-osmotic pressure ratio (see Table D.1) to estimate the Leo J. Vander Lans facility’s feed osmotic pressure as 0.41 bar.





**Fig. 3.** Estimated energy requirement of several reuse schemes, broken down by process. “Water loss” represents the energy used by other processes to treat water that is ultimately lost through leakage in local pipe networks. DWT = drinking water treatment; BAF = biologically active filtration; AOP = advanced oxidation process; RO = reverse osmosis; MF = microfiltration; UF = ultrafiltration.

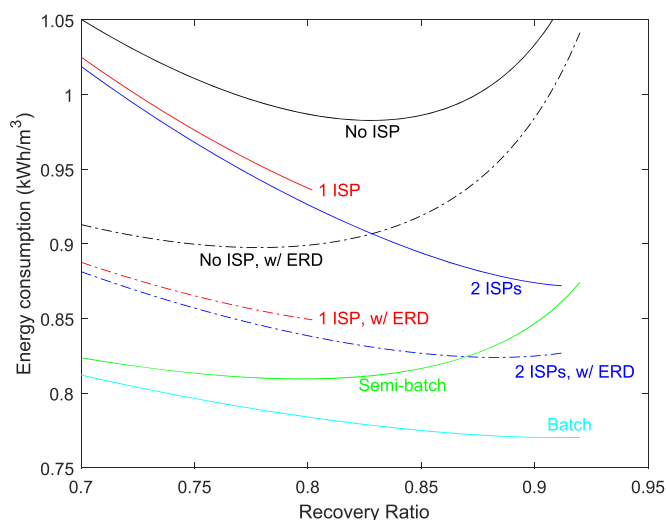


**Fig. 4.** Estimated energy consumption ranges for reuse schemes (in green) and other supply augmentation options (in blue). DPR = direct potable reuse; IPR = indirect potable reuse; GMF = granular media filtration; SAT = soil aquifer treatment; GAC = granular activated carbon; DWT = drinking water treatment; RO = reverse osmosis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

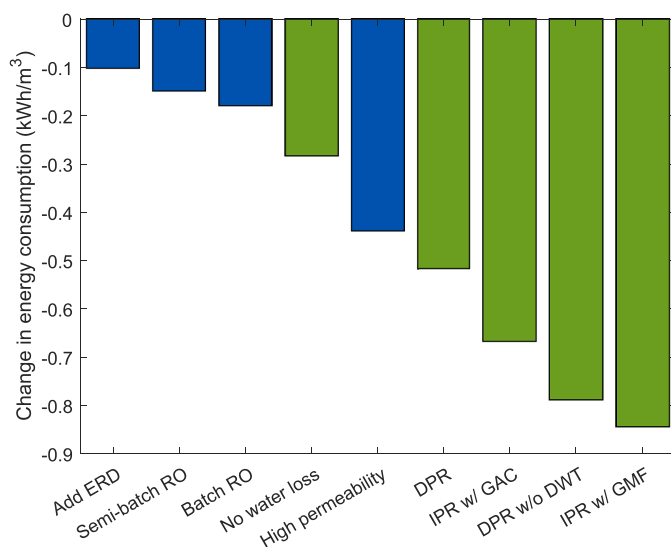
the energy consumption within several reuse schemes. Energy consumption was calculated as described in Section 3, assuming 15% water loss in transit and, when applicable, utilizing continuous RO at 80% recovery with one inter-stage pump and no energy recovery device. Other parameters were also assigned the default values listed in Table 1. Additional energy consumption required due to treating extra water to make up for water loss is tagged separately as “water loss.”

Figure 3 shows that the largest contributors to SEEC are likely to be RO (if used) and, in IPR, water conveyance. In IPR with aquifer recharge, the conveyance SEEC shown in Fig. 3 includes the energy used to convey water to and from the aquifer used for recharge, which can vary widely depending on the location of the aquifer relative to the wastewater and

drinking water treatment facilities. Although the RO energy consumption is significant, it is much lower than that of seawater RO (see Section 2.4.1) because the SEEC of RO scales approximately linearly with solution osmotic pressure (Eq. (1)) and municipal wastewater effluent has a very low osmotic pressure (see Table D.1) compared to seawater. Furthermore, modern RO membranes designed for low-salinity water tend to have a high permeability, allowing for lower energy consumption (Cohen-Tanugi et al., 2014). MF, BAF (modeled here as an ozone-GAC process), buffering, drinking water treatment, and the energetic effect of water loss are also significant in their energy use; the energy use associated with local water transport and AOPs are relatively small but not negligible based on default values, but these processes



**Fig. 5.** Energy consumption of full advanced treatment trains as a function of reverse osmosis (RO) recovery ratio for several configurations: continuous RO with up to 3 stages, with or without interstage pumps (ISPs) and with or without ERDs (energy recovery devices), as well as batch RO and semi-batch RO.



**Fig. 6.** Change in scheme-level energy consumption, with respect to standard indirect potable reuse (IPR), when process changes are implemented. Blue bars represent changes to the reverse osmosis subsystem, while green bars are scheme-level changes. ERD = Energy recovery device; RO = reverse osmosis; DPR = direct potable reuse; GAC = granular activated carbon; GMF = granular media filtration; SAT = soil aquifer treatment; DWT = drinking water treatment. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

could be significant energy consumers in some regions. The energy requirements of individual processes may vary between different treatment plants and reuse schemes, and the sensitivity of overall SEEC to fractional changes in individual processes' energy requirements is given in Table 1. As a result of the energy consumption associated with these individual processes, DPR without subsequent drinking water treatment and IPR using BAF and natural buffering (without RO) use less energy than the other options, which involve more redundancy.

#### 4.2. Comparison of potable reuse to alternatives

Representative SEECs for several reuse schemes and other water supply augmentation options are shown in Fig. 4. For potable reuse schemes, model-generated representative SEEC values are shown, and the error bars estimate uncertainty in SEEC based on a propagation of uncertainty analysis<sup>6</sup>; for other options, the chart shows the means and standard deviations of available data (see Section 2.4). With SEECs of approximately 1.2 kWh/m<sup>3</sup>, GMF-based IPR and DPR without subsequent drinking water treatment and are predicted to be the lowest-energy options for potable reuse among the situations considered. DPR (with DWT), groundwater desalination (when brackish groundwater is available), and GAC-based IPR are all fairly low-energy, with scheme SEECs of approximately 1.4–1.5 kWh/m<sup>3</sup>. The RO-free IPR options using BAF have the advantage of not producing a brine reject stream<sup>7</sup> and more efficiently removing trace organic compounds (Schimmoller, 2014), but a potential disadvantage is that they do not reduce water salinity.

Among the higher-energy options are IPR with RO, long-distance water transfer (in many cases), and seawater desalination. An IPR scheme with RO has a predicted SEEC of 2.0 kWh/m<sup>3</sup> due to the combination of a relatively high-energy reuse process (RO) and transportation to and from an environmental buffer. Long distance transportation (including drinking water treatment), with an estimated SEEC of 2.6 kWh/m<sup>3</sup>, has a very large confidence interval due to the wide range of distances over which it has been implemented (Wakeel et al., 2016a). Seawater desalination is the most energy-intensive process considered, with a mean SEEC of around 4.0 kWh/m<sup>3</sup> for modern RO plants (Cooley et al., 2012).

Given the magnitude of variability and the importance of non-energetic factors not analyzed here, it is not possible to state that one of these options is universally superior. However, some findings are clear: seawater desalination and some energy-intensive water transfers use much more energy than potable reuse; if no source of low-salinity groundwater or surface water is nearby, potable reuse is likely to be the least energy-intensive option. Furthermore, both DPR and RO-free IPR use significantly less energy than RO-based IPR, and eliminating redundant drinking water treatment after DPR can have a significant energetic benefit.

#### 4.3. Variation in energy consumption

Given the low energy use of potable reuse schemes relative to long-

<sup>6</sup> The propagation of uncertainty analysis assumed the following five sources of uncertainty might be most significant, based on sensitivities reported in Table 1 and the magnitude of variation in different parameters: the water transport RR, the SEEC of the AWT process, and the SEECs associated with drinking water treatment and environmental buffering. The uncertainty in each independent variable was estimated from variations seen in the literature review (Section 2) as 0.1 for transport RR, 0.12 kWh/m<sup>3</sup> for drinking water treatment, 0.175 kWh/m<sup>3</sup> for environmental buffering, 0.08 kWh/m<sup>3</sup> for GMF-based AWT, 0.05 kWh/m<sup>3</sup> for GAC-based AWT, 0.08 kWh/m<sup>3</sup> for full advanced treatment (estimated from Fig. 5). A one-at-a-time sensitivity analysis was conducted to determine the change in SEEC of each reuse scheme shown in Fig. 4 due to changing each of the parameters listed above by the stated amount. Consistent with a numerical propagation of uncertainty analysis, the overall uncertainty (shown as error bars) in scheme SEEC was calculated as the square root of the sum of the squares of the changes to scheme SEEC due to the above changes in individual parameters. Reuse schemes involving more processes with significant uncertainty had higher uncertainty in SEEC.

<sup>7</sup> We reiterate that the model did not consider energy consumption due to deep well injection or further concentration of RO brine, which would add to the energy consumption of reuse schemes involving RO anywhere surface or sewer discharge are not possible and likely shift favor toward RO-free reuse schemes.

distance water transfer and seawater desalination, this section explores how variations in potable reuse system design and operation could affect energy consumption. The baseline reuse scheme, with respect to which variations are considered, is IPR using full advanced treatment and SAT, as practiced at the OCWD GWRS. Default values from Table 1 are used, except where noted.

Because RO can account for a large fraction of a reuse scheme's energy consumption (see Fig. 3), changes to the design and operation of the RO subsystem affect the overall energy consumption considerably. Figure 5 shows how the energy consumption of a full advanced treatment train varies as a function of the type of RO and the recovery ratio of the RO step. Figure 5 was created by using Eqs. (1)–(3) to model RO energy consumption as a function of RO recovery ratio (up to 0.555 per stage) and inputting the recovery ratio and calculated RO SEEC into Eq. (8) to predict treatment train SEEC. For continuous RO systems, the number of ISPs was varied between 0 and 2 (RO systems with ISPs are modeled as having one more stage than the number of ISPs indicated), and systems were modeled both with and without 70%-efficient energy recovery devices. Other parameters such as membrane permeability were assumed to have the default values provided in Table 1.

According to Fig. 5, batch RO, semi-batch RO, and 3-stage continuous RO with inter-stage pumps and energy recovery are predicted to be the most energy efficient processes, although the SEEC of semi-batch RO requires more energy at very high recovery ratios due to recirculation-induced mixing (Warsinger et al., 2016). Depending on the RO process used, the energy-optimized operating RR for the RO step is in the range of 75–90% due to the balance of increasing concentrate osmotic pressure, reduced MF/UF flowrate (per unit RO permeate), and reduced brine throttling (when ERDs are not used) as the RO RR rises. In general, Fig. 5 shows that the energy consumption of continuous RO can be reduced by utilizing more complex process designs, such as a time variant (batch or semi-batch) system or a continuous system with one or more ISPs and an energy recovery device; however, complexity tends to be accompanied by capital costs. As an example, Wei (2021) estimated that batch RO would have a 10% greater capital cost than conventional RO for seawater desalination, but found that batch RO's more uniform flux distribution would enable recovery of the additional capital cost by operating at higher average flux. Future research on the capital cost–energy efficiency trade-off might shed light on which process improvements tend to be sound investments for potable reuse facilities.

The energy consumption of the full advanced treatment train, as shown in Fig. 5, is largely in the range of 0.85–1 kWh/m<sup>3</sup> (excluding complex RO configurations rarely used in practice) for a set of default parameters (Table 1) including fixed feed osmotic pressure, membrane permeability, pump efficiency, and average flux. While this model was successfully validated with several reuse facilities' data in Section 3.4, this predicted energy consumption range is lower than the range of data reported by facilities (1.1–1.4 kWh/m<sup>3</sup>) and on the low end of the range (0.9–2.2 kWh/m<sup>3</sup>) estimated by the process-based model of Sim and Mauter (2021). The higher range of facility energy use data reviewed by Sim and Mauter likely reflects the energy consumption associated with pumping treated water into the water supply network, as it was in the 1.41 kWh/m<sup>3</sup> reported for the Big Spring DPR plant (Office of Ground Water and Drinking Water, 2017), which was instead categorized as part of the reuse scheme beyond the full advanced treatment train in the present analysis.

Figure 6 shows how different choices affect the SEEC of potable reuse. It was created by using the present model and default values (Section 3) to calculate the SEEC of a baseline reuse scheme (IPR utilizing continuous RO at 80% recovery with two stages, one inter-stage pump, and no energy recovery device, with a SEEC of 2.08 kWh/m<sup>3</sup>) and then changing one parameter at a time and reporting the difference in scheme SEEC. The differences explored included changes to the RO process and changes to the reuse scheme. Changes to the RO process (such as adding an energy recovery device), though not insignificant, tend to have less impact on the overall SEEC of the potable reuse scheme.

The use of novel ultra-high permeability RO membranes (modeled as 18 LMH/bar, a 5× increase from the default value used in modeling) could provide a 21% decrease in energy consumption; this is consistent with previous findings that ultra-high permeability membranes have significant promise in reducing the energy consumption of low-salinity water desalination (Cohen-Tanugi et al., 2014). Eliminating transit water losses (by updating pipe networks) could significantly reduce energy consumption per unit volume delivered to the user by reducing the volume of water that must pass through the reuse process; such a fix would also save non-reused water from loss. Eliminating either RO or environmental buffering (i.e., using DPR or a non-RO IPR process) reduces energy consumption substantially. DPR schemes with RO may be able to forego drinking water treatment, which is a significant user of energy relative to the differences between these low-energy reuse schemes, by blending upstream of a drinking water plant. Therefore, DPR without subsequent drinking water treatment was also considered. Although uncertainty in these effects was not quantified, we anticipate the uncertainties in SEEC associated with changes modeled in Fig. 6 would be smaller than seen in scheme-level predictions (e.g., error bars in Fig. 4) due to only changing one parameter at a time.

By incorporating several energy efficiency improvements, the model demonstrates how the energy consumption of potable reuse might be reduced further. For example, a DPR scheme using a three-stage RO system with 85% recovery, 80%-efficiency pumps, two inter-stage pumps, an energy recovery device with 70% efficiency, and membranes with a permeability of 4 L/m<sup>2</sup>-hr-bar (33% higher than the base case), without further drinking water treatment, and with only 7.5% water lost in transit was predicted to have an SEEC of 0.90 kWh/m<sup>3</sup> for the entire reuse scheme. In this high-efficiency scenario, potable reuse of wastewater effluent could be accomplished for less than one quarter of the energy required for seawater desalination.

## 5. Discussion: context and limitations

This study's focus on direct energy consumption in potable reuse schemes does not account for embodied energy, cost, or environmental harm. In limiting the focus to direct energy consumption, we have not considered the embodied energy of the chemicals used in advanced water treatment, even though the embodied energy of chemicals can be significant in drinking water treatment (Mo, 2012). While Sim and Mauter (2021) showed that the vast majority of health and greenhouse gas externalities associated with potable reuse result from the generation of electricity consumed, the capital costs, pretreatment and cleaning chemicals, labor and other inputs must be considered in techno-economic-environmental analysis of any water reuse project. Gingerich and Mauter (2012) present the Water AHEAD model and associated software for conducting a holistic environmental analysis of water treatment processes and facilities, which they have already used to analyze the environmental impact of existing potable reuse plants in the United States (Sim and Mauter, 2021). In widening the scope of analysis to encompass entire reuse schemes, including complementary processes such as environmental buffering, the present study narrowed its focus to direct energy consumption as a single aspect of environmental impact; however, it could be fruitful for future research to employ the Water AHEAD model in combination with the scheme-level model presented here to analyze the environmental impact of reuse schemes. Given the correlation between direct energy consumption and environmental harm (Sim and Mauter, 2021), the lowest-energy reuse schemes identified by the present analysis could be ideal candidates for full environmental analysis at the reuse scheme level.

An additional limitation of this study is that the analysis does not consider decentralized potable reuse. In contrast to the centralized reuse schemes explored in this study, decentralized potable reuse has the potential to reduce the energy consumption required for water conveyance and domestic water heating as well as enable almost complete local recycling of wastewater (Englehardt et al., 2016). Based on

pilot-scale testing and modeling, a 1 MGD decentralized plant was predicted to more than offset the primary energy it requires for water treatment (at a SEEC of 2.98 kWh/m<sup>3</sup>, similar to the 2.76 kWh/m<sup>3</sup> this study predicts for IPR with RO plus conventional wastewater treatment) by retaining heat and thus reducing the primary energy required for domestic water heating (Wu and Englehardt, 2016). While energy-positive water reuse is a promising concept, small-scale systems have additional challenges related to robustness and the need for operator intervention, as shown in the development of a potable reuse system to meet the water needs of 120 people at Davis Station, Antarctica (Zhang et al., 2017).

Energy consumption is also not the only challenge limiting the spread of potable reuse. Although potable reuse has been implemented across the globe (Gerrity et al., 2013), challenges of public perception due to disgust at the idea of drinking recycled wastewater (Englehardt et al., 2016) persist. Furthermore, fluctuations in the feeling of urgency surrounding water supply augmentation—often on drought-driven timescales too short for development of reuse facilities—impede the implementation of potable reuse, as demonstrated by Australia's history with water reuse (Radcliffe and Page, 2020). Continuous improvement to potable reuse technology (at the process, facility, and scheme levels), increasing public awareness of reused water quality, and anticipation of the effects of climate change on water resources may shift attitudes in favor of potable water reuse.

## 6. Conclusions

- Modeling-based analysis found a range of 1.2 to 2.1 kWh/m<sup>3</sup> for the typical energy consumption of potable water reuse schemes, including advanced treatment processes and water conveyance but excluding conventional wastewater treatment. The lower end of the energy range corresponds to IPR without RO and DPR without drinking water treatment, while the higher end corresponds to IPR processes that include RO.
- Groundwater desalination and water transfer over moderate distances fall within the same range of energy cost as potable reuse, so those options may be competitive with potable reuse when low-salinity groundwater or surface water are accessible. However, seawater desalination uses far more energy than potable reuse, and should only be implemented once lower-energy options have been exhausted.
- Examining entire reuse schemes, rather than individual plants or processes, revealed the similarity in energy consumption of DPR and RO-free IPR, which were the lowest-energy options identified. Depending on the proximity of a suitable aquifer for SAT and the availability of surface/sewer discharge of RO concentrate, either a natural process-based IPR scheme or a membrane-based DPR scheme (especially without redundant drinking water treatment) is likely to be the lowest-energy water reuse option.
- Further reductions in energy consumption are possible. Fixing leaks in the water supply network would have a significant effect on each scheme's energy consumption by reducing the amount of water

subject to energy-intensive advanced treatment. High-permeability RO membranes, which are an area of ongoing research, would also reduce energy consumption in potable reuse meaningfully. Other changes to RO systems used in reuse plants, such as installing energy recovery devices, would have small but still significant effects on energy consumption. With a few efficiency upgrades, a DPR system without subsequent drinking water treatment could have a total scheme energy consumption of less than 1 kWh/m<sup>3</sup>.

- As potable reuse becomes more widespread, the technology will continue to benefit from research and optimization. Additional analysis of the environmental impact, cost, and efficacy of direct and RO-free indirect potable reuse schemes is needed to increase adoption of water reuse and improve the sustainability of water supplies. However, future potential aside, potable reuse is already a far less energy-intensive option than seawater desalination—and, often, long-distance water transfer—and a powerful tool for sustainable water supply management.

## CRediT authorship contribution statement

**Emily W. Tow:** Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Anna Letcher Hartman:** Data curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Aleksander Jaworowski:** Data curation, Writing – original draft, Writing – review & editing. **Ines Zucker:** Conceptualization, Data curation, Writing – original draft, Writing – review & editing. **Soyoon Kum:** Data curation, Writing – original draft, Writing – review & editing. **Mojtaba AzadiAghdam:** Data curation, Writing – original draft, Writing – review & editing. **Ernest R. Blatchley:** Data curation, Writing – original draft, Writing – review & editing. **Andrea Achilli:** Data curation, Writing – original draft, Writing – review & editing. **Han Gu:** Data curation, Writing – review & editing. **Gulsum Melike Urper:** Project administration, Writing – review & editing. **David M. Warsinger:** Conceptualization, Visualization, Writing – review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

We thank Mehul Patel of OCWD for providing data from the GWRS and Ido Negev from Mekorot Water for providing guidance and technical information on the process in Shafdan. We thank our anonymous peer reviewers for generously constructive feedback. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

## Appendix A. MF/UF energy consumption

In a typical MF/UF system for pretreating RO feed, major energy-consuming components are pumps (feed pump, backwash pump, cleaning pumps, backwash and concentrate transfer pump) and the air compressors and air blowers used for air scouring in cleaning.

As an example, the Orange County Water District Advanced Water Purification Facility (OCWD AWPFF) utilizes a multiple-barrier approach to recycle secondary-treated wastewater for IPR which includes MF (Ishida et al., 2015). Their MF system is designed for 86 MGD production of MF filtrate using 0.2 μm polypropylene hollow fiber membranes operating at 88–90% recovery. Backwashing and air scouring was conducted every 22 min. The normalized energy cost for the MF system was 0.072 kWh/m<sup>3</sup>. Additional data for MF/UF energy consumption in a range of plants are reported in Table A.1.

**Table A.1**

Reported values for MF/UF system energy consumption.

Filtration process	SEEC (kWh/m <sup>3</sup> )
MF (Judd and Hillis, 2001)	0.11–0.24
MF (Reardon et al., 2005)	~0.2
MF (Tchobanoglous et al., 2014)	0.2–0.3
MF/UF (Cooley et al., 2012)	0.085–0.20
MF/UF (AWW, 2016)	0.16–0.26
MF/UF (Pearce, 2008) (after conventional treatment)	~0.1
MF/UF (Pearce, 2008) (in place of conventional treatment)	~0.2
UF (Mackey et al., 2001)	~0.13
UF (Van Houtte and Verbauwheide, 2008)	0.177–0.201
UF (Tchobanoglous et al., 2014)	0.2–0.3

## Appendix B. Batch and semi-batch RO energy modeling

In the present model, osmotic pressure will be assumed to vary linearly with salinity (reasonable for low salinity feeds (Lienhard et al., 2017), such as municipal wastewater) and the RO module will be assumed to be very short. Additionally, concentration polarization, salt permeation, and viscous friction will be neglected; due to the final assumption, the power required by the circulation pumps shown in Fig. 1 is calculated as zero. As shown by Warsinger et al. (2016), batch and semi-batch RO have lower osmotic pressure at the RO module feed outlet than continuous RO. For an idealized, very short RO module with an infinitesimal recovery ratio, the feed pressure can be related to instantaneous recovery ratio ( $RR_i$ , defined as the ratio of the volume of permeate produced by a given time to the volume of feed that will be consumed in an entire batch cycle) as follows. For batch RO, the total salt mass in the system stays constant throughout each cycle, so the salinity (and thus, assuming it is proportional, osmotic pressure) rises inversely with the remaining volume of feed. In the absence of concentration polarization, the feed pressure required for batch RO,  $\Delta P_{BRO,i}$ , is approximated by Eq. (B.1):

$$\Delta P_{BRO,i} = \frac{J_w}{A_m} + \pi_f \frac{1}{1 - RR_i}, \quad (B.1)$$

where  $J_w$  is the water flux,  $A_m$  is the membranes water permeability, and  $\pi_f$  is the feed osmotic pressure.

In semi-batch RO, the system volume is constant, and therefore feed must be introduced at a constant rate to make up for the permeate produced. As a result, the feed osmotic pressure increases linearly with permeate production and instantaneous recovery ratio (see Fig. 10 in Warsinger et al. (2016)). Therefore, the feed pressure required for semi-batch RO,  $\Delta P_{SBRO}$ , can be approximated by Eq. (B.2):

$$\Delta P_{SBRO,i} = \frac{J_w}{A_m} + \pi_f \frac{1 - RR + RR_i}{1 - RR} \quad (B.2)$$

where  $RR$  is the total recovery ratio of the RO system.

For a constant-volume batch or semi-batch RO system, the flow rate through high-pressure pump is equal to the permeate flow rate during permeate production and concentrate is discharged at atmospheric pressure at the end of a cycle. The SEEC for either of these systems,  $w$ , is then the ratio of the permeate-volume-averaged pressure to the pump efficiency:

$$w = \frac{1}{\eta_p V_p} \int_0^{V_p} \Delta P_i dV_{p,i} = \frac{1}{\eta_p RR} \int_0^{RR} \Delta P_i dRR_i \quad (B.3)$$

where  $\eta_p$  is the high-pressure pump efficiency and  $V_p$  is the permeate volume of one cycle, and  $V_{p,i}$  is the permeate volume produced during a cycle at a particular time. Integrating Eq. (B.3) for batch RO and semi-batch RO, lead to Eqs. 2 and 3, respectively, in the main text. byt

## Appendix C. Energy consumption of advanced oxidation processes

For direct photolysis applications in which the contaminant is present at low concentration, it can be shown that local reaction rates are first-order with respect to (local) fluence rate and reactant concentration. For UV-based AOPs, the governing reactions are first-order or pseudo-first-order processes as well, at least to a first approximation. As such, the concept of  $E_{EO}$  can be used for approximate comparisons of energy use among UV-based water treatment processes and for approximate scaling of energy costs from small-scale reactors to larger reactors of similar design (Bolton et al., 2001).

A fundamental expression to describe photochemical kinetics is as follows:

$$r_B = -\frac{d[B]}{dt} = I_a \phi(\lambda), \quad (C.1)$$

where  $r_B$  is the rate of reaction of the target molecule, B (in mol/L-s),  $[B]$  is the activity of B in solution (mol/L),  $t$  equals time (s),  $I_a$  is the volumetric rate of photon absorption by B (einstein/L-s), and  $\phi$  is the primary quantum yield for reaction of interest (mol/einstein).

The volumetric rate of photon absorption by the photochemical target (B) will depend on system geometry and other factors. Perhaps the simplest reactor system to consider is a shallow, well-mixed batch reactor that is subjected to a beam of uniform, collimated radiation.

If the effects of reflection, dissipation, and beam divergence are ignored, it is possible to define the volumetric rate of photon absorption for this system:

$$I_a = \frac{A(E_i' - E_t')}{VU} \quad (C.2)$$

where  $A$  is the surface area of irradiated fluid,  $E_i'$  and  $E_t'$  are the incident and transmitted fluences, respectively,  $V$  is the volume of irradiated fluid, and  $U$  is the energy per einstein of incident radiation.

By application of the Beer-Lambert law, Eq. (2) can be re-written as:

$$I_a = E_i' \frac{1 - 10^{-\epsilon[B]l}}{lU} \quad (C.3)$$

For dilute solutions, the exponent of the term on the right-hand side of this system can be re-defined using a Taylor series expansion, such that:

$$r_B = -\frac{d[B]}{dt} = \frac{2.3E_i' \epsilon[B]}{U\phi} \quad (C.4)$$

Equation (4) indicates that in the limit of dilute solution, the kinetics of a photochemical process are first-order with respect to the fluence rate and the concentration of the reacting compound. This equation also indicates that the rate of this photochemical reaction is directly proportional to the values of the molar absorption coefficient ( $\epsilon$ ) and the quantum yield ( $\phi$ ).

Thus, the reaction extent and the actual power consumption per unit flow rate  $w$  can be related to single parameter—the electrical efficiency per order  $E_{EO}$ —as follows (Bolton et al., 2001; Bolton and Stefan, 2002):

$$E_{EO} = \frac{w}{\log_{10} \left( \frac{[B]_0}{[B]} \right)} \quad (C.5)$$

Thus, the energy consumption of the UV-AOP scales linearly with both  $E_{EO}$  and log removal, as seen in Eq. (4).

#### Appendix D. Potable reuse plants and their feedwater characteristics

The composition of secondary wastewater effluent affects the reuse process in terms of the treatment steps needed, their energy consumption, and practical limits on water recovery due to the fouling and scaling potential of concentrated wastewater effluent (Warsinger et al., 2018a). The wastewater effluents fed to potable reuse tend to be low-salinity compared to other types of desalination plant feeds. Table D.1 lists the feed total dissolved solids (TDS) and osmotic pressure from several potable reuse plants which publish this data.

**Table D.1**

Reuse plants with reported feed characteristics.

Project	Type of reuse	Project size, MGD (m <sup>3</sup> /d)	Treatment process	TDS, mg/L	Feed osmotic pressure, bar	Ref.
West Basin Water Recycling Plant, CA	Groundwater recharge via direct injection	40 (151416)	Ozone, MF, RO, UV-AOP	1151 - 1282	0.65 - 0.69	Li (2016)
Singapore Public Utility Board	Reservoir augmentation	>50 (>189270)	MF, RO, UV disinfection	557 - 7494 <sup>a</sup>	0.32 - 0.48	Qin et al. (2006)
Groundwater Replenishment System, Orange County, CA	Groundwater recharge via direct injection and spreading basins	100 <sup>b</sup> (378541)	MF, RO, UV-AOP	950 - 1150	0.55 - 0.67	Burris (2018)
Colorado River Municipal Water District, Big Spring, Texas	Direct potable reuse	2 (7571)	MF, RO, UV-AOP	1694 - 218	1.05 - 1.37	Sloan and Dhanapal (2007)

<sup>a</sup> TDS estimated from electrical conductivity in pilot study data for reclamation of domestic sewage at Bedok Water Reclamation Plant in Singapore.

<sup>b</sup> Installed as 70 MGD; expanded to 100 MGD in 2015.

#### Appendix E. SEEC of conventional wastewater treatment

Wastewater treatment improves wastewater quality to allow its discharge to the environment or reuse in an AWT plant. In 2013, a report from the Electric Power Research Institute estimated an overall energy consumption by WWTPs in the U.S. of 30.2 billion kWh/year (almost 1% of the country's energy use) to treat approximately 32,200 MGD at an average SEEC of 0.68 kWh/m<sup>3</sup> (Pabi et al., 2013). The SEEC typically ranges from 0.42 to 0.87 kWh/m<sup>3</sup>, with lower SEECs occurring in larger plants, especially those treating more than 16 MGD (Pabi et al., 2013). These values from the U.S. are comparable to those found from surveys of WWTPs worldwide (Longo et al., 2016; M. Mauricio Iglesias, 2016). Within wastewater treatment, aeration is the principal energy consumption step, accounting for approximately 54% of the WWTP's total energy consumption (Gude, 2015).

Because wastewater requires conventional treatment whether or not it goes on to engineered reuse, the energy consumption associated with conventional wastewater treatment is not included in this paper's analysis of the total energy consumption associated with water reuse schemes.

#### Supplementary material

Supplementary material associated with this article can be found, in the online version, at [10.1016/j.wroa.2021.100126](https://doi.org/10.1016/j.wroa.2021.100126).

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