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Energy considerations associated with increased adoption of seawater desalination in the United States

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ABSTRACT

Due in part to increased water demand and uncertainty around the availability of existing freshwater resources, there is interest in expanding the use of seawater desalination in the U.S. In order for greater adoption to occur, existing barriers need to be mitigated. One of these barriers is the energy consumption of seawater desalination. This paper reviews the existing energy requirements for membrane and thermal-based seawater desalination systems to produce potable water. Through literature review, it identifies the commercially-available option with the lowest energy intensity and the thermodynamic minimum energy requirement for each unit operation of the system. The paper then estimates the energy requirements to expand seawater desalination capacity to meet the potable water needs of water-stressed regions in the U.S. The results show that supplying 10% of the potable water demand for these regions located within 250 miles of a coastline using the lowest energy-intensity seawater desalination system commercially available would require < 0.1% of 2018 U.S. electricity consumption. This increases to approximately 0.5% if all public water for these same regions is supplied via desalinated seawater. These estimates of the energy implications of broader adoption provide an initial comparison to current U.S. electricity consumption.

1. Introduction

Global water demand in 2050 is projected to be 155% of 2000 levels [1]. By this time, limits on human consumption of freshwater are expected to exceed the Earth's safe limit for stability [2,3]. In the U.S., state water planners are already concerned about meeting growing demand. In a survey conducted in 2013 by the U.S. Government Accountability Office, 40 of 50 state water managers expected freshwater shortages within their state in the following ten years under typical weather conditions, and 42 expected shortages in the subsequent 10–20 years [4]. The shortages are expected in the absence of impacts from climate change, which is projected to exacerbate water shortages globally [5–8]. Additionally, irreversible damages to the environment and water resources can occur from depleting our freshwater resources. For example, heavy reliance on groundwater can lead to aquifer contamination by seawater intrusion or depletion beyond the point of recharge. Land subsidence and infrastructure damage are other potential consequences of overdrawing from groundwater sources [9,10]. Developing water plans that meet projected demands and are resilient against uncertain future water availability is an emerging challenge for regional planners. The consequences of inaction are severe; the World Economic Forum recently cited water crisis as one of the most likely and impactful global risks in the near term [11].

The utilization of seawater can be part of a diverse water supply portfolio to meet projected water demands. However, in the U.S., seawater is a far less utilized water source for potable water compared to fresh ground or surface water. In 2010, < 1% of public water supply in the U.S. was sourced from saline (sea or brackish) water [12]. This is due in part to the energy intensity (defined as energy consumption/unit of product water) necessary to treat seawater for potable use. In the U.S., the estimated energy intensity of installed seawater desalination facilities (between 3.2 kWh/m^3 and 4.5 kWh/m^3) can be over 25 times larger than it is for freshwater systems (0.12 kWh/m^3 in New York state) [13–16]. For reference, the average home in the U.S. consumes 29.5 kWh in a day [17]. The energy required to produce 1 m^3 of potable water (typical per person use in the U.S. is 0.37 m^3/day) from seawater at an energy intensity of 3.2 kWh/m^3 is equivalent to the energy consumed by a typical U.S. home in 2.6 h [18]. For further context, a small

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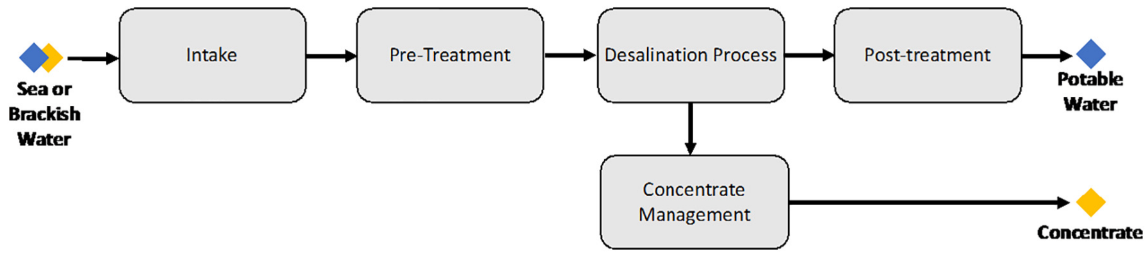

Fig. 1. Unit operations of a desalination system, as defined in this paper. Adapted from U.S. Department of Energy [23].

room air conditioner operating for 1.4 h consumes 2.5 kWh [19]. This suggests that the energy intensity of seawater desalination is high when compared to other water supply options but comparable with other energy-consuming services.

In addition to the higher energy intensity compared to existing water supply options, there are several other barriers to the adoption of seawater desalination in the U.S. One major barrier is the high initial cost of large, centralized desalination facilities (which include not only the capital costs, but also costs to acquire coastal land, permits for siting and the environmental impacts of seawater intake and concentrate discharge) and subsequent amortization. This, along with the increased energy consumption, leads to higher cost of water produced through seawater desalination relative to potable water produced from freshwater. However, seawater desalination offers several benefits. The feedwater (the oceans) are vast and generally available at no-cost. Due in part to this, seawater desalination offers a water supply option that is resilient against water stress. Further, while the cost of water produced through seawater desalination is relatively high, it can also be predictable and relatively steady. This provides water planners with more certainty when developing multi-year plans to meet projected water demands. Additionally, seawater desalination in conjunction with water storage offers the potential to facilitate the integration of intermittent renewable electricity generation (e.g., solar) into the electric grid.

As regional water planners consider seawater desalination, a question that emerges is the impact on the regional energy sources from adding seawater desalination to their water supply portfolio. Energy and water – two important resources/services for human development – cannot be fully decoupled, and there is a need to consider one when planning on the development of the other [20,21]. Further, while the energy intensity for desalination has dropped significantly over the past forty years, future research and development has the potential to lower it further [22].

In order to better understand the energy consumption of different seawater desalination systems and the energy implications associated with their increased adoption in the U.S., this paper will:

1. Define the desalination system, based on consistent set of key unit operations/components.
2. Map the various desalination technology options from a variety of water sources for a range of end-uses, based on salinity and capacity requirements.
3. Briefly summarize installed seawater desalination capacity globally and in the U.S., and relevance to water stressed regions in the U.S.
4. Review several membrane and thermal-based seawater desalination system technologies to produce potable water, and identify the state-of-the-art (SOA) and thermodynamic minimum (TM) energy intensities for each component of the desalination system.
5. Develop scenarios that estimate the energy requirements associated with broader adoption of SOA membrane-based seawater desalination systems to serve the water supply needs of water stressed regions in the U.S. These estimates are intended to provide general guidance on the energy implications of increased adoption. Reductions achievable through optimization of the water conveyance system are likely possible, but not explored in this paper.
6. Discuss other considerations and barriers when planning for increased adoption of seawater desalination.

The results are intended to assist regional and national water planners in the U.S. to better assess the full energy implications associated with increasing seawater desalination capacity for potable water production. It can also be used by policymakers who are developing research and development portfolios related to desalination to better understand the limit for energy reductions in seawater desalination systems over commercially-available ones.

2. Background

2.1. Desalination system and applications

For the purposes of this paper, the desalination system is subdivided into five unit operations: intake, pre-treatment, the desalination process, posttreatment of the product water, and disposal of the concentrate (concentrate management). These steps are illustrated in Fig. 1. Additionally, pumping energy will be required to integrate the product water with the existing water supply network.

The selection and pairing of the system components will be dependent upon many factors, including the desalination system application, where the *application* refers to the desalination of an alternate water source for a given end use. The feasibility of a system component for an application will depend at minimum on the salinity and available/required flow rates of the water source, end use, and concentrate disposal site. To help identify feasible desalination pathways, Fig. 2, originally developed by the U.S. Department of Energy and adapted for this paper, shows typical ranges of capacity (m^3/day) and salinity (% total dissolved solids) for various freshwater-alternate sources, end use requirements, concentrate disposal thresholds, and commercially-available desalination technology operating ranges [23]. As shown in the legend to Fig. 2, three sets of capacity and salinity ranges are shown for the desalination technologies. The first describes the feedwater input, while the second and third describe the concentrate and product water. By matching the output capacity and salinity of a preceding system component with those of the input requirements for the next system component, feasible desalination pathways can be identified. These pathways are not intended to show an optimized system (in terms of energy efficiency, cost, etc.), but to eliminate technically infeasible pathways for a selected application. For example, from Fig. 2 one can determine that capacitive deionization is not appropriate for seawater and multi-stage flash is not appropriate for low salinity feedwaters.

The pathways explored in this paper - seawater to municipal potable water - are one of many, with a single exemplary pathway shown in Fig. 2 with arrows. One water source (seawater) was selected for one end-use (municipal-scale potable water) and one concentrate disposal option (ocean). Many desalination technologies can be used for these specified conditions, including reverse osmosis (RO), multi-effect distillation (MED), and multi-stage flash (MSF). This paper will review RO,

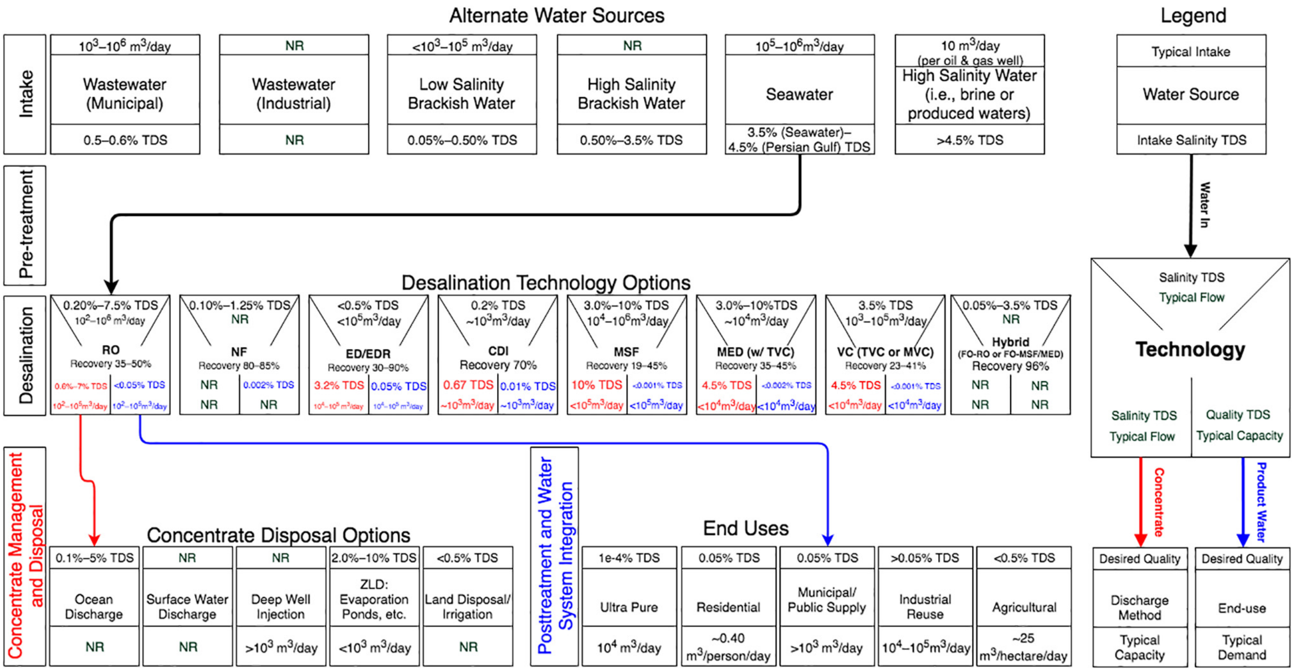

Fig. 2. Adapted from U.S. Department of Energy [23]. All values shown are typical salinity and capacities as reported in the literature. Cooling water for thermal processes has not been included. In order to for one step to match the next (e.g., an alternate water source match a desalination technology, a desalination technology match a concentrate disposal/end use option), the output salinity and capacity ranges of the first should be within the input salinity and capacity ranges of the second. Definitions: m^3 = cubic meters, NR = typical values not found in literature, RO = reverse osmosis, NF = nanofiltration, ED/EDR = electrodialysis/electrodialysis reversal, CDI = capacitive deionization, MSF = multistage flash, MED = multi-effect distillation, TDS = total dissolved solids, TVC = thermal vapor compression, VC = vapor compression, MVC = mechanical vapor compression, FO = forward osmosis [18,24–41].

MED, and MSF with a focus on RO (pathway shown in Fig. 2).

2.2. Seawater desalination and water stress in the U.S.

As of 2016, U.S. cumulative seawater desalination capacity is 0.4 million m^3/day, all of which is provided by RO membrane systems. U.S. desalination capacity represents 0.5% of global capacity (89 million m^3/day). Between 2000 and 2016, global thermal desalination capacity doubled (from 12 million m^3/day to 24 million m^3/day), with the growth largely dominated by MED and MSF. During the same period, global membrane desalination capacity (mainly RO) increased by 342% (from 15 million m^3/day to 65 million m^3/day) [42].

Seawater desalination is of emerging interest in drought prone parts of the U.S. For example, as of 2015 the Metropolitan Water District of Southern California, which provides water for much of the Southern California region, had one permitted and four planned seawater desalination facilities ranging in capacity from 68,000 m^3/day (18 million gallons per day (MGD)) to 568,000 m^3/day (150 MGD) in addition to the fully-operational Claude "Bud" Lewis Desalination Facility in Carlsbad, CA which treats 189,000 m^3/day (50 MGD) of seawater for potable water use in San Diego County [43,44].

San Diego County and the desalination facility in Carlsbad provide a practical example of a region developing a resilient water portfolio in response to potentially severe droughts and associated constraints on traditional water supplies. In 1991 San Diego County was supplied by two water sources, one of which constituted 95% of the total water supply and was imported from outside of the county. Spurred by curtailments in water allotments due to regional drought, the county invested in conservation efforts and diversified its water sources. In 2017, the county was served by 7 water sources, including the Carlsbad seawater desalination facility, none of which constituted > 40% of the total water supply portfolio [45].

Many of the aforementioned detractions of seawater desalination are less consequential in water stressed areas like San Diego County. For example, the cost of potable water from freshwater sources in these areas may rise in the future as water stress conditions worsen such that it is comparable to the cost of potable water from seawater desalination. Hence, coastal water stressed areas are one market for early adoption of seawater desalination in the U.S. The potential to provide desalinated water to other (non-coastal) markets depends on the current regional water supply cost structures in context with the candidate desalination systems costs plus conveyance, which are highly dependent upon source (e.g. pumping desalinated seawater long distances vs. sourcing local brackish water if available). While not a substitute for a thorough, regional assessment of the viability of desalination for a specific market, water stressed regions provide a useful initial starting point to perform scenario analysis of the national energy implications for increased utilization of seawater desalination.

One metric for determining water stress is the Water Supply Stress Index (WaSSI) as introduced by Sun et al. [46]. This index is a ratio of a region's annual water demand to the amount naturally replenished:

$$WaSSI = \frac{Water\ Use + Water\ System\ Loss}{Surface\ Water\ Supply + Groundwater\ Supply + Return\ Flows}$$

A WaSSI > 1 indicates that the region has greater anthropogenic water demand than the natural water replenishment rate. The *WaSSI Ecosystems Services Model* from North Carolina State University, the U.S. Department of Agriculture, and the U.S. Forest Service calculates this index at the 8-digit hydrological unit (HUC), as defined by the United States Geological Survey (USGS), for each year between 1985 and 2010 [47]. This unit divides the continental U.S. into 2264 "watersheds". At this level of disaggregation, the long term WaSSI from 1985 to 2010 for each U.S. county (3142) was estimated. This is shown in Fig. 3. Unsurprisingly, the southwestern regions in the U.S. are water-stressed. However, other regions in the U.S. – the Appalachian, parts surrounding the Great Lakes, and the eastern foothills of the Rocky Mountains – show water stress per the WaSSI index as well.

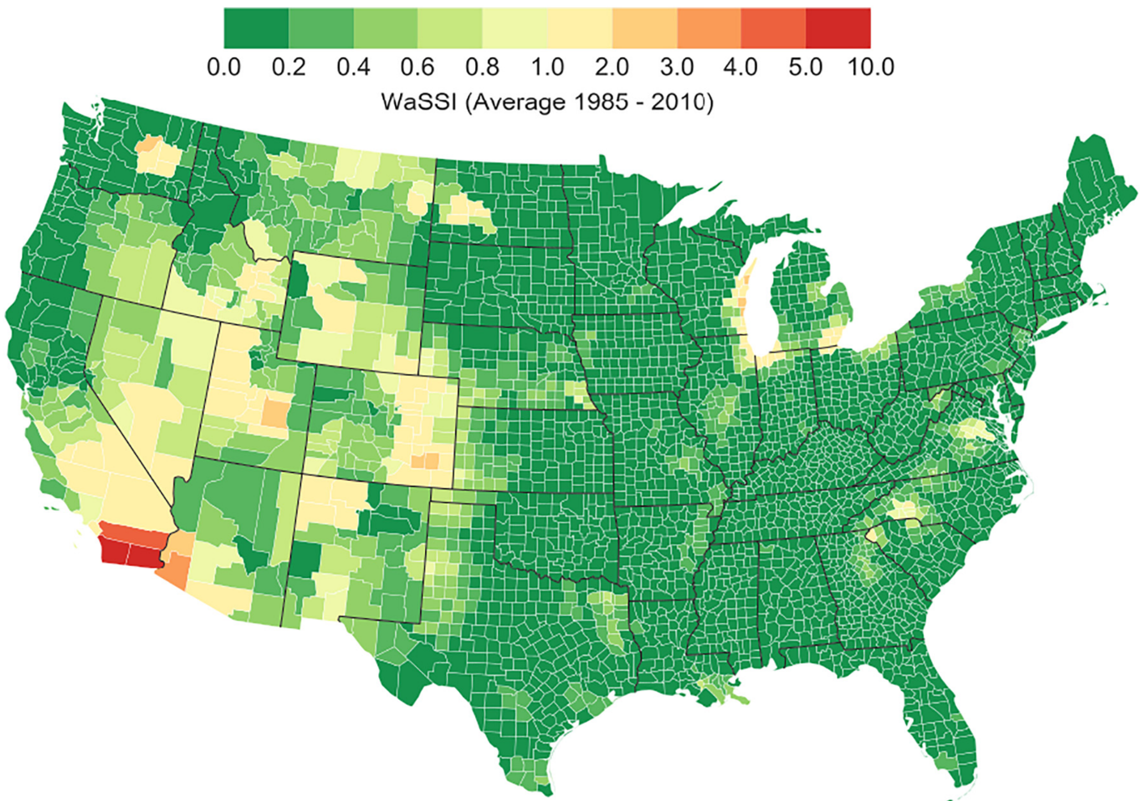

Fig. 3. WaSSI for each continental U.S. county calculated over the period from 1985 to 2010.
Data taken from WaSSI Ecosystems Services Model by North Carolina State University, U.S. Department of Agriculture, and U.S. Forest Service [47].

3. Energy intensity of seawater desalination systems producing potable water

Since this paper seeks to better understand the energy implications of greater adoption of seawater desalination in the U.S., a more detailed review and examination of the energy consumption associated with the various system components is required. The energy intensity of each component of the desalination system as reported in the literature was reviewed for membrane and thermal systems. Two categories of energy intensity were evaluated:

- State-of-the-Art (SOA) - Describes the energy intensity based on best commercially available technology, with "best" qualified as having the lowest energy intensity.
- Thermodynamic Minimum (TM) – Describes the minimum energy intensity under ideal conditions (i.e., a reversible process). This value cannot be reached in real applications and no technology can operate below this intensity value.

An evaluation and comparison of the SOA and TM allows for a better understanding of how close commercially-available technologies operate to their thermodynamic limit.

For each component of the desalination system, technologies/processes representing the SOA and TM were identified based on the literature and are described below. In order to compare energy intensities across systems utilizing different types of energy sources (e.g., electricity, thermal), three units are employed to report the energy consumption (the numerator in the energy intensity metric):

- kWh_e (and TWh_e): kilowatt-hour (kWh_e) or terawatt-hour (TWh_e) of electrical energy. This is used when the energy source is entirely from electricity.
- $kWh_{e,equiv}$: kilowatt-hour of electrical equivalent thermal energy. This used when the energy source is thermal. To arrive at the electrical equivalent, the thermal energy intensity is multiplied by 33% to account for the amount of electricity the thermal energy could produce using the typical efficiency of the U.S. electrical grid [48]. As the U.S. electricity grid modernizes (e.g. coal power plants are replaced with more efficient natural gas power plants), the average grid efficiency is expected to increase. Further, regional differences in electricity generation mix leads to some regions in the U.S. having a more efficient electricity grid than others. A more efficient electricity grid will place thermal desalination technologies at further disadvantage when its electrical equivalent thermal energy consumption is compared to electrically-driven technologies [49].
- $kWh_{T,equiv}$: kilowatt-hour of total electrical equivalent energy (kWh_e + $kWh_{e,equiv}$). This is used when a system component (or combination of system components) employs both electrical and thermal energy.

3.1. Intake

The main energy requirement for the intake is to pump seawater from the ocean to the plant location to be desalinated. For seawater desalination, there are two options for intake: open-ocean or subsurface. Open-ocean intake is typically more cost-effective (and more common), whereas sub-surface intake can have lower pre-treatment requirements, but its feasibility is highly site specific.

The energy intensity for intake is based upon the total dynamic head (TDH)[1] associated with pumping. The TDH will be dependent upon site-specific conditions such as elevation changes, piping geometry and

[1] TDH is defined as the sum of the static head (difference in elevation of the supply and delivery point) and friction head (the energy required to overcome friction losses in the system).

layout, and piping material. Due to this variability, normalizing the energy intensity of pumping to one unit of TDH (expressed in meters) allows for an evaluation of the intake energy requirements across all sites, regardless of site-specific conditions. The following formula is used to determine the energy intensity for intake pumping normalized to the TDH:

$$\text{Energy intensity/TDH} = \frac{\rho \bullet g}{\eta_{pump} \bullet \eta_{motor}}$$

where ρ is the density of seawater (1029 kilograms [kg]/m^3), g is gravitational acceleration (9.8 meters per second squared [m/s^2]), η_{pump} is the pump efficiency, and η_{motor} is the motor efficiency. For the SOA energy intensity, it was assumed that $\eta_{pump} = 81\%$ and $\eta_{motor} = 95.8\%$. These values are based on the use of a National Electrical Manufacturers Association (NEMA) Premium Efficiency motor and a new large vertical turbine pump operating at its rated efficiency (i.e., no degradation due to deferred maintenance).[2,3] NEMA Premium Efficiency motors are the motor industry standard for high efficient motors. For the TM energy intensity, the efficiencies of the pump and motor were set to 100%.

With these values, the SOA and TM energy intensities for intake were estimated to be 0.0036 (kWh$_e$/m^3)/m and 0.0028 (kWh$_e$/m^3)/m respectively. These values are applicable for both membrane and thermal systems.

3.2. Pre-treatment

For membrane-based desalination systems with open ocean intake, a combination of flocculation, coagulation, sand filtration, and cartridge filtration was selected as representative of seawater pre-treatment processes. The combined SOA energy intensity for these processes was identified to be 0.21 kWh$_e$/m^3. This assumes the energy intensity of the combined flocculation and coagulation components is 0.06 kWh$_e$/m^3 [50], sand filtration is 0.13 kWh$_e$/m^3, and cartridge filtration is 0.02 kWh$_e$/m^3 [51,52].

The pre-treatment requirements for thermal seawater desalination are less than those for membrane desalination. Thermal pre-treatment methods include gravity-fed media filtration and chlorination. The SOA energy intensities reported were 0.05 kWh$_e$/m^3 and 0.001 kWh$_e$/m^3, respectively [27,53]. The energy intensity of any added anti-scalants was assumed to be negligible.

For all pre-treatment processes, the TM was assumed to be 0 kWh$_e$/m^3. The basis for this assumption is that the feedwater in the TM case is pure sodium chloride and does not need any pre-treatment.

3.3. Desalination

Fig. 4 shows the range of reported energy intensity values (in kWh$_{T,equiv}$/m^3) for various desalination technologies. The salinities and recoveries at which the energy intensities are taken are not consistently reported in much of the literature. Therefore, no attempt has been made by the authors of this paper to adjust the reported energy intensities to consistent conditions before inclusion in Fig. 4. The figure only intends to show the reported ranges by technology. In subsequent analysis and comparisons conducted in this paper, the reported energy intensity values are adjusted to consistent recovery and salinity conditions.

As can be seen, RO has the lowest reported energy intensity of any of the technologies reviewed. For this reason, RO was identified as the SOA technology for the desalination unit operation of a membrane system. As of 2017 in the U.S., it is the only desalination technology used by seawater desalination systems for producing potable water [42]. Also as of 2017, the Carlsbad desalination facility represents the SOA energy intensity for RO systems. It uses a single-pass RO system with energy recovery, operating at an energy intensity of 2.70 kWh$_e$/m^3 at 50% recovery of 0.5% salinity product water from 3.5% salinity feedwater.[4] For lower recovery (e.g., < 50%) of product water, the energy intensity will be higher. For a thermal system, MED-TVC was identified as the SOA. The SOA energy intensity for MED-TVC as reported in the literature was found to be 11.00 kWh$_{T,equiv}$/m^3 (1.00 kWh$_e$/m^3 electrical and 10.00 kWh$_{e,equiv}$/m^3 thermal). This system operated at 220–250 kilopascal [kPa] for 33%–37.5% recovery of product water with salinity < 0.025% from feedwater with 4.5% salinity [60].

For the purposes of this paper, the TM for the desalination operation only considers its dependency on feedwater and product water salinity and recovery. This allows for equitable comparisons between the SOA and TM values. For more detailed treatise on the thermodynamic minimum for desalination, the reader is referred to several references [19,22,28,61–67]. Three of these references were used in the analysis for this paper: Mistry et al., Nayar et al., and Sharqawy et al. [61,66,67]. These references provided the equations and seawater properties used to calculate the TM for the desalination operation for the salinity and recovery conditions specified. The TM for 50% recovery of 0% salinity product water from 3.5% salinity feedwater is 1.06 kWh$_{T,equiv}$/m^3. This is used to compare the energy intensity of RO SOA. The TM for 35% recovery of 0% salinity product water from 4.5% feedwater is 1.20 kWh$_{T,equiv}$/m^3. This is used to compare the energy intensity of MED-TVC SOA.

3.4. Post-treatment

For membrane and thermal seawater desalination, post-treatment includes a combination of remineralization, disinfection, and fluoridation technologies. Thermal desalination systems remove more minerals from the water than membrane systems and therefore require more remineralization during post-treatment. Therefore, the SOA energy intensity for remineralization for membrane systems was taken as the lower bound reported in the literature, 0.04 kWh$_e$/m^3, and the upper bound of 0.07 kWh$_e$/m^3 was considered appropriate for thermal systems. The energy intensity for disinfection was assumed to be 0.04 kWh$_e$/m^3 for both systems [24,50]. The energy intensity for fluoridation was assumed to be negligible based on a review of the available literature. Therefore, the SOA energy intensity for post-treatment for membrane-based systems is estimated to be 0.08 kWh$_e$/m^3. For thermal-based systems, it is estimated to be 0.11 kWh$_e$/m^3.

For the post-treatment TM, the product water is assumed to be pure and not requiring any post-treatment. Therefore, the TM is taken to be 0 kWh$_e$/m^3.

3.5. Concentrate management

Since this paper sought to understand the lowest energy options for each component of the desalination system, open ocean discharge with dilution was selected for the concentrate management. Like the intake operation, the energy requirement of open ocean discharge is primarily due to pumping. The energy intensity was assumed to be identical to the intake energy intensity. However, for the purposes of dilution, the volume of water pumped for concentrate management will be significantly higher than the volume pumped for intake.

The SOA and TM energy intensities for each component in the desalination system for both membrane and thermal designs are summarized in Table 1. Different units are used for membrane and thermal

[2] Motor efficiency representative of a 500 hp 2-pole AC squirrel cage induction motor meeting the minimum efficiency specified in NEMA Table MG 12-12 (used to set "Premium" efficiency designation).

[3] Pump efficiency taken from manufacturer specification of a 600 hp vertical turbine pump.

[4] Author's personal communication with plant.

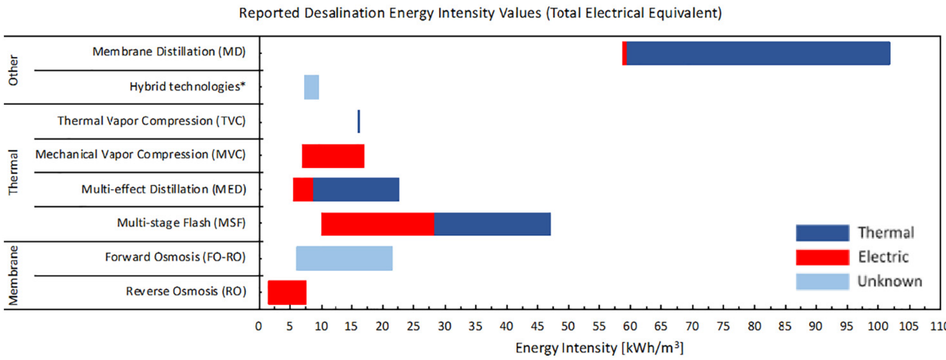

Fig. 4. Energy intensities (in $kWh_{T,equiv}/m^3$) of various seawater desalination technologies as reported in the available literature. Energy intensities have been broken down by energy source (thermal or electric). "Unknown" distinguishes technologies where the energy source was not reported. All energy intensities are reported in total electrical equivalent; the thermal energy has been multiplied by 33% to account for the amount of electricity that could be generated using the same thermal energy at the efficiency of the U.S. electrical grid [25–29,54–59].

Table 1
Energy intensities used in the analysis in this paper.

	Membrane[a] (kWh_e/m^3)		Thermal[a] ($kWh_{T,equiv}/m^3$)	
	SOA	TM	SOA	TM
Intake[b]	0.0036	0.0028	0.0036	0.0028
Pre-treatment	0.21	0	0.05	0
Desalination[c]	2.70	1.06	11.00	1.20
Post-treatment	0.08	0	0.11	0.00
Concentrate management[b]	0.0036	0.0028	0.0036	0.0028

[a] For thermal processes, energy is expressed in terms of kilowatt-hour of total electrical equivalent energy ($kWh_{T,equiv}$) which is the sum of the electrical energy (kWh_e) and the thermal energy converted to the electrical equivalent ($kWh_{e,equiv}$). Since there are no thermal requirements for the membrane processes selected here, kWh_e is sufficient to describe the energy requirement.

[b] In order to account for total dynamic head (TDH) loss, intake and concentrate management energy intensities were normalized per unit head loss (kWh_e/m^3-m TDH).

[c] For membrane: 50% recovery from 3.5% salinity feedwater. SOA and TM product water salinity is 0.5% and 0% respectively. The Carlsbad Desalination Facility was selected as representative of the SOA energy intensity for membrane technologies. For thermal: 35% recovery from 4.5% feedwater. SOA and TM product water salinity is 0.00025% and 0% respectively.

systems to retain information regarding the energy source. However, since thermal energy has been converted to electrical equivalent, the values in the table are comparable across the two system types.

Based on a review of the literature, the desalination process (RO for membrane and MED-TVC for thermal) offers the greatest opportunity for energy reduction within a desalination system. This is partly attributable to it having the highest energy intensity of any of the desalination system components. To understand the potential for future research and development to lower the SOA, calculating the TM is instructive. The SOA for the RO desalination operation is 2.5 times greater than the thermodynamic minimum at the same operating conditions. The SOA for thermal-based desalination is 9 times greater than the TM at the same operating conditions. However, the comparison between the SOA and TM should be conducted with caution. The TMs shown in Table 1 do not consider the ability for the system component to operate at the reversible limit. For an evaluation of the entropy generation associated with each of the thermodynamic processes of the various components (i.e., pumping, expanding, compressing, heating), the reader is referred to Lienhard et al. and Mistry et al. [61,68].

There are desalination technologies that have demonstrated lower energy intensities at lab-scale than the SOA cited here. One of these is semi-batch RO [69,70]. Gal & Efraty reported an energy intensity for semi-batch RO of 1.48 kWh_e/m^3 for a 556 m^3/day capacity unit operating at 42% recovery, 3.6% feedwater salinity, 0.38% product water salinity and a pressure of 4850 KPa [69]. Results from modeling show that fully-batch RO may be able to operate at even lower energy intensities, but this has not been demonstrated at physical-scale to the best of the authors' knowledge [71,72]. For thermal desalination processes, condensing MED had the lowest reported energy intensity demonstrated at lab-scale of the literature reviewed by the authors. The reported energy intensity for the condensing MED system is 4.00 $kWh_{T,equiv}/m^3$ (1.00 kWh_e/m^3 electrical and 3.00 $kWh_{e,equiv}/m^3$ thermal) for feedwater salinity of 4.5%, 33%–37.5% recovery, and product water salinity of 0.0025% [60].

4. Energy implications of greater adoption in the U.S.

The energy intensities reported above bound the maximum potential to reduce the energy requirements for each component of a seawater desalination system. To facilitate a better understanding of the magnitude of energy consumption potentially impacted by advances in seawater desalination technology, a parallel consideration is the overall impact of increased seawater desalination adoption on total U.S. energy consumption. Currently in the U.S., seawater desalination is not widely adopted and is therefore a negligible portion of total U.S. annual energy consumption. However, as water stressed regions seek alternate water sources, seawater desalination adoption may grow. To better understand the potential energy-related implications of increased adoption, estimates of the combined desalination system and pumping energy requirements to provide desalinated seawater to water-stressed counties was conducted and compared to total 2018 U.S. electricity consumption [75]. The potable water demand used in the analysis was based on the most recent USGS estimates for public water supply available at the time the analysis was conducted [47]. Note that scenarios were limited to coastal seawater desalination plus conveyance to water stressed regions. Brackish water desalination was not considered in this scenario analysis, but could provide additional alternative source of feedwater.

Two scenarios were considered. The first considered supplying potable water demand with desalinated seawater using RO membrane systems for counties with a long-term (1985–2010) WaSSI > 1. The second considered counties with a WaSSI > 0.5 over the same period. The first scenario addresses counties where water demand exceeds water replenishment rates. In these cases, water managers will be seeking alternate water sources in order to meet demand. The second scenario seeks to expand the potential market for desalinated seawater to include counties that: 1) may experience water stress on shorter time scales, 2) where factors reducing water availability could lead to water stressed conditions in the future, 3) existing replenishment rates may not meet projected demands or 4) some combination of the above. In both scenarios, 10% of the 2010 USGS estimated public water supply for these counties was considered. This value was chosen to align with the approximate share of desalinated seawater serving San Diego County (9%) as of 2017 [45].

For this evaluation, only RO was considered due to: 1) its significantly lower energy intensity than thermal systems and 2) its dominance of desalination in the U.S. (there are no thermal seawater desalination systems in the U.S. as of 2017 to the authors' knowledge).

The SOA energy intensity with open ocean intake was selected as the basis for the energy consumption projections. An implicit assumption is that any new facility built in the U.S. will follow the design implemented at Carlsbad, which is used to represent the SOA.

The system of seawater desalination facilities was designed and modeled similar to the methodology described in U.S. Department of Energy and is summarized here [23]. The seawater RO membrane-based desalination facilities are located along the coast. This minimizes the energy requirements for intake and concentrate management by reducing the distances for feedwater and concentrate pumping. Pumping energy requirements for conveying potable water to each location was based on each county's water demand, distance from the coast, and net elevation above sea level. Potable water is conveyed to the geographic centroid of each county. This determines the distances and elevations for determining the potable water pumping energy requirements. Once the potable water is pumped to the county centroid, the energy requirements for delivering it to the point of use within the county were not evaluated. ArcGIS software is used to determine the shortest distance to each county centroid from the coast without passing through Canada or Mexico. The elevation of each county centroid is determined using information from USGS [73]. An adjustment to the location of potable water pumping for Los Angeles County was made due to a significant discrepancy between the population and geographic centroids. The geographic centroid of the county is 1387 m in the mountains within the county, but the population center is in the City of Los Angeles at an elevation of 65.5 m. Given the importance of this county in terms of being water stressed with significant water demand, an adjustment was warranted.

Pumping energy is estimated using engineering equations defined in Appendix A with variables defined in Appendix B. First, the velocity of water flow through a pipe is assumed to be 1.22 m/s (4 ft/s) [74]. Combined with the volume flow, this determines the diameter of the potable water conveyance pipe for each county. With the pipe diameter and flow rate determined, a Reynolds Number is calculated. A relative pipe roughness is also determined and used to determine a Moody friction factor for each county. The work performed by the potable water conveyance pumps for each county is taken to be the sum of the friction and elevation heads. The corresponding electricity requirement in kWh_e is determined using pump and motor efficiencies. Using this methodology, the electricity requirements for pumping potable water from the nearest coastline to each county of interest is determined.

The results of the two scenarios are shown in Fig. 5. For counties 25 miles from a coastline and with a WaSSI > 1, the energy requirement for adding RO membrane seawater desalination to provide 10% of public water demand (50 MGD) is 0.2 TWh_e. If the number of counties is extended to include those with a WaSSI > 0.5, the energy requirements increase to 0.4 TWh_e to provide 76 MGD. For comparison, 1 TWh is about the annual electricity consumption of 93,000 homes in the U.S., based on an average annual electricity consumption of 10,766 kWh for a household in the U.S. [76]. Seawater desalination will likely be of greater interest to coastal counties (e.g., 25 miles from the coastline) and those further away may have better options including brackish water desalination. However, use of brackish water desalination requires the identification of a sufficient method for managing the concentrate and sustainable groundwater withdrawal. Unsustainable groundwater withdrawals can cause permanent damage to aquifers particularly during severe droughts, when communities are likely to be most reliant on it. This is the case in California's Central Valley where 2% of the aquifer storage capacity has been permanently lost due to in part to overdraft and drought [75].

For counties within a 25 mile distance from a coastline, RO membrane desalination energy requirements dominate the Total Energy Requirement (93% for WaSSI > 1, and 77% for WaSSI > 0.5). However, pumping energy requirements become more dominant as the distances from coastlines increase. For counties with a WaSSI > 1 and within 25 miles of a coastline, pumping energy is 7% of total system

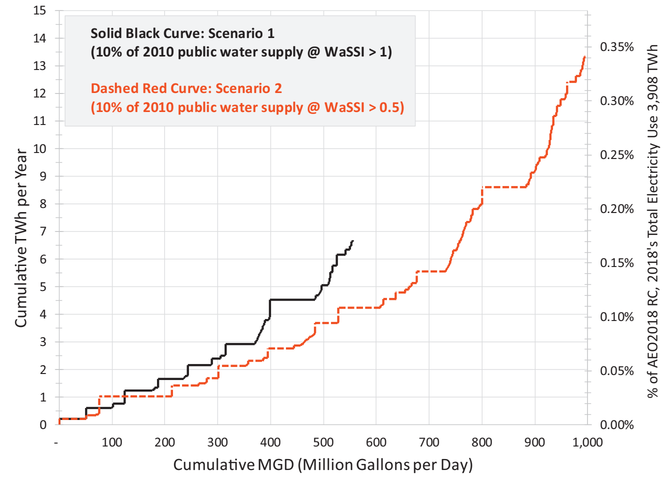

Fig. 5. Energy requirements to provide 10% of 2010 public water supply to U.S. counties with a WaSSI > 1 (Scenario 1) and WaSSI > 0.5 (Scenario 2). In both cases, RO-based systems designed and operated at the SOA energy intensities are employed. The secondary axis compares the resulting energy requirements for the scenario to the U.S. total electricity use in 2018 [77]. The graph is ordered by cumulative water production which scales with distance from a coastline. As the distance from a coastline increases, so does the cumulative water production. 1 MGD = 3785.4 m^3/day.

energy consumption. This increases to 45% for counties 250 miles from a coastline, and 65% for all distances from a coastline. Including counties with lower water stress index (WaSSI > 0.5), pumping energy becomes 23%, 40%, and 69% of the Total Energy Requirement in the 25 miles, 250 miles and all distance from a coastline groups respectively.

The breakdown of the energy requirements by distance from a coastline are shown in Table 2. The results are disaggregated into the energy required to desalinate seawater and pump potable water to the county.

In order to estimate an upper bound on the energy requirements for these two scenarios, Fig. 6 and Table 3 show the energy requirements assuming 100% of the 2010 USGS estimated public water supply intake are supplied from coastal RO membrane desalination facilities (as opposed to 10%) to the same counties (those with WaSSI > 1 and WaSSI > 0.5). While supplying all water from desalinated seawater is not recommended or a likely prospect, this upper bound scenario provides a notional maximum energy requirement for an order of magnitude larger adoption of seawater desalination.

For counties within 25 miles from a coastline and with a WaSSI > 1, the energy requirement for desalinated seawater to supply 100% of public water demand (504 MGD) increases to 2.25 TWh_e (from 0.23 at TWh_e at 10% supply). If the number of counties is extended to include those with a WaSSI > 0.5, the energy requirements increase to 3.2 TWh_e at 100% supply of 763 MGD (from 0.4 TWh_e at 10% supply).

When seawater desalination supplies 100% of public water demand, desalination energy dominates the Total Energy Requirement in all cases. Although the energy for pumping compared to the Total Energy Requirement is higher (21% in the 100% supple scenario versus 7% in the 10% supply scenario), it remains below 50% in all the distance and water stressed categories.

When considering the energy requirements for new desalination capacity, the capacity of available energy sources locally as well as the types of energy available (renewable vs. fossil sources) should be considered. Citing desalination plants in areas where the electricity grid is already under stress (e.g. not enough generation capacity is available to meet existing demand), or in areas where the grid has a large share of non-renewable and carbon intensive generation sources, may cause complications.

Table 2
Energy consumption implications of Scenarios 1 and 2. The energy requirements are broken out by distance from a coastline. The Total Energy Requirement is the sum of the Desalination Energy Requirement and the Pumping Energy Requirement. The percentage of 2018 U.S. electricity consumption is calculated by comparing the Total Energy Requirement to U.S. total electricity use in 2018 [77]. 1 MGD = 3785.4 m^3/day.

RO membrane seawater desalination supplying 10% of 2010 public water supply intake to water stressed US counties		Distance from coastline		
		25 miles	250 miles	Entire continental US
Scenario 1 (WaSSI > 1)	Cumulative MGD (million gallons per day)	50	288	555
	Desalination Energy Requirement (TWh_e)	0.2	1.2	2.3
	Pumping Energy Requirement (TWh_e)	0.02	1.0	4.4
	Total Energy Requirement (TWh_e)	0.2	2.2	6.7
	% of 2018 U.S. electricity consumption	0.01%	0.06%	0.17%
	Desalination % of Total Energy Requirement	92.5%	55.0%	34.6%
Scenario 2 (WaSSI > 0.5)	Cumulative MGD (million gallons per day)	76	527	994
	Desalination Energy Requirement (TWh_e)	0.3	2.2	4.1
	Pumping Energy Requirement (TWh_e)	0.1	1.5	9.2
	Total Energy Requirement (TWh_e)	0.4	3.7	13.3
	% of 2018 U.S. electricity consumption	0.01%	0.09%	0.34%
	Desalination % of Total Energy Requirement	77.1%	60.1%	31.2%

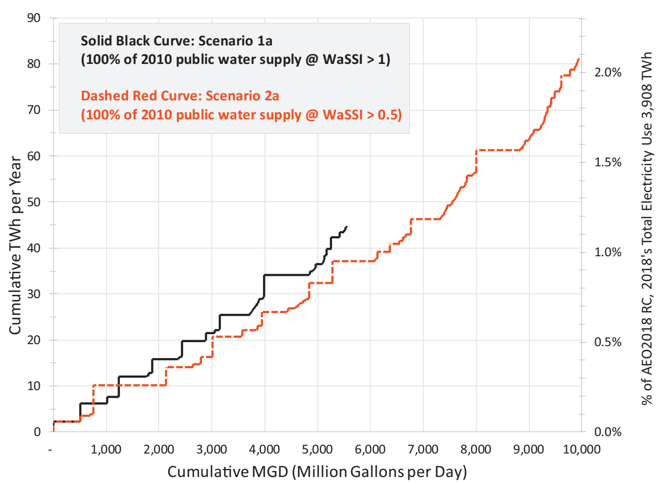

Fig. 6. Energy requirements to provide 100% of 2010 public water supply intake to U.S. counties with a WaSSI > 1 (Scenario 1a) and WaSSI > 0.5 (Scenario 2a). In both cases, RO-based systems designed and operated at the SOA energy intensities are employed. The secondary axis compares the resulting energy requirements for the scenario at a distance from a coastline to the U.S. total electricity use in 2018 [77]. The graph is ordered by cumulative water production which scales with distance from a coastline. As the distance from a coastline increases, so does the cumulative water production. 1 MGD = 3785.4 m^3/day.

5. Discussion

The two scenarios explored are intended to inform the energy needs associated with greater adoption of RO membrane-based seawater desalination in the U.S. This information can help regional energy and water planners understand the energy infrastructure required if they are considering increasing adoption seawater desalination. However, energy is one of many factors when considering greater adoption of seawater desalination.

First presented in Rao et al., Fig. 7 shows some of the considerations when evaluating any (membrane or thermal) seawater desalination system [78]. These considerations can be broadly categorized as: 1) process requirements and 2) system impacts. The first includes understanding the water, chemical, and energy requirements to treat the incoming water and resulting concentrate based on the desired quality of the product water. The system impacts include economic and environmental impacts of the system. For each consideration, several parameters are identified to provide further insight.

Economic and environmental considerations are two important factors that can influence how the scenario results are interpreted. The cost of desalinated water includes the initial capital cost for the entire desalination system, the infrastructure for supplying that water to the counties, and the operating cost of the system (e.g. cost of energy, chemicals, labor). This cost, along with the cost for regulatory compliance, is an important barrier that should be considered when evaluating greater adoption of seawater desalination. Another factor

Table 3
Energy consumption implications of Scenarios 1a and 2a where 100% of all public water supply is supplied by RO membrane-based seawater desalination. The energy requirements are broken out by distance from a coastline. The Total Energy Requirement is the sum of the Desalination Energy Requirement and the Pumping Energy Requirement. The percentage of 2018 U.S. electricity consumption is calculated by comparing the Total Energy Requirement to U.S. total electricity use in 2018 [77]. 1 MGD = 3785.4 m^3/day.

RO membrane seawater desalination supplying 100% of 2010 public water supply intake to water stressed US counties		Distance from coastline		
		25 miles	250 miles	Entire continental US
Scenario 1a (WaSSI > 1)	Cumulative MGD (million gallons per day)	504	2877	5553
	Desalination Energy Requirement (TWh_e)	2.1	12.0	23.1
	Pumping Energy Requirement (TWh_e)	0.2	7.8	21.6
	Total Energy Requirement (TWh_e)	2.3	19.8	44.8
	% of 2018 U.S. electricity consumption	0.06%	0.51%	1.15%
	Desalination % of Total Scenario Energy	93.3%	60.6%	51.7%
Scenario 2a (WaSSI > 0.5)	Cumulative MGD (million gallons per day)	763	5273	9938
	Desalination Energy Requirement (TWh_e)	3.2	22.0	41.4
	Pumping Energy Requirement (TWh_e)	0.8	10.0	39.2
	Total Energy Requirement (TWh_e)	4.0	32.0	80.7
	% of 2018 U.S. electricity consumption	0.10%	0.82%	2.06%
	Desalination % of Total Scenario Energy	79.1%	68.7%	51.3%

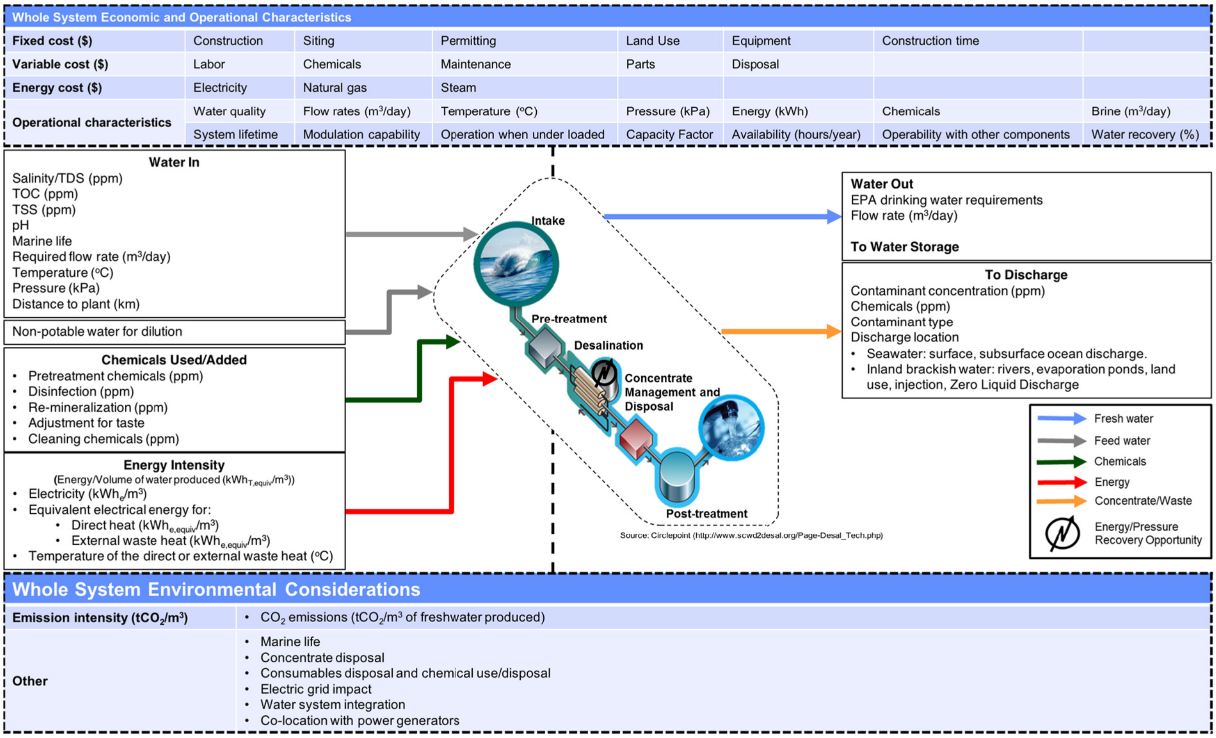

Fig. 7. Considerations for seawater desalination, including characteristics of the feedwater, chemical requirements, energy consumption, product water requirements, concentrate characteristics, environmental considerations for the whole system, and economic considerations including capital and operating costs. For each consideration, metrics to consider are highlighted.
Figure from Rao et al. [78].

contributing to high cost of desalinated water is the difficulty in acquiring the coastal land and required permits for development. Devising novel approaches such as innovative financing schemes and more streamlined permitting processes could potentially address those barriers. Further, if a facility can attain low cost energy, then the economic concerns over energy consumption could be alleviated to such an extent that energy may no longer be a concern. Low cost energy may even dictate the technology selections: if no-cost utilizable sufficient waste heat is available, then a thermal desalination system may be more economically competitive with an RO-system. Similarly, powering the desalination process with renewable energy may become a more attractive option to achieve cost reductions as renewable energy technologies mature. Between 1974 and 2009, 131 renewable energy desalination plants were installed worldwide, with 36% powered by solar-thermal, 34% by photovoltaics, and the balance by wind, hybrid or other technologies [79].

Fig. 7 may also help identify additional value from seawater desalination beyond the water it provides. For example, seawater desalination could facilitate the integration of renewable energy. With many U.S. states pursuing ambitious renewable portfolio standards, the electricity grid requires a large share of storage capacity and flexible loads to address the variability of renewable generation. Dynamic loads that can adjust their demand based on real-time grid conditions will become valuable resources to the grid operator. In particular, dispatchable electricity uses that can utilize excess renewable electricity generation will be needed. Large desalination plants, capable of modulating their demand or storing excess energy in the form of treated water during periods of excess generation, could be a valuable resource for balancing the grid and facilitating higher penetration of renewable sources.

As suggested by the scenario analysis in the previous section, seawater desalination alone is not a feasible solution to provide water to all water stressed U.S. counties. Therefore, desalination should be part of a portfolio of solutions. Other water sources might include brackish water, water reuse/recycling, and storm water capture. Additionally, water conservation can be considered another source as it reduces demand. A schedule of options ordered by their marginal cost of water production ($\$/m^3$) could help regional planners better compare water supply options.

A challenge to developing such a schedule is determining the real value of water. Currently available water sources across the nation are heavily subsidized [80] and the current price of water does not reflect its real value. An artificially low price of freshwater puts other alternatives such as conservation and seawater desalination at a disadvantage. Increasing inability to meet water demands (current or projected) could potentially drive policy makers to re-evaluate the pricing of water.

6. Conclusion

This paper identified the SOA and TM energy requirements for each component of a seawater desalination system for providing potable water. Using the SOA energy intensity for an RO membrane-based system, the energy requirements for broader adoption of seawater desalination in the U.S. was evaluated. This was done by considering scenarios where RO membrane-based seawater desalination systems are used to meet the public water demand for water-stressed counties in the U.S. Using the definitions of water-stressed employed in this paper, the energy requirement for serving the 10% of the potable water needs of water stressed communities within 25 miles of a coastline through seawater desalination is 0.2 TWh_e (WaSSI > 1; 50 MGD)–0.4 TWh_e (WaSSI > 0.5; 76 MGD).

The results of this paper can be used to develop energy reduction targets for research and development portfolios focused on seawater desalination systems. They are also useful to water planners seeking to better understand the energy infrastructure requirements of expanded seawater desalination capacity in the U.S. The intent of this paper is to better understand the energy implications of seawater desalination.

This alone is not sufficient to remove barriers to its broader adoption, and further economic and environmental analysis and research is required.

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Appendix A. Pumping load methods and equations

Table A1
Parameters and equations used to determine pumping energy consumption for each county under each scenario.

	Variable units
Variable	
Flow (potable water being pumped)	m^3/s
Velocity (of potable water in pipes)	m/s
Static head (elevation relative to sea level)	m
Distance (between coasts and potable water demand)	m
Specific roughness (specific to pipe material; plain cast iron = 0.0008)	m
Viscosity (water at 21 °C and atmospheric pressure = 0.0000141)	m^2/s
Gravitational constant = 9.8	m/s^2
Moody friction factor (from tables, based on relative roughness factor and Reynolds number)	
Potable water conveyance pump efficiency = 90%	
Potable water conveyance motor efficiency = 95%	
Equations	
Eq. (1) $Diameter = 2 \times \sqrt{\frac{Flow}{Velocity} \times \frac{1}{\pi}}$	m^2
Eq. (2) $\text{Relative Roughnes} = \frac{\text{Specific Roughness}}{\text{Diameter}}$	m
Eq. (3) $\text{Reynolds Number} = \text{Diameter} \times \frac{\text{Velocity}}{\text{Viscosity}}$	N/A
Eq. (4) $\text{Friction Head} = \frac{\text{Moody Friction Factor} \times \text{Distance} \times \text{Velocity}^2}{2 \times \text{Diameter} \times \text{Gravitational Constant}}$	m
Eq. (5) $\text{Total Pump Head} = \textit{Friction Head} + \textit{Elevation Head}$	m
Eq. (6) $\text{Pump Power} = \frac{\text{Total Pump Head} \times \text{Flow Rate}}{3956}$	kW
Eq. (7) $\text{Pumping Electric Load} = \frac{\text{Pump Horsepower} \times 0.7457}{\textit{Pump Efficiency} \times \textit{Motor Efficiency}}$	kW
Eq. (8) $\text{Pumping Electric Energy} = \text{Pumping Electric Load} \times 8760$	kWh_e
Eq. (9) $\text{Total Electric Energy} = \text{Desalination Electrical Energy} + \text{Pumping Electric Energy}$	kWh_e

Appendix B. Scenario parameter assumptions

Table B1
Parameters used in evaluation of Scenario 1 and 2 for 10% of public water supply.

Variable	Black curve	Red curve
Legend name	Black curve: Scenario 1 (WaSSI > 1)	Red curve: Scenario 2 (WaSSI > 0.5)
Capacity factor (8760 h/year)	1	1
Velocity (ft/s)	4	4
Pump efficiency	0.81	0.81
Motor efficiency	0.958	0.958
Los Angeles County, CA elevation (ft)	215	215
Flow rate assumption	USGS public supply intake (MGD)	USGS public supply intake (MGD)
Distance assumption	No crossing Canada or Mexico	No crossing Canada or Mexico

(*continued on next page*)

Table B1 (*continued*)

Variable	Black curve	Red curve
Percent of public water demand	10%	10%
WASSI factor	Mean WaSSI	Mean WaSSI
WASSI limit	1.0000	0.5000
Piping roughness factors	Plain cast iron	Plain cast iron
System type	RO SOA	RO SOA

Table B2
Parameters used in evaluation of Scenario 1 and 2 for 100% of public water supply.

Variable	Black curve	Red curve
Legend name	Black curve: Scenario 1 (WaSSI > 1)	Red curve: Scenario 2 (WaSSI > 0.5)
Capacity factor (8760 h/year)	1	1
Velocity (ft/s)	4	4
Pump efficiency	0.81	0.81
Motor efficiency	0.958	0.958
Los Angeles County, CA elevation (ft)	215	215
Flow rate assumption	USGS public supply intake (MGD)	USGS public supply intake (MGD)
Distance assumption	No crossing Canada or Mexico	No crossing Canada or Mexico
Percent of public water demand	100%	100%
WASSI factor	Mean WaSSI	Mean WaSSI
WASSI limit	1.0000	0.5000
Piping roughness factors	Plain cast iron	Plain cast iron
System type	RO - SOA	RO - SOA

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