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Bandwidth Study on Energy Use and Potential Energy Savings Opportunities in U.S. Seawater Desalination Systems

October 2017

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Preface

Reducing energy consumption through investment in advanced technologies and practices can enhance American manufacturing competitiveness. Energy bandwidth studies of U.S. industrial sectors serve as general data references to help understand the range (or *bandwidth*) of potential energy savings opportunities.[1] The U.S. Department of Energy's (DOE's) Advanced Manufacturing Office (AMO) has commissioned a bandwidth study to analyze the different unit operations used for seawater desalination for municipal (defined here as systems serving more than 10,000 people) systems providing potable water, and provide hypothetical, technology-based estimates of potential energy savings opportunities across the desalination system. The consistent methodology used in the bandwidth studies provides a framework to evaluate and compare energy savings potentials within and across sectors of energy end use.

Four different energy *bands* (or measures) are used consistently in this series to describe different levels of on-site energy consumption, to utilize specific unit operations and to compare potential energy savings opportunities in U.S. seawater desalination plants (see Figure P-1). **Current typical** (CT) refers to U.S. energy consumption in 2016; **state of the art** (SOA) is the energy consumption that may be possible through the adoption of existing best technologies and practices available worldwide; **practical minimum** (PM) is the energy consumption that may be possible if applied R&D technologies under development worldwide are deployed; and the **thermodynamic minimum** (TM) is the least amount of energy required under ideal conditions, which cannot be attained in commercial applications. CT energy consumption serves as the benchmark of seawater desalination energy consumption for this study. TM energy consumption serves as the theoretical minimum that is used in calculating energy savings potential.

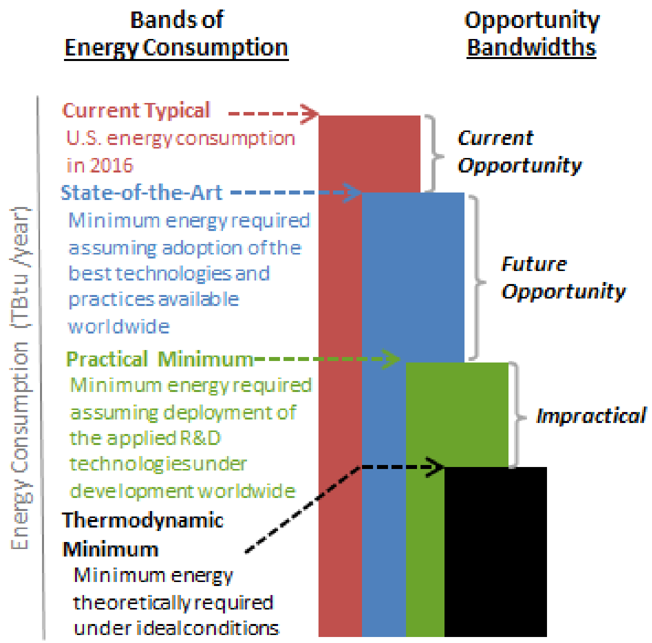

Figure P-1. Energy consumption bands and opportunity bandwidths estimated in this study
Source: EERE

Two on-site energy savings opportunity bandwidths are estimated: the ***current opportunity*** spans the bandwidth from CT energy consumption to SOA energy consumption, and the ***R&D opportunity*** spans the bandwidth from SOA energy consumption to PM energy consumption. The difference between PM energy consumption and TM energy consumption is labeled as *impractical*—a term that is used because the PM energy consumption is based on today's knowledge of research and development (R&D) technologies tested between laboratory and demonstration scale; further decreases in energy intensity have not been defensibly displayed at any physical scale to the best of the authors' knowledge at the time of this report. However, decreasing the PM energy consumption with future R&D efforts in desalination is evident, and emerging technologies being investigated through modeling and theoretical calculations may eventually indicate that the PM energy consumption may move closer to the TM energy consumption.

[1] The concept of an energy bandwidth, and its use as an analysis tool for identifying potential energy saving opportunities, originated in AMO in 2002 (when it was called the *Office of Industrial Technologies*). Most recently, revised and consistent versions of bandwidth studies for the *Chemicals*, *Petroleum Refining*, *Iron and Steel*, and *Pulp and Paper* sectors were published in 2015.

Significant investment in technology development and implementation would be needed to fully realize the energy savings opportunities estimated. The study did not consider the costs associated with achieving SOA and PM energy consumption. However it does provide a brief analysis on the impact on the total cost of water from the energy savings realized through adoption of the technologies identified. A comprehensive techno-economic analysis of the costs and benefits of future R&D technologies was not in the scope of this study.

The four energy bands are estimated for select individual unit operations of the seawater desalination process. The estimation method involved a detailed review and analytical synthesis of data from diverse industry, governmental, and academic sources. Where published data were unavailable, best engineering judgment was used. This report builds upon the foundational information and analysis approach described in *Volume 1: Survey of Available Information in Support of the Energy-Water Bandwidth Study of Desalination Systems* (Rao, et al. 2016).

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List of Acronyms and Abbreviations

AEO	Annual Energy Outlook (from the U.S. Energy Information Administration)
AMO	Advanced Manufacturing Office
bbl	barrel (1 bbl = 40 gal)
Btu	British thermal unit
BBtu	billion British thermal unit (1 BBtu = 0.2931 GWh)
BWRO	brackish water reverse osmosis
CO_2	carbon dioxide
CT	current typical energy consumption/intensity or CO_2 emission/intensity
DAF	dissolved air flotation
DOE	U.S. Department of Energy
ED	electrodialysis
EDR	electrodialysis reversal
EERE	DOE Office of Energy Efficiency and Renewable Energy
EPA	U.S. Environmental Protection Agency
ERD	energy recovery device
FO	forward osmosis
G	Gibbs free energy (available energy)
gal	gallon
GOR	gained output ratio
GWh	gigawatt-hour
GWI	Global Water Intelligence
hp	horsepower
K	kelvin
kgal	kilogallon (1 kgal = 3.785 m^3)
kPa	kilopascal
kW	kilowatt
kWh	kilowatt-hour
kWh_e	kilowatt-hour of electrical energy
$kWh_{e,equiv}$	kilowatt-hour of electrical equivalent thermal energy
$kWh_{T,equiv}$	kilowatt-hour of total electrical equivalent energy (kWh_e+$kWh_{e,equiv}$)
lb	pound
lb_f	pound-force
lb_m	pound-mass
m^3	cubic meter (1 m^3 = 0.2642 kgal)
MD	membrane distillation
MED	multi-effect distillation
MF	microfiltration
MGD	million gallons per day
MMBtu	million British thermal units
MMton	million short tons (ton) (1 ton = 2,000 lb = 0.9072 tonne = 907.2 kg)
MSF	multi-stage flash
MT	metric ton (tonne) (1 tonne = 1,000 kg = 1.102 tons = 2,204.6 lb)
Mton	thousand short tons

MVC	mechanical vapor compression
NF	nanofiltration
PFD	process flow diagram
PM	practical minimum energy consumption/intensity or CO_2 emission/intensity
ppm	parts per million
RO	reverse osmosis
rpm	revolutions per minute
SOA	state of the art energy consumption/intensity or CO_2 emission/intensity
SWRO	seawater reverse osmosis
TBtu	trillion British thermal units
TDH	total dynamic head
TDS	total dissolved solids
TM	thermodynamic minimum energy consumption/intensity
TWh	terawatt-hour
µm	micrometer
USGS	U.S. Geological Survey
WaSSI	Water Supply Stress Index
ZLD	Zero liquid discharge

Executive Summary

Desalination is a long-standing method for increasing fresh water availability through use of saline feedwater. This bandwidth study examines energy consumption, carbon dioxide (CO_2) emissions, and potential energy savings opportunities in U.S. seawater desalination systems producing municipal potable water at municipal scales (defined here as serving more than 10,000 people). Industrial, government, and academic data were used to estimate the energy consumed in the five main unit operations of a desalination system. These five main operations are intake, pre-treatment, desalination process, post-treatment, and concentrate management. Three different energy consumption *bands* (or levels) were estimated for these select unit operations based on referenced energy intensities of current, state of the art, and R&D technologies. A fourth theoretical minimum energy consumption *band* was also calculated. The *bandwidth*—the difference between bands of energy consumption—was used to determine the potential energy savings opportunity. While the costs associated with realizing these energy savings was not in the scope of this study, the impact on total cost of water attributable to the reduction in energy intensity for each band was estimated. The energy cost saving associated with current and R&D opportunities are realizable; however, the energy cost saving associated with achieving the thermodynamic minimum is not realizable since no commercial technology will be able to operate at the thermodynamic limit.

The complete information for this study is provided in two volumes. *Volume 1: Survey of Available Information in Support of the Energy-Water Bandwidth Study of Desalination Systems* (Rao, et al. 2016) reviewed the parameters that affect energy, emissions, and cost considerations, and provides background research and a framework for volume 2, the *Bandwidth Study on Energy Use and Potential Energy Savings Opportunities in U.S. Seawater Desalination Systems* (this report). Readers should refer to Volume 1 for an explanation of the boundary analysis framework established as a basis for this report, background research conducted on the current typical energy intensities for five unit operations of desalination, an overview of the thermodynamic minimum for seawater desalination, and information on the framework for establishing desalination uptake scenarios. The division of topics addressed in each report is outlined in Table ES-1.

Table ES-1. Contents of Volume 1 and Volume 2 Reports

Volume	Contents
Volume 1: Survey of Available Information in Support of the Energy-Water Bandwidth Study of Desalination Systems	• Boundary Analysis Framework • Energy Intensities for Five Desalination System Unit Operations • Framework for Establishing Desalination Uptake Scenarios
Volume 2: Bandwidth Study on Energy Use and Potential Energy Savings Opportunities in U.S. Seawater Desalination Systems (this report)	• Energy Consumption and CO_2 Emissions for Seawater to Municipal Potable Water Evaluated at: o Current Typical (CT) Energy and CO_2 Intensity o State of the Art (SOA) Energy and CO_2 Intensity o Practical Minimum (PM) Energy and CO_2 Intensity o Thermodynamic Minimum (TM) Energy Intensity • Energy Savings from Current and R&D Advancements Opportunity • Energy Consumption and CO_2 Emissions for Brackish Water to Municipal Water at CT Energy and CO_2 Intensity

The purpose of this data analysis is to provide macro-scale estimates of energy and related cost savings opportunities for each desalination unit operation. This is a step toward understanding the processes that could most benefit from technology and energy efficiency improvements.

Study Organization and Approach: The present document is organized as described below. The organization reflects the study approach.

- Chapter 1 provides an overview of the bandwidth methodology and boundaries.
- Chapter 2 provides an overview of desalination systems and identifies 2016 U.S. production capacities.
- Chapter 3 estimates current typical (CT) energy consumption and CO_2 emissions for five select unit operations and system-wide for seawater desalination systems.
- Chapter 4 estimates the state of the art (SOA) energy consumption and CO_2 emissions for five select unit operations and system-wide for seawater desalination assuming adoption of best available technologies and practices worldwide.
- Chapter 5 estimates the practical minimum (PM) energy consumption and CO_2 emissions for five select unit operations and system-wide for seawater desalination assuming the deployment of applied R&D technologies available worldwide.
- Chapter 6 estimates the thermodynamic minimum (TM), i.e., the minimum amount of energy theoretically required, for five select unit operations and system-wide for seawater desalination, assuming ideal conditions.
- Chapter 7 provides the estimated Current and R&D energy savings opportunity *bandwidths*, i.e., the differences between the energy consumption *bands* (CT, SOA, PM, TM).
- Chapter 8 provides analysis on the impact on the cost of product water from the energy intensity reductions associated with each band.
- Chapter 9 provides the hypothetical energy consumption under various scenarios where seawater desalination has greater uptake in the United States.
- Chapter 10 provides a summary and conclusion.

This study estimated CT, SOA, PM, and TM energy consumption and CT, SOA, and PM CO_2 emissions for five *individual* desalination unit operations from multiple referenced sources. The focus of this bandwidth study is on seawater desalination in the United States, but the current typical (CT) energy intensity measure was investigated for brackish desalination systems due to the large current domestic presence of the technology.

Study Results: Two on-site energy savings opportunity *bandwidths*—current opportunity and R&D opportunity—are presented in Table ES-2 and Figure ES-1 for seawater desalination systems producing potable water for municipal systems in the United States in billion British thermal units (BBtu) per year.[2] The system featured in Table ES-2 and Figure ES-1 is reverse osmosis (RO)-based, utilizing an open-ocean intake and corresponding pre-treatment, operating at 50% recovery to supply 500 parts per million (ppm) total dissolved solids (TDS) product water from 35,000 ppm feedwater for the CT, SOA, and TM energy consumption, and operating at 42% recovery to supply 379 ppm product water from 36,357 ppm feedwater for the PM energy consumption. Different recoveries and feed and product water salinities are noted, as they provide the necessary contextual information for evaluating the available energy intensity data in the literature. In this report, *recovery* is defined as the percentage of feedwater converted to product water across the desalination unit operation. The *current opportunity* is the difference between the reference 2016 CT energy consumption and estimated SOA energy consumption; the *R&D opportunity* is the difference between estimated SOA energy consumption and the estimated PM energy consumption. Potential energy savings opportunities are presented as a total and broken out by unit operation—intake, pre-treatment, desalination, post-treatment, and concentrate management. The energy consumption for intake and concentrate management will be site specific and depend on characteristics such as distance and elevation from/to the source/disposal site. To develop national estimates, these influences have been normalized by assuming minimal elevation gain and distances. Further, the energy savings opportunities presented reflect the estimated production of potable drinking water in the United States <u>in baseline year 2016</u>. This is important to note for two reasons. First, there

[2] The energy estimates presented in this study are for macro-scale consideration; energy intensities and energy consumption values do not represent energy consumption in any specific facility or any particular region in the United States. The costs associated with achieving energy savings are not considered in this study. All estimates are for on-site energy consumption (i.e., energy consumed within the plant boundary).

is a distribution in capacity of the seawater desalination systems operating in the United States in 2016, ranging from small community scale to large municipal scale. Due to insufficient data availability, this report does not consider the effect of system capacity on the energy intensity of each unit operation. Second, potable water production from desalination has seen growth in the past several years, especially with increased application in areas with historic and projected water scarcity. Therefore, it is important to note that the total energy opportunities would scale with increasing production. This is further explored through analysis of various uptake scenarios in Chapter 9.

Table ES-2. Potential On-site Energy Savings Opportunities in the United States for Seawater Desalination Systems Producing Potable Water

Opportunity Bandwidths	Estimated On-site Energy Savings Opportunity (per year)
Current Opportunity – energy savings if the best technologies and practices available are used to upgrade production	**320 BBtu[3] (94 GWh)** (28% energy savings)[4]
R&D Opportunity – additional energy savings (to the Current Opportunity) if the applied R&D technologies under development worldwide are deployed	**544 BBtu[5] (160 GWh)** (47% energy savings)[6]

[3] Current opportunity = CT – SOA, as shown in Table 4-2.
[4] Current opportunity (or SOA) percentage = $\left(\frac{CT-SOA}{CT-TM}\right) x100$, as shown in Table 4-2.
[5] R&D opportunity = SOA – PM, as shown in Table 5-2.
[6] R&D opportunity percentage = $\left(\frac{SOA-PM}{CT-TM}\right) x100$, as shown in Table 5-2.

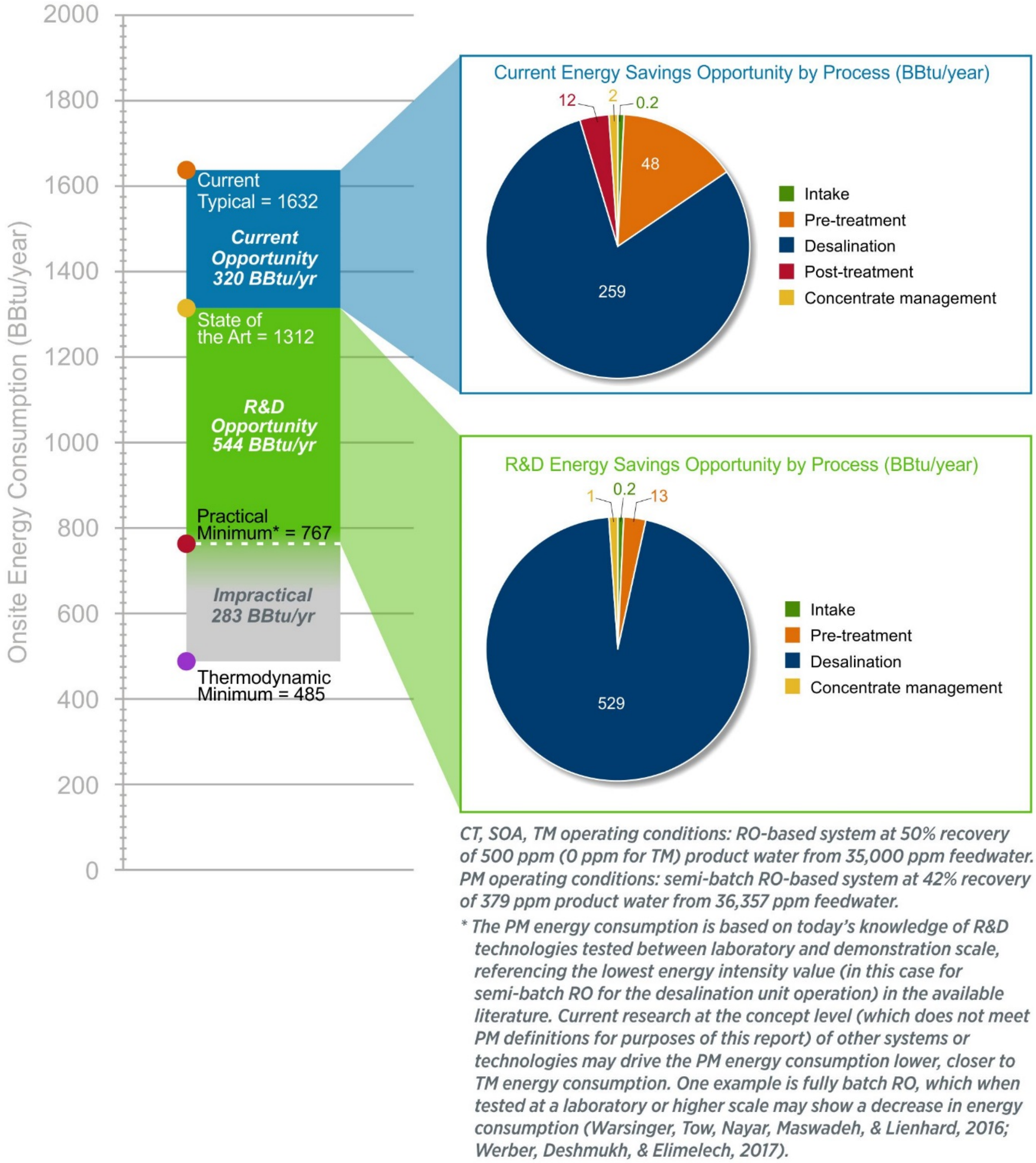

Figure ES-1. Current and R&D energy savings opportunities for the seawater desalination system unit operations studied
Source: EERE

The PM energy consumption estimates are speculative because they are based on technologies that are currently unproven at large scale. The estimates assume the successful deployment of R&D technologies that are under development; where multiple technologies were considered for a similar application, only the most energy efficient technology was considered in the energy savings estimate. The difference between PM and TM is labeled "impractical" in Figure ES-1 because the PM energy consumption is based on today's knowledge of R&D technologies tested between laboratory and demonstration scale; further decreases in energy intensity have not been displayed at any physical scale. However, it is shown as a dashed line with color fading because decreasing the PM energy consumption with future R&D efforts in desalination is evident at the time of publication. Emerging technologies being investigated through modeling and theoretical calculations may eventually bring the PM energy consumption further into the faded region and closer to the TM energy consumption. One example of a desalination technology that claims energy savings potential when modeled and/or evaluated theoretically but has not been demonstrated at physical scale (and therefore does not meet PM definitions for the purposes of this report) is fully batch RO. Models of its energy intensity show a decrease in energy consumption over the technology chosen for the PM in this report (semi-batch RO), but has not yet been demonstrated at the laboratory or higher scale (Warsinger, et al. 2016, Werber, Deshmukh and Elimelech 2017). Decreasing energy consumption beyond the TM level is not possible. The TM energy intensity represented here is a lower level that will apply to any technology seeking to achieve the desired output product (e.g., potable, or drinking, water) from seawater.

An estimated 1,632 BBtu (478 gigawatt-hours [GWh]) of on-site energy was consumed under the CT band for U.S. seawater desalination systems in 2016, for a total operating seawater desalination capacity of 128 million cubic meters (m^3)/year (33.7 billion gallons/year). This estimate is based on the current energy intensity of all seawater to potable water desalination systems in the United States in 2016. As a point of reference, the energy consumption for sourcing the same volume of water from freshwater instead would be 127 BBtu (37 GWh), assuming a national energy intensity for freshwater extraction, conveyance, and treatment of 0.29 kilowatt-hours of electrical energy per cubic meter (kWh_e/m^3). This national average varies throughout the United States; in Southern California it is 2.6 kWh_e/m^3, and the resulting energy consumption for sourcing the same volume of potable water but from freshwater in Southern California is 1,136 BBtu (333 GWh).

Based on the results of the current study, an estimated annual on-site energy savings of 320 BBtu could be expected if capital investments in the best technologies and practices available worldwide were used to upgrade the desalination system unit operations studied as applicable (*Current Opportunity* in Table ES-2); an additional 544 BBtu could be saved through the adoption of applied R&D technologies under development worldwide (*R&D Opportunity in* Table ES-2). Adoption of applied R&D technologies to current U.S. seawater desalination systems could realize a 33% reduction in total water cost.

The top three current energy savings opportunities for the unit operations are as follows:

- Desalination – 259 BBtu (76 GWh: 81% of the current opportunity)
- Pre-treatment – 48 BBtu (14 GWh: 15% of the current opportunity)
- Post-treatment – 12 BBtu (3 GWh: 4% of the current opportunity)

The top three R&D energy saving opportunities for the unit operations are as follows:

- Desalination – 529 BBtu (155 GWh: 97% of the R&D opportunity)
- Pre-treatment – 13 BBtu (4 GWh: 2% of the R&D opportunity)
- Concentrate management – 1 BBtu (0.4 GWh: 0.2% of the R&D opportunity)

The CT energy consumption for seawater desalination in the United States in 2016 resulted in an estimated 282 thousand short tons (Mton) (256 kilotonnes) of carbon dioxide (CO_2) emissions. This is equivalent to the annual emissions from 54,010 passenger vehicles.

To better understand the implications of wider adoption of seawater desalination to meet U.S. municipal water demand, this report examined the energy consumption implications associated with two uptake scenarios:

1) Providing desalinated seawater for all public water demand for counties within 25 miles and 250 miles of a coastline, and the entire continental United States
2) Providing desalinated seawater for all public water demand for water-stressed counties within 25 miles and 250 miles of a coastline, and the entire continental United States

The results of the scenario analyses are shown in Table ES-3.

Table ES-3. Estimated Energy Requirements for the Desalination System (Intake, Pre-treatment, Desalination, Post-treatment, Concentrate Management) and Potable Water Conveyance Pumping (From Desalination Facility to Points of Water Demand) Under Scenarios of Increased Seawater Desalination Uptake Scenarios

	Distance from Coastline	25 Miles	250 Miles	Entire Continental U.S.
Scenario 1: All Counties	Desalination System Energy Requirement (terawatt-hours, TWh)	34	105	171
	Potable Water Conveyance Pumping Energy Requirement (TWh)	4	27	75
	Total (Desalination System + Potable Water Conveyance Pumping) Energy Requirement (TWh)	38	132	246
	Percentage of 2017 U.S. electricity consumption	1%	3.4%	6.3%
	Desalination System Energy Percent of Total Energy	89%	80%	69%
Scenario 2: Water-Stressed Counties	Desalination System Energy Requirement (TWh)	2	12	23
	Potable Water Conveyance Pumping Energy Requirement (TWh)	0.1	7	14
	Total (Desalination System + Potable Water Conveyance Pumping) Energy Requirement (TWh)	2	19	37
	Percentage of 2017 U.S. electricity consumption	0.1%	0.5%	1.0%
	Desalination System Energy Percent of Total Energy	94%	65%	62%

The results of these scenarios, which are fully discussed in Chapter 9, estimate the electrical energy consumption associated with using SOA seawater desalination systems to produce potable water at the coast and pump it to population centers in the continental United States. Scenario 1 would require approximately 38 TWh to supply populations within 25 miles of a coastline (equating to 1% of 2017 U.S. electricity consumption), 132 TWh for those 250 miles of a coastline (3.4%), and 246 TWh (6.3%) for the entire continental United States. If all water-stressed counties were to be provided 100% of their municipal potable water through seawater desalination (scenario 2), electricity production would need to increase 1% over estimated 2017 U.S. electric grid production. This information can be useful towards understanding the impact on national electricity production if potable water from seawater desalination were to become a much larger portion of municipal water supply than it is today.

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1. Introduction

1.1. Overview

This bandwidth study examines energy consumption and potential energy savings opportunities in U.S. seawater desalination for the production of potable water at municipal scales. For the purposes of this report, *municipal-scale* systems are defined as those serving more than 10,000 people. This definition encompasses systems that serve 78% of the U.S. population in 2011 (EPRI 2013). The purpose of this data analysis is to provide macro-scale estimates of on-site energy savings opportunities for desalination unit operations and system-wide. In this study, four different energy consumption *bands* (or measures) were estimated. The *bandwidth*—the difference between bands of energy consumption—is the estimated potential energy savings opportunity.

The four bands of energy consumption estimated in this report include: the on-site energy consumption associated with seawater desalination unit operations using the 2016 installed production capacity values; (two hypothetical energy consumption levels with progressively more energy efficient technologies and practices (state of the art and practical minimum); and one energy consumption level based on the minimum amount of energy needed to theoretically complete a desalination unit operation (thermodynamic minimum). The bands of energy consumption are used to calculate *current* and *R&D opportunity* bandwidths for energy savings.

1.2. Comparison to Other Bandwidth Studies

Energy bandwidth studies have previously only been prepared by the U.S. Department of Energy's Advanced Manufacturing Office (AMO) for manufacturing sectors (see inset), and this desalination bandwidth is the first for a different type of industrial sector. The U.S. manufacturing industries for which energy bandwidth studies have been completed include eight traditional sectors: chemicals, iron and steel, petroleum refining, pulp and paper, food and beverage products, cement, glass, and plastic and rubber products. They also include six studies to characterize the energy use in manufacturing lightweight structural materials in the United States: aluminum, magnesium, titanium, advanced high strength steel, carbon fiber reinforced polymer composites, and glass fiber reinforced composites (U.S. Department of Energy 2017). These studies followed the same analysis methodology and presentation format as the previous energy bandwidth studies.

Collectively, these studies explore the potential energy savings opportunities available through existing technology and with investment in research and development (R&D) technologies. Unlike previous bandwidth studies, this seawater desalination study

History of DOE Advanced Manufacturing Office Energy Bandwidth Reports

Before 2013, the U.S. Department of Energy (DOE)'s Industrial Technologies Program (now known as the Advanced Manufacturing Office [AMO]) conducted industrial sector analyses (not necessarily conducted harmoniously) meant to quantify savings opportunities.

- 2013: Developed and refined a consistent methodology for bandwidth studies such that comparisons could be made across the manufacturing sectors.
- 2015: Published revised reports for four U.S. manufacturing sectors: chemicals, iron and steel, petroleum refining, and pulp and paper.
- 2016: Published six additional bandwidth studies on the energy use in manufacturing lightweight structural materials (aluminum, magnesium, titanium, advanced high strength steel, carbon fiber reinforced polymer composites, and glass fiber reinforced composites) in the United States, following the same analysis methodology and presentation format.
- 2017: Prepared bandwidth studies for four U.S. manufacturing sectors—cement, food and beverage products, glass, and plastics and rubber products—and seawater desalination for municipal potable water production.

All of these reports are available on the AMO website (U.S. Department of Energy 2017).

considers carbon dioxide (CO_2) intensities and emissions using the U.S. Environmental Protection Agency's (EPA's) greenhouse gas conversion factors (U.S. Environmental Protection Agency 2014). It also considers the total cost of water reductions attributable to energy intensity reductions associated with each band. In addition, this study forecasts the overall energy consumption for seawater desalination under several scenarios of increased uptake within the United States.

1.3. Definitions of Energy Consumption Bands and Opportunity Bandwidths

The consistent methodology used in the bandwidth studies provides a framework to evaluate and compare energy savings potentials within and across industrial sectors at the macro-scale. There are four energy consumption bands referenced throughout this report: *current typical* (CT), *state of the art (*SOA), *practical minimum* (PM), and *thermodynamic minimum* (TM) energy consumption. These bands describe different levels of energy consumption to manufacture products. In this report, potable water is considered the product.

Definitions of the four energy bands are provided in the inset on the next page.

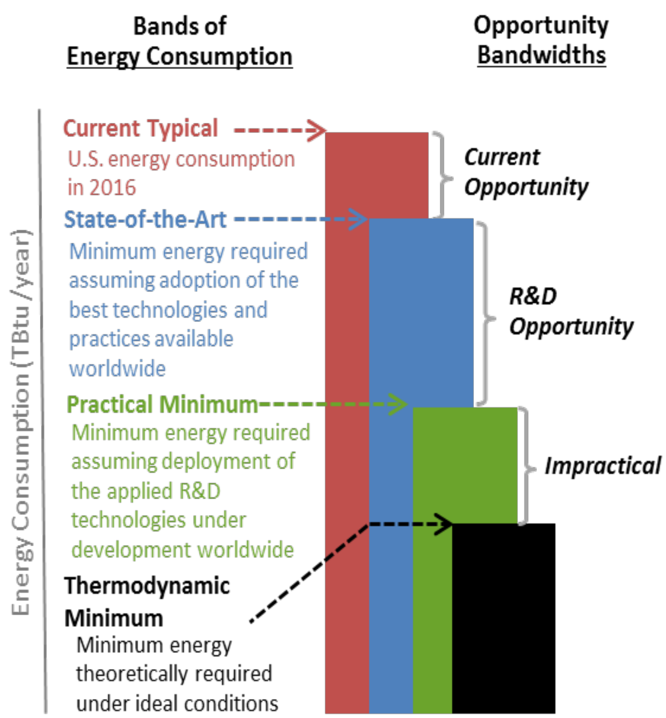

Figure 1-1. Energy consumption bands and opportunity bandwidths estimated in this study
Source: EERE

As shown in Figure 1-1, the bands progress from higher to lower levels of energy consumption, reflecting the use of increasingly more efficient technologies and practices. The upper bound is set by a mix of new and older technologies and practices in current use (the current typical level of energy consumption). The lower bound is defined by the theoretical minimum energy requirement assuming ideal conditions and zero energy losses (the thermodynamic minimum level of energy consumption).

Each of these two bounds defining the extremes of energy consumption can be compared to hypothetical measures in the middle of this range. If system designers use the most energy efficient technologies and practices commercially available in the world, energy consumption could decrease from the current typical to the level defined by the state of the art. Since these state of the art technologies already exist, the difference between the current typical and the state of the art energy consumption levels defines the *current opportunity* to decrease energy consumption. Given that this is an evaluation of technical potential, fully realizing the current opportunity would require investments in capital that may not be economically viable for any given facility.

Widespread deployment of future advanced technologies and practices under investigation by researchers around the globe could help system designers attain the practical minimum level of energy consumption. The difference between state of the art and practical minimum levels of energy consumption defines the *R&D opportunity* for energy savings.

The difference between PM and TM energy consumption is labeled as *impractical*—a term that is used because the PM energy consumption is based on today's knowledge of R&D technologies tested between laboratory and demonstration scale; further decreases in energy intensity have not been displayed at any physical scale. However, decreasing the PM energy consumption with future R&D efforts in desalination may be possible. One example of a desalination technology that shows potential to reduce energy requirements based on models and theoretical calculations but has not been tested at any physical scale (and therefore does not meet PM definitions for the purposes of this report) is fully batch RO. Models of its energy intensity show a decrease in energy consumption over the technology chosen for the PM in this report (semi-batch RO), but has not yet been demonstrated at the laboratory scale or higher (Warsinger, et al. 2016, Werber, Deshmukh and Elimelech 2017).

Definitions of Energy Bands Used in the Bandwidth Studies

The following definitions are used to describe different levels of U.S. energy consumption to manufacture a specific product industry-wide:

Current Typical (CT) energy consumption:

U.S. energy consumption in 2016.

State of the Art (SOA) energy consumption:

The minimum amount of energy required assuming the adoption of the best technologies and practices available worldwide.

Practical Minimum (PM) energy consumption:

The minimum amount of energy required assuming the deployment of the best applied R&D technologies under development worldwide. This measure is expressed as a range to reflect the speculative nature of the energy impacts of the unproven technologies considered.

Thermodynamic Minimum (TM) energy consumption: The minimum amount of energy theoretically required assuming ideal conditions typically unachievable in real-world applications.

Decreasing beyond the TM energy consumption is not possible. The TM energy intensity represented here is a lower level that will apply to any technology seeking to achieve the desired output product (e.g., potable water at a given water recovery ratio) from seawater at a specified salinity. It is important to calculate the energy savings potential using the difference between any band and the TM. This will adjust the energy savings to the thermodynamic minimum and allow for comparisons across system options. Failure to do so will lead to potentially incorrect conclusions regarding the energy savings options for one system compared to another.

1.4. Bandwidth Analysis Method

This section describes the method used in this bandwidth study to estimate the four bands of energy consumption and the two corresponding energy savings opportunity bandwidths. This section can also be used as a guide to understanding the structure and content of this report.

In this study, U.S. energy consumption is labeled as either "on-site energy" or "primary energy" and defined as follows:

- **On-site energy** (sometimes referred to as *site* or *end use* energy) is the energy consumed (electrical, thermal, etc.) within the desalination plant boundary (i.e., within the plant gates).
- **Primary energy** (sometimes referred to as *source* energy) includes energy that is consumed off site to generate the on-site energy requirements for the desalination process and the transmission and distribution losses associated with bringing electricity and/or steam to the plant boundary. Primary energy is frequently referenced by governmental organizations when comparing energy consumption across sectors.

The four bands of energy consumption described above are quantified for each desalination system unit operation and for the total system. The bands of energy consumption and the opportunity bandwidths presented herein consider on-site consumption. To determine the total annual on-site CT, SOA, PM, and TM energy consumption (billion British thermal units [Btu] per year), energy intensity values per volume of potable water produced in kilowatt-hour total equivalent ($kWh_{T,equiv}$) per cubic meter (m^3) were estimated and multiplied by the production amount (cubic meters per year of potable water produced). For thermal processes, the energy intensity is broken out into its electrical (kWh_e) and thermal ($kWh_{e,equiv}$) components, with the latter converted to an electrical equivalent. $kWh_{T,equiv}$ would be equal to kWh_e for processes and/or unit operations that use only electricity. The study used 2016 as a base year since it was the most recent year for which consistent energy consumption and installed production capacity data were available for all five unit operations. The resulting energy consumption, in units of total electrical equivalent ($kWh_{T,equiv}$) was converted to BBtu to align with reporting in previous bandwidth studies. Energy consumption totals are presented in gigawatt-hours (GWh) in tables in Appendix A3.

The estimates presented are for macro-scale consideration of energy consumption in desalination. The estimates reported herein are representative of overall U.S. seawater desalination; they do not represent energy consumption in any specific facility or any particular region in the United States or the world.

The calculated energy consumption values in this report are based on an examination of referenced data and extrapolation to sector-wide energy savings opportunities. Data sources, assumptions, and the peer-reviewed methodology employed for this analysis are documented in detail throughout the bandwidth study.

The complete information for this study is provided in two volumes. *Volume 1: Survey of Available Information in Support of the Energy-Water Bandwidth Study of Desalination Systems* (Rao, et al. 2016) reviewed the parameters that impact energy, emissions, and cost considerations, and provides background research and a framework for this second volume, *Bandwidth Study on Energy Use and Potential Energy Savings Opportunities in U.S. Seawater Desalination Systems*. Readers should refer to Volume 1 for an explanation of the boundary analysis framework established as a basis for this report, background research conducted on the current typical energy intensities for five unit operations of desalination, an overview of the thermodynamic minimum for seawater desalination, and information on the framework for establishing desalination uptake scenarios. This report is divided into the following chapters:

Chapter 2 presents an **overview of the desalination sector and technologies,** and the **U.S. installed production capacity volumes** for seawater to municipal potable water (million m^3 of potable water produced per year) in 2016.

Chapter 3 presents the calculated on-site **CT energy and carbon intensity** ($kWh_{T.equiv}$ per m^3 of potable water produced and pound (lb) CO_2 per m^3 of potable water produced) and **CT energy consumption and carbon emissions** (BBtu per year and Mton CO_2 per year) for each individual desalination unit operation and the desalination system as a whole (along with data sources).

Chapter 4 presents the estimated on-site **SOA energy and carbon intensity** ($kWh_{T.equiv}$ per m^3 water and lb CO_2 per m^3) and **SOA energy consumption and carbon emissions** (BBtu per year and Mton CO_2 per year) for each individual desalination unit operation and the desalination system as a whole (along with data sources).

Chapter 5 presents the estimated on-site **PM energy and carbon intensity** ($kWh_{T.equiv}$ per m^3 water and lb CO_2 per m^3) and **PM energy consumption and carbon emissions** (BBtu per year and Mton CO_2 per year) for each individual desalination unit operation and the desalination system as a whole (along with data sources).

Chapter 6 presents the estimated on-site **TM energy intensity** ($kWh_{T.equiv}$ per m^3 water) and **TM energy consumption** (BBtu per year) for each individual desalination unit operation and the desalination system as a whole (along with data sources).

Chapter 7 provides a **summary of current and R&D opportunity** analysis based on bandwidth summary results.

Chapter 8 estimates the **impact on total cost** of water attributable to the reduction in energy intensity for each band.

Chapter 9 presents the **calculated energy consumption under scenarios** of broader uptake in the United States of seawater desalination for municipal-scale potable water based on bandwidth summary results.

Chapter 10 provides a **summary and conclusion** for this report

1.5. Boundaries of the Desalination Bandwidth Study

This report evaluates the energy savings potential for municipal-scale desalination systems treating seawater to potable water. The applications of desalination technologies are much broader than the scope of this report. Figure 1-2 shows the potential applications for various desalination technologies across freshwater-alternate water sources, end use requirements, and concentrate disposal options. It provides minimum and maximum capacity and salinity ranges as observed in the literature for each. For the alternate water sources and end uses, these ranges indicate the amount of water typically utilized and the salinity ranges of these sources. For the concentrate disposal options, the range indicates the feasible capacity and salinity limits for disposing to each option. For the desalination technology, three sets of capacity and salinity ranges are shown. The first indicates the feedwater capacities and salinities each technology can typically process. The second and third indicate the output capacity and salinity ranges for the concentrate and product water, respectively. By matching capacity and salinity requirements for each of the steps, feasible desalination pathways can be identified. To form a pathway, there should be an overlap between the output salinity and capacity range for one step with the input capacity and salinity range of the next step. These pathways may not be optimal (in terms of energy efficiency, cost, or any other parameter), but help to eliminate technically infeasible pathways for a selected application. There are numerous pathways for desalination depending on the system requirements; seawater to municipal potable water is one set of pathways. While the results of this report should only be interpreted for the intended pathway, it is hoped that the underlying information published in the companion Volume 1 report and the analysis methodology (but not results) adopted here can be leveraged for similar analysis of other pathways.

As a part of this desalination bandwidth study efforts, a detailed boundary analysis was developed for application to each individual unit operation within a desalination system and the system as a whole. This analysis framework allows an assessment of energy and CO_2 emission intensities for each unit operation. The consistency within the analysis framework makes it applicable to each individual unit operation, as well as to the whole integrated desalination system. The whole system boundary analysis, shown in Figure 1-3, collapses all the unit operations and provides an overview of all the material and energy inputs and outputs of a desalination system, as well as the associated system operating and cost parameters. The consistent boundary analysis framework allows for tracking of feedwater quality, chemicals added, and constituents removed. The use of a consistent analysis framework across all desalination system options enables equitable comparisons and a more robust analysis regarding energy consumption and CO_2 reduction potential. Figure 1-3 represents an aspirational tracking of system parameters. In reality, data in the literature are generally not reported with the appropriate contextual information outlined in the figure. For this report, salinity and recovery were tracked and reported as a minimum for each unit operation. For more information on the boundary analysis framework, including an explanation of the significant metrics considered for each of the five unit operations—intake, pre-treatment, desalination, post-treatment, and concentrate management—refer to Section 4 of the report *Volume 1: Survey of Available Information in Support of the Energy-Water Bandwidth Study of Desalination Systems* (Rao, et al. 2016).

The energy consumption (for the CT, SOA, PM, and TM bands) and associated CO_2 emissions (for the CT, SOA, and PM bands) were determined for seawater desalination systems producing municipal potable water. Brackish water desalination energy consumption and CO_2 emissions were determined for CT only and can be found in Appendix A6. This study focuses on seawater desalination, but brackish water desalination was also reviewed because of its large presence in the United States (as compared to brackish water desalination uptake globally). This study does not consider life cycle energy consumed during raw material extraction, off-site treatment, transportation of materials, product use, or disposal.

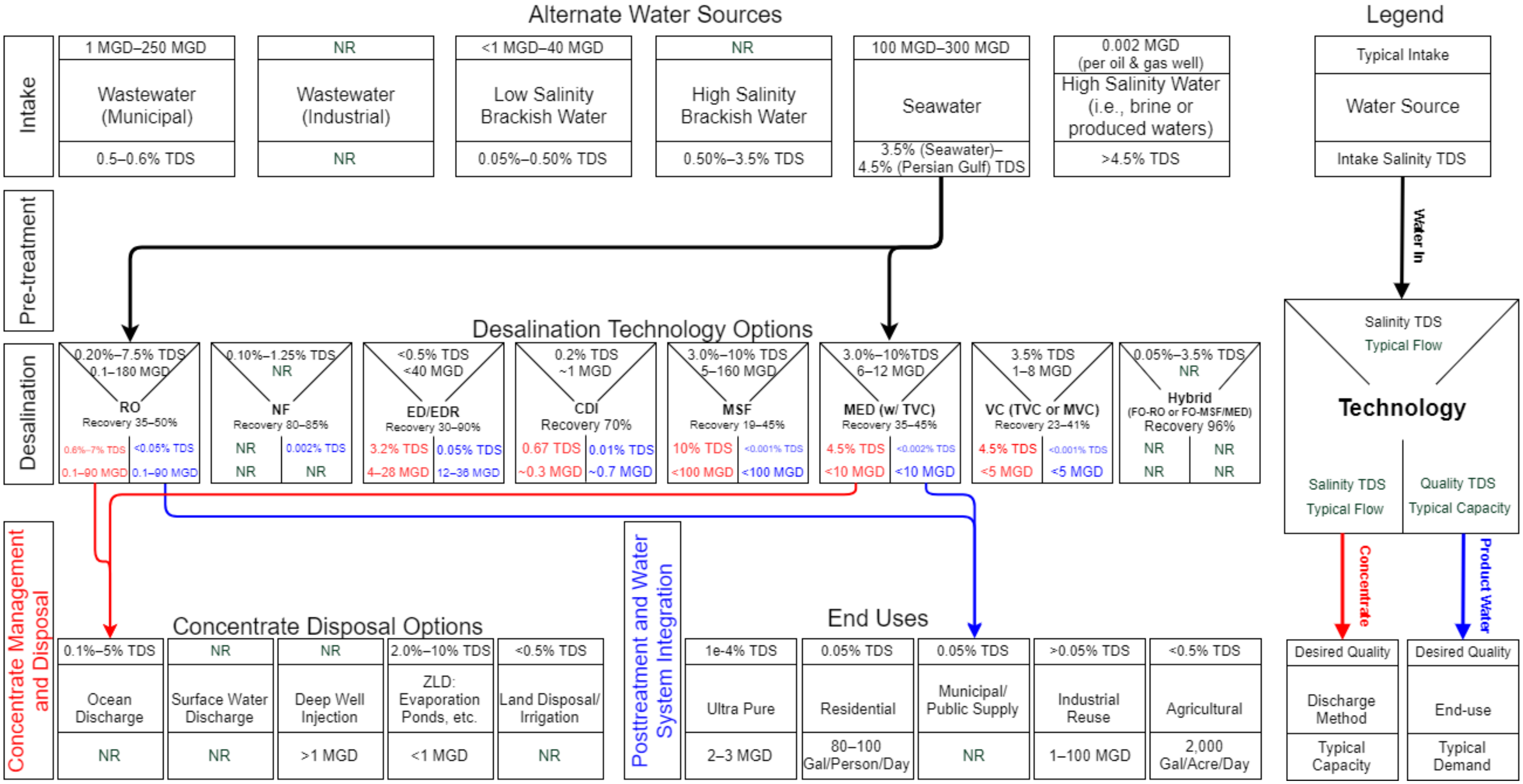

Figure 1-2. Technology choices for desalination are dependent on water source, product water end-use, and contaminant disposal options.
Source: LBNL

All the values included in this figure are typical intake, plant, and end use capacities. Thermal process flows do not include cooling water. For an alternate water source to match a technology option or a technology option to match a concentrate disposal or end use option, the output salinity and capacity range of the first should overlap with the input salinity and capacity range of the second. For this report, one water source (seawater) was selected for one end use (municipal-scale potable water) and one concentrate disposal option (ocean) was selected, as shown by the arrows. Although many desalination technologies can be used for this pathway, reverse osmosis and multi-effect distillation were selected for this report based on their relatively low energy intensity and, in the case of reverse osmosis, its common usage in the United States. Salinities are represented with the units of % TDS. Percent TDS can be converted to ppm using the following conversion: 1% = 10,000 ppm. A version of this figure in SI units can be found in Appendix A3. Sources: (Rao, et al. 2016) (Alameddine and El-Fadel 2006) (Imbrogno and Belfort 2016) (Jenkins, et al. 2012) (Lenntech 2017) (U.S. Geological Survey 2017a) (U.S. Geological Survey 2017c) (McIlvaine and Bagga 2017) (Wu, Tam and Wong 2008) (Clark and Veil 2009)

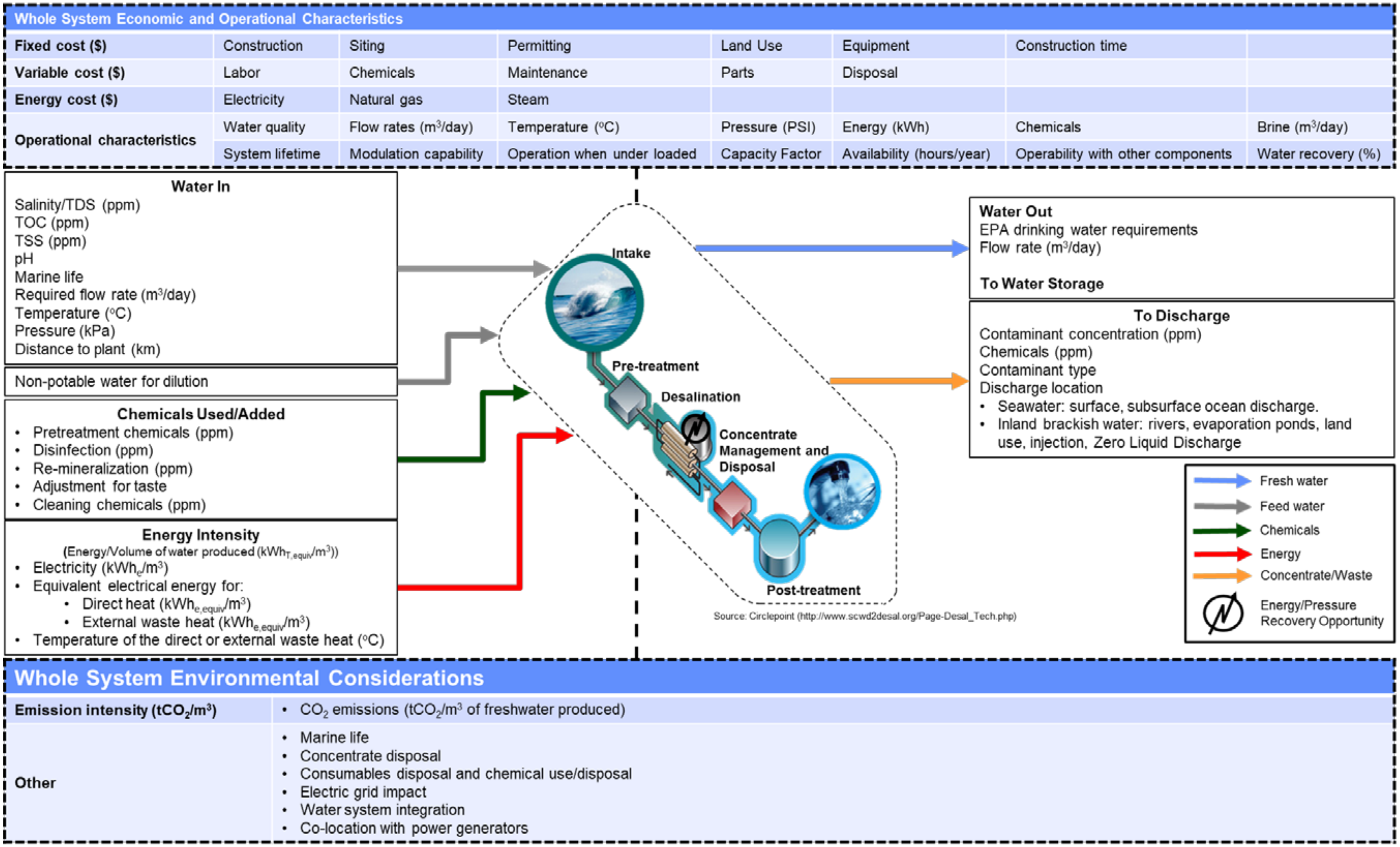

Figure 1-3. General desalination system boundary analysis framework overview
Source: LBNL

2. Overview of Desalination Systems

2.1. Overview

In 2016, the United States annual installed seawater desalination production capacity was 128 million m^3 of potable water, accounting for about 0.4% of total world production (Virgili, Pankratz and Gasson 2016, Global Water Intelligence 2017). Additionally, the United States' annual installed brackish water capacity for potable water was 2,070 million m^3 (Global Water Intelligence 2017). This potable water was produced at seven seawater desalination facilities and 505 brackish water desalination facilities in the United States (Global Water Intelligence 2017).

This study focuses on energy consumption of the five energy consuming unit operations in seawater desalination: intake, pre-treatment, the desalination process, post-treatment, and concentrate management. Figure 2-1 shows the desalination system process flow diagram addressing the unit operations that were considered in this bandwidth analysis. Within each of these unit operations, energy consumption was analyzed, including energy consumed for pumping (for feedwater conveyance and/or pressurization), as well as energy/pressure recovery for the desalination process. The energy required for intake water conveyance pumping and concentrate pumping will be dependent on elevation change, distances, and piping design and wear, all of which are site-specific conditions. For this study, these variables were assumed to be negligible. Additionally, further steps, such as water system integration and distribution of the produced potable water to consumers, were outside the scope of this study.

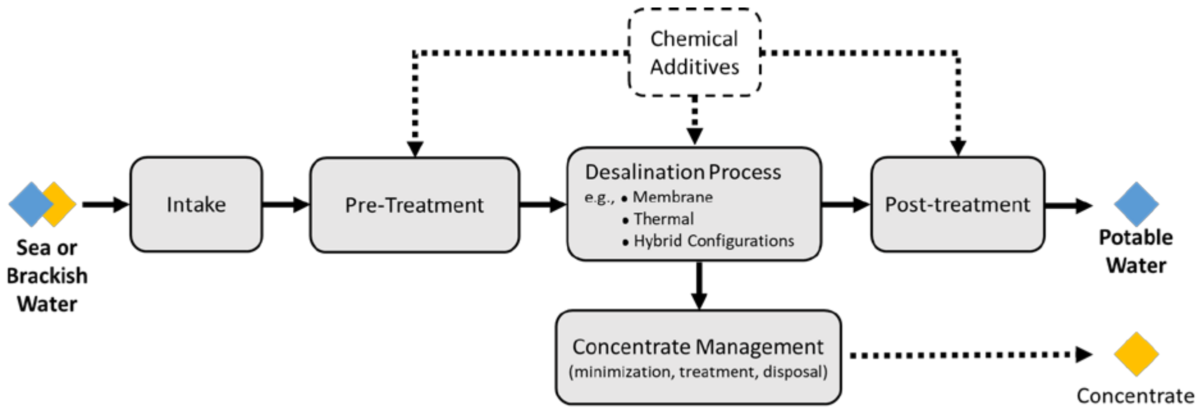

Figure 2-1. A typical desalination system process flow diagram (PFD)
Source: EERE

These unit operations are further identified in Table 2-1, along with some major processes associated with that unit operation. Energy intensity and consumption are evaluated by unit operation for CT, SOA, PM, and TM in sections 3 through 6 of this report.

Table 2-1. Desalination System Unit Operations Considered in the Energy Bandwidth Analysis

Unit Operation	Processes

Intake	Open-ocean intake
	    Screened
	Subsurface intake
	    Beach wells
	    Offshore radial collector wells

Pre-treatment	Strainers
	Membrane filtration
	    Microfiltration
	    Ultrafiltration
	Pressure sand filtration
	Cartridge filtration
	Disc filtration
	Granular media filtration
	Dissolved air flotation (DAF)
	Flocculation
	Coagulation
	Sedimentation
	Chlorination

Desalination	Reverse osmosis
	Multi-stage flash distillation
	Multi-effect distillation
	Vapor compression
	    Mechanical vapor compression
	    Thermal vapor compression
	Energy recovery systems

Post-treatment	Remineralization Disinfection Boron removal
Concentrate Management	Surface water discharge Brine concentration Crystallizers

2.2. Types of Systems: Membrane versus Thermal versus Hybrid

A brief summary of the types of desalination systems studied for this report is provided here; this section is not meant to include all desalination technologies. For more background information and details on these and other desalination systems and unit operations, please refer to the report, *Volume 1: Survey of Available Information in Support of the Energy-Water Bandwidth Study of Desalination Systems* (Rao, et al. 2016).

2.2.1. Membrane Desalination

Membrane-based desalination technologies are pressure, concentration gradient, or ion-charge driven, where the feedwater components are physically separated through a membrane barrier. A membrane-based technology requires mechanical or electrical energy derived from fossil fuels, renewable sources, or a combination of both. Variations of this technology include reverse osmosis (RO), electrodialysis (ED), and forward osmosis (FO). RO is by far the most dominant membrane technology in the United States (and globally).

2.2.2. Thermal Desalination

Thermal desalination processes were the first to be built at large commercial scales. Thermal desalination accounts for nearly 50% of current global seawater desalination installed capacity, with 42% coming from multi-stage flash desalination, and 8% from multi-effect distillation (MED) (Global Water Intelligence 2017). Thermal technologies use phase change to separate salts from the feedwater. Vacuum components are sometimes incorporated as well to increase evaporation at lower temperatures. In thermal technologies, seawater is heated using thermal energy and is then exposed to partial vacuum. The combination of the thermal energy and the partial vacuum will cause pure water to flash (vaporize). Freshwater is then produced by condensing the resulting water vapor using a cooler surface. The thermal energy extracted from the vapor during condensation is then reused to pre-heat the incoming feedwater (Miller 2003).

Multi-effect distillation (MED), multi-stage flash distillation (MSF), mechanical vapor compression (MVC), and MED coupled with thermal vapor compression (MED-TVC) are all applications of this technology. Steam, low-grade heat, or waste heat (e.g., low-grade heat from power plants, jacket water from generators, compressor stations, or diesel engines) is typically the source of energy as well as mechanical energy for pumping (Gude, Nirmalakhandan and Deng 2010).

Thermal technologies are generally more energy intensive than membrane processes, owing in part to large losses due to entropy generation and the need to change phases. Though having significantly lower product water salinities, thermal systems tend to operate at lower recoveries than membrane technologies (Voutchkov 2013).

2.3. U.S. Seawater Desalination Installed Production Capacity Values for Municipal Potable Water

Seawater desalination installed production capacity data were gathered to calculate the sector-wide annual energy consumption by unit operation and for the overall system. Global Water Intelligence's (GWI) DesalData.com provides global, individual country, and individual facility level data for desalination capacity.

The 2016 U.S. installed production capacity for seawater and brackish water for the purpose of potable water production is summarized in Table 2-2. It is recognized that not all facilities will be operating at full capacity year round; however, GWI does not provide load factors (capacity utilization rates). It was assumed that the facilities operate near full capacity for the purposes of this report. At the time of this report, 2016 was the most recent year and was therefore selected. Only facilities that were noted as online or presumed online are included in the numbers provided in Table 2-2. As can be seen, there is significantly larger brackish water desalination capacity than seawater desalination capacity in the United States. Of the 505 brackish water desalination facilities, 86% were operating using reverse osmosis desalination technology, 7% using nanofiltration, and 6% using electrodialysis (Global Water Intelligence 2017). The brackish water desalination facilities ranged in size from less than 1 million gallons per day (MGD) (4 m^3/day) to 40 MGD (151,400 m^3/day). All seawater desalination facilities in the United States utilize RO; a single RO facility in Carlsbad, California, accounted for 54% of U.S. seawater desalination capacity in 2016. The seawater desalination facilities ranged in size from 0.27 MGD (1,030 m^3/day) to 50 MGD (189,300 m^3/day).

Table 2-2. U.S. Seawater and Brackish Water Desalination Installed Production Capacity for Drinking Water Production, 2016

Feedwater	Number of Facilities*	Total Installed Desalination Capacity (million m^3/year)	Total Installed Desalination Capacity (million gal/year)
Seawater**	7	128	33,700
Brackish water***	505	2,070	546,800

* Only facilities that were noted as online or presumed online were included in the numbers provided.
Source: Based on data from (Global Water Intelligence 2017)
** *Seawater* is defined in GWI's database as water that has a total dissolved solids (TDS) level between 20,000 ppm and 50,000 ppm.
*** Both brackish water and river water are included in the total, with a TDS between 500 ppm and 20,000 ppm.

For the majority of unit operations studied in this report, the capacities in Table 2-2 are directly applied to the energy intensity (measured in $kWh_{T.equiv}$ /m^3 of product water) of each operation. For intake and concentrate management, additional considerations regarding the water flow rate through these operations are required when calculating total energy consumption. For the intake, it is necessary to pump more water than the installed capacity of the product water. The additional feedwater needed is dictated by the recovery of the desalination system. For the concentrate management, the amount of water pumped will be greater than the amount of concentrate since most desalination facilities are required to dilute the concentrate before it is disposed into the ocean (due to various regulations requiring the disposal salinity to be similar to the receiving water salinity). This disposal option may be required in certain states, and where it is available, wastewater, instead of seawater, might be available for dilution.

The use of seawater to dilute the concentrate has been selected for the purposes of this report because wastewater or power plant effluent may not be available for all sites. Regulations require that the type of outfall utilized (e.g., a pipe with diffusers or a simple outfall at the shore) for concentrate management is site-specific. The flow rate requirements for concentrate management shown in Table 2-3 were calculated using the formula below, which is provided in Mickley (2006).

$$x + 2{,}000 = \frac{y + i \cdot x}{i + 1}$$

where x is the receiving water salinity (35,000 ppm for standard seawater for the purposes of this report), y is the concentrate salinity (70,000 ppm with a recovery of 50% for membrane systems and 53,800 ppm with a recovery of 35% for thermal systems), and i is the number of dilutions.

Another factor that will vary for desalination facilities for both intake and concentrate management is the head loss associated with pumping the water from the water source to the plant and the concentrate from the plant to the discharge site. Total energy requirements for a pumping system is referred to as Total Dynamic Head (TDH), which is defined by 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). Because this variable would affect the energy consumption values and is highly site-specific, a value of one meter (m) of TDH is used for calculating energy consumption for the intake and concentrate management operations.

Table 2-3 below provides the flow rate capacity values that were utilized in calculating energy consumption for seawater desalination systems. Although there were no thermal seawater desalination plants in the United States in 2016, this study applied the same installed production capacity value for RO systems of 128 million m^3 as a hypothetical benchmark to calculate energy consumption values for thermal systems to compare to membrane systems. Thermal systems also will require large amounts of water for cooling operations, which they may be able to obtain from power plants with which they are co-located; however, because this water is not directly part of the desalination operation, it is not included in Table 2-3. This water for cooling operations should still be kept under consideration, especially in the United States where power plants are phasing out once-through cooling and this cooling water may not be available to future thermal desalination facilities.

Table 2-3. U.S. Seawater Desalination Capacity Values Applied for Each Unit Operation, 2016

Unit Operation	Total Installed Desalination Capacity (million m^3/year)	Total Installed Desalination Capacity (million gal/year)
System Type: Membrane		
Intake	255[a]	67,400
Pre-treatment	128[b]	33,700
Desalination	128	33,700
Post-treatment	128[b]	33,700
Concentrate Management	2,231[c]	589,400
System Type: Thermal[d]		
Intake	364.2[a]	96,200
Pre-treatment	128[b]	33,700
Desalination	128	33,700
Post-treatment	128[b]	33,700
Concentrate Management	1,071[c]	282,900

[a] For intake, the energy intensity is based on the amount of water pumped. Recoveries of 50% for membrane systems and 35% for thermal systems were applied to calculate the amount of water needed to reach the product water capacity of 128 million m^3.
[b] This value is the same as desalination capacity.
[c] For concentrate management, the energy intensity is based on the amount of water pumped. The capacity for this unit operation was calculated using the formula from Section 8.2.5 of Mickley (2006), assuming a standard seawater salinity of 35,000 ppm and recoveries of 50% for membrane systems and 35% for thermal systems. A recently published summary of RO recoveries for global facilities (Pankratz 2017), which range from 39% to 50%, cites the Carlsbad, California, facility operating at about 50% recovery.
[d] Despite the absence of thermal desalination in the United States in 2016, the same capacity value as membrane systems was applied for comparison purposes.
Source: (Global Water Intelligence 2017) and calculations as described above

3. Current Typical Energy Intensity, Energy Consumption, and CO_2 Emissions for U.S. Seawater Water Desalination

This chapter presents estimates of the energy consumption at total 2016 installed U.S seawater desalination capacity levels for individual desalination system unit operations performing at energy intensities representative of current U.S. facilities. Energy consumption in a unit operation can vary for diverse reasons, such as intake water salinity. The energy intensity estimates reported herein are representative of average U.S. seawater desalination; they do not represent energy consumption in any specific facility or any particular region in the United States.

This chapter is organized as follows. A summary of the Current Typical energy intensities and consumption is provided for seawater membrane systems. Brackish water desalination energy consumption and CO_2 emissions were determined for CT only and can be found in Appendix A6. A brief review of the global-typical current energy intensity of seawater thermal systems is also provided. This is followed by a description of the technologies identified as most representative of current U.S. practice for each unit operation, as well as estimates for CO_2 emissions. The chapter concludes with a description of the references used to determine the energy intensity of each unit operation.

3.1. Current Typical Energy Intensity and Energy Consumption

3.1.1. Membrane Desalination Systems

Table 3-1 presents the energy intensities in $kWh_{T,equiv}/m^3$ and estimated on-site and primary CT energy consumption in BBtu per year for seawater desalination unit operations studied. A table presented in GWh per year for energy consumption can be found in Appendix A3. As noted in Section 2.1., two different types of intake systems may be utilized for seawater desalination plants—sub-surface and open-ocean—which will affect the type of pre-treatment required. These systems are presented as "membrane sub-surface" and "membrane open-ocean." The energy intensities are presented in terms of $kWh_{T,equiv}$ per m^3 of potable water produced for the pre-treatment, desalination, and post-treatment unit operations, and $kWh_{T,equiv}$ per m^3 of fluid pumped per meter of TDH for the intake and concentrate management unit operations.

The CT was evaluated using a weighted average of two energy intensities for each unit operation. The first represented the 54% of seawater desalination in the United States already operating at SOA conditions (equivalent to the amount of U.S. seawater desalination annual operating capacity of the Carlsbad, California, plant, which represents SOA in this report), and the second represented the 46% operating at less-efficient conditions (the remainder of U.S. seawater desalination annual operating capacity).

The energy consumption under CT conditions in 2016 for these unit operations is estimated to be 1,523 BBtu of on-site energy and 4,587 BBtu of primary energy for membrane sub-surface systems, and 1,632 BBtu and 4,915 BBtu for membrane open-ocean systems. Primary energy is estimated based on on-site CT energy consumption data adjusted to include off-site generation and transmission losses (U.S. Department of Energy 2014a).

Table 3-1. On-site Current Typical Energy Intensity and Calculated On-site Energy Consumption and Primary Energy Consumption for U.S. Seawater Desalination for Municipal Potable Water Production in 2016

Unit Operation	On-site CT Energy Intensity ($kWh_{T,equiv}/m^3$)	Capacity (million m^3/year)	On-site CT Energy Consumption, Calculated (BBtu/year)	Off-site Losses, Calculated* (BBtu/year)	Primary CT Energy Consumption, Calculated (BBtu/year)
System Type: Membrane Sub-surface					
Intake[a] Sub-surface intake	0.0038	255	3	7	10
Pre-treatment Bag filtration Cartridge filtration[c]	[b] 0.02	128 128	[b] 9	[b] 18	[b] 26
Desalination Reverse osmosis[d]	3.3	128	1,434	2,885	4,319
Post-treatment Remineralization Disinfection Fluoridation	0.05 0.06 [b]	128 128 128	23 25 [b]	47 50 [b]	70 74 [b]
Concentrate management[a] Surface water discharge	0.0038	2,231	29	58	87
Total System Type: Membrane Sub-surface**			**1,523**	**3,064**	**4,587**
System Type: Membrane Open-ocean					
Intake[a] Open-ocean intake	0.0038	255	3	7	10
Pre-treatment					
Flocculation	0.06	128	27	53	80
Coagulation	[b]	[b]	[b]	[b]	[b]
Sand filtration	0.19	128	82	166	428
Cartridge filtration[c]	0.02	128	9	18	26
Desalination Reverse osmosis[d]	3.3	128	1,434	2,885	4,319
Post-treatment Remineralization Disinfection Fluoridation	0.05 0.06 [b]	128 128 128	23 25 [b]	47 50 [b]	70 74 [b]
Concentrate management[a]					
Surface water discharge	0.0038	2,231	29	58	87
Total System Type: Membrane Open-ocean**			**1,632**	**3,283**	**4,915**

Current typical (CT)

* Accounts for off-site electricity and steam generation and transmission losses. Off-site electrical losses are based on a 33% grid generation efficiency.

** Totals may not sum due to independent rounding.

[a] To account for pump and motor efficiencies, as well as total dynamic head (TDH), intake and concentrate management energy intensities were normalized per unit head (kWh_e/m^3-m TDH). For the CT energy intensity, a combined system efficiency of 69.3% was applied (pump efficiency * motor efficiency = 72.9% * 95% = 69.3%) (DETR 1998, U.S. Department of Energy 2014b). There were limited reported values in the literature for concentrate management; therefore,

energy intensities for intake and concentrate management were assumed to be the same (as pumping is the primary energy-intensive mechanism for open-ocean intake and surface water discharge). Intake water was assumed to be standard seawater at 35,000 ppm. Concentrate was assumed to be diluted to 37,000 ppm to be discharged into the ocean.
[b] No values were determined specifically for coagulation or bag filtration in the pre-treatment unit operation or for fluoridation process in post-treatment, due to lack of referenceable energy intensity data. These processes will not be presented in further tables.
[c] Unit operation conditions: feedwater salinity of 40,000 ppm, 50% recovery for RO operation, and plant capacity of 35,000 m^3/day. (Shahabi, McHugh and Ho 2015)
[d] Based on weighted average energy intensity (see Section 3.2.3.).Unit operation conditions: feedwater salinity of 34,500 ppm, 50% recovery, and product water salinity of 500 ppm (Voutchkov 2013, Personal communication with plant employee 2017).

3.1.2. Thermal Desalination Systems

The CT energy consumption for thermal desalination was not considered, as this process is not used in the United States. However, a global CT representative of the desalination unit operation for thermal technologies was estimated using MSF as the baseline technology, as it accounts for 42% of total installed global capacity of seawater desalination (Global Water Intelligence 2017). The global CT energy intensity for seawater desalination unit operation using MSF is estimated to be 15.0 $kWh_{T,equiv}/m^3$ (4.0 kWh_e/m^3 electric, 11.05 $kWh_{e,equiv}/m^3$ thermal). For thermal processes, it is necessary to break down the energy intensity into its electrical (kWh_e) and thermal ($kWh_{e,equiv}$) components. The thermal component is reported as an electrical equivalent by assuming an efficiency of 33% for converting thermal energy to electrical work. The Gained Output Ratio (GOR) will typically range between 4 and 8, while the recovery is between 19% and 28%, with a product water quality of 10 ppm–25 ppm (Voutchkov 2013). Information on the typical energy intensities of thermal desalination can be found in *Volume 1: Survey of Available Information in Support of the Energy-Water Bandwidth Study of Desalination Systems* (Rao, et al. 2016).

The water fed to a thermal desalination process requires less extensive pre-treatment compared to a membrane desalination process (Ghaffour, Missimer and Amy 2013). Estimates from (Rao, et al. 2016) include 0.26 kWh_e/m^3 for sand filtration and 0.0021 kWh_e/m^3 for chlorination (Kennedy/Jenks Consultants 2011, Pacific Gas & Electric 2006). The intake, post-treatment, and concentrate management unit operations would likely be the same as membrane systems. The post-treatment may require more mineralization than membrane systems.

In potential desalination sites where large amounts of “waste” heat—or heat from a process that would otherwise be rejected to the environment (i.e., waste heat from fossil fuel-powered electricity generation)—or large amounts of solar thermal energy are available, thermal desalination may be energy cost competitive with membrane systems. One can use the CT estimates provided here to understand the amount of waste heat or solar thermal energy necessary to power a desalination plant in these situations.

3.2. Current Typical Technology Selections by Unit Operation

3.2.1. Intake and Concentrate Management

As discussed in Chapter 6 of the Volume 1 report (Rao, et al., 2016), the main energy requirement of intake and concentrate management is to pump water from the place of intake to the plant location and to pump the discharge and concentrate to the disposal area, respectively. For seawater desalination, open-ocean intake is typically the technology of choice due to cost-effectiveness, but sub-surface intake can result in reduced pre-treatment requirements for the plant. Both systems are shown in chapter summary tables for completeness, as future plants may be required to use one intake over the other based on environmental regulations or site-specific conditions. For concentrate management, the lowest energy intensity option is surface water discharge.

References for energy intensity for both of these unit operations were found to be site specific, as they will depend upon the TDH associated with pumping. Due to this variability, the energy intensity for intake and concentrate management was instead calculated based upon the amount of energy required to pump water assuming negligible TDH (1 meter of TDH representing the lower bound of energy intensity for these operations) using referenced pump and motor efficiencies in the following formula:

$$Energy\ intensity = \frac{\rho \cdot g}{\eta_{pump} \cdot \eta_{motor}}$$

where ρ is the density of seawater (1,029 kilograms [kg]/m^3), g is gravitational acceleration body force (9.8 meters per second squared [m/s^2]), η_{pump} is the pump efficiency, and η_{motor} is the motor efficiency. For the CT energy efficiency, it was assumed that η_{pump} = 72.9% and η_{motor} = 95% (U.S. Department of Energy 2014b, DETR 1998). The pump efficiency assumes a vertical turbine 600 horsepower (hp) pump with a nameplate efficiency of 81%, but whose performance has degraded over time due to maintenance lapses. The degradation in performance was assumed to be 10%, aligning with expected degradation after 10 years for poorly maintained large water conveyance systems. The motor efficiency is the EPAct regulated minimum efficiency requirement for a large (500 hp) squirrel cage AC induction motor. This was the motor regulation in place in the early 2000s. For the portion of the potable water already produced under SOA conditions in 2016, the pump performance assumed no degradation. The motor efficiency was assumed to be the rated minimum to qualify for the National Electrical Manufacturers Association (NEMA) Premium Efficiency motor label, which is 95.8% for a 500 hp motor. The weighted average of the two conditions results in a CT energy intensity of 0.0038 kWh_e/m^3-m TDH. This same energy intensity was assumed for both open-ocean and sub-surface intakes, as well as for concentrate management.

3.2.2. Pre-treatment

Typical pre-treatment for a desalination plant will require a combination of technologies, including filtration. The type of filtration will vary depending upon the plant. For a seawater desalination plant using a sub-surface intake, it was found that only a cartridge filtration system was used with an energy intensity of 0.02 kWh_e/m^3 (Shahabi, McHugh and Ho 2015). However it may be necessary to use other types of filtration, such as bag filters, to accommodate varying intake water conditions. No energy intensity values were found for bag filtration, but it is listed in the summary tables for completeness.

For this report, a combination of flocculation, coagulation, sand filtration, and cartridge filtration was used as a CT seawater pre-treatment process utilizing an open-ocean intake based on the references. There are often multiple sand filtration stages or in some cases mixed media filtration necessary for certain plants (energy intensity data for mixed media filtration were unavailable). It was difficult to reference an energy intensity value for coagulation specifically, but a combined flocculation and coagulation energy intensity of 0.07 kWh_e/m^3 was determined as the current typical values (Park and Bennett 2010). The energy intensities for sand and cartridge filtration were assumed to be 0.26 kWh_e/m^3 and 0.02 kWh_e/m^3, respectively (Kennedy/Jenks Consultants 2011, Shahabi, McHugh and Ho 2015).

3.2.3. Desalination

Reverse osmosis (RO) was chosen as the CT technology for the desalination unit operation for seawater systems. It is the only technology in use for seawater desalination systems in the United States for potable water production (Global Water Intelligence 2017). For seawater desalination, the Claude "Bud" Lewis Desalination Facility in Carlsbad, California, comprises 54% of all potable water production from seawater in the United States. This report identifies this facility as representative of the SOA energy intensity for RO systems. The CT RO intensity for the purposes of this report was determined by weighting the production of potable water from seawater by the assumed energy intensity of the Carlsbad facility and legacy RO plants in operation in the United States. A value of 2.7 kWh_e/m^3 (with energy recovery) at the Carlsbad facility for the RO unit operation (as confirmed by staff at the facility) was used to represent the 54% of U.S. potable water production via seawater desalination. RO technologies only consume electrical energy; therefore, units of kWh_e/m^3 are used to show their energy intensity. No thermally driven RO technologies were identified in the literature. The remaining 46% was assumed to operate at a global typical energy intensity for seawater desalination. For a seawater RO desalination unit operation operating at 50% recovery and with intake water salinity of 35,000 ppm TDS, an energy intensity of 4.00 kWh_e /m^3 was chosen (Voutchkov 2013). The resulting weighted CT energy intensity used in this is report is 3.3 kWh_e/m^3, which includes energy recovery.

3.2.4. Post-treatment

Seawater post-treatment methods require a combination of remineralization, disinfection, and fluoridation technologies. The higher values for remineralization and disinfection, approximately 0.07 kWh_e/m^3 each for a product water salinity range of 129–194 ppm TDS, were taken from the available literature as an estimate for the CT energy intensity (Dundorf, et al. 2009, Park and Bennett 2010).

3.3. Current Typical CO_2 Emissions

Carbon dioxide emission estimates consider the emissions associated with generating, transmitting, and distributing the energy consumed on-site. Since the energy source for membrane systems is entirely electricity, this study considered CO_2 emissions associated with the U.S. electric grid. For the purposes of this estimate, it was assumed that all electricity consumed on-site was purchased from the electric grid and generated at a typical U.S. utility-scale power plant. Use of alternative electricity generation technologies (e.g., on-site solar or wind) was not considered in this analysis.

To calculate CO_2 emissions associated with purchased electricity, the CT energy intensity was multiplied by a national grid-average CO_2 emission factor. This emission factor was calculated based on the overall CO_2 emissions per unit of electricity generated in the electric power industry in the United States in 2015 (the most recent year for which data are available in EPA's eGRID2014 v2).[7] To account for the additional energy losses in transmission and distribution, the emission factor was multiplied by a factor accounting for these losses. National estimates for grid transmission and distribution losses are 4.95% (also provided by eGRID 2014 v2) (U.S. Environmental Protection Agency 2017). The total CO_2 emission intensity (accounting for generation, transmission, and distribution) is in units of lb $CO_2/kWh_{T,equiv}$. This value is multiplied by the CT energy intensity of each unit operation to arrive at a CO_2 emissions intensity of lb CO_2/m^3 of water. That is then multiplied by the respective capacity value for each unit operation to calculate the total associated CO_2 emissions.

Table 3-2 presents the CO_2 intensities and annual emissions based on the estimated on-site CT energy consumption for each seawater desalination system unit operation. The CO_2 intensities are shown in terms of lb CO_2 per m^3 potable water produced for the pre-treatment, desalination, and post-treatment unit operations, and lb CO_2 per m^3 pumped water/concentrate per m of TDH for the intake and concentrate management unit operations. Appendix A3 presents a table in kg $CO_2/kWh_{T,equiv}$ and emissions of kilotonnes of CO_2/year. The CT CO_2 emissions for these unit operations at 2016 U.S. installed production capacity are estimated to be 263 thousand tons CO_2 (assuming membrane sub-surface system CT energy consumption) and 282 thousand tons CO_2 (assuming membrane open-ocean system CT energy consumption). This is equivalent to the annual CO_2 emissions from 50,397 and 54,010 passenger vehicles for the sub-surface and open-ocean membrane systems, respectively.

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[7] Based on U.S. EPA's Emissions & Generation Resource Integrated Database (eGRID). eGRID2014 Version 2 (updated 02/27/2017). (U.S. Environmental Protection Agency 2017).

Table 3-2. Associated Current Typical CO_2 Emissions for U.S. Seawater Desalination for Municipal Water Production in 2016

Unit Operation	On-site CT Energy Intensity ($kWh_{T,equiv}/m^3$)	Capacity (million m^3/year)	CO_2 Emission Factor (lb CO_2/ $kWh_{T,equiv}$)	CO_2 Emission Intensity (lb CO_2/m^3)	Total CO_2 Emissions (Mton CO_2/year)
System Type: Membrane Sub-surface (Reverse osmosis)					
Intake*	0.0038	255	1.18	0.004	1
Pre-treatment	0.02	128	1.18	0.01	2
Desalination**	3.30	128	1.18	3.87	248
Post-treatment	0.11	128	1.18	0.06	8
Concentrate management*	0.0038	2,231	1.18	0.004	5
Total System Type: Membrane Sub-surface* **					**263**
System Type: Membrane Open-ocean (Reverse osmosis)					
Intake*	0.0038	255	1.18	0.004	1
Pre-treatment	0.27	128	1.18	0.32	20
Desalination**	3.30	128	1.18	3.87	248
Post-treatment	0.11	128	1.18	0.13	8
Concentrate management*	0.0038	2,231	1.18	0.004	5
Total System Type: Membrane Open-ocean* **					**282**

Current typical (CT)

* To account for pump and motor efficiencies, as well as total dynamic head (TDH) loss, intake and concentrate management energy intensities were normalized per unit head loss (kWh_e/m^3-m TDH). For the CT energy intensity, a combined system efficiency of 69.3% was applied (pump efficiency * motor efficiency = 72.9% * 95% = 69.3%) (DETR 1998, U.S. Department of Energy 2014b). There were limited reported values in the literature for concentrate management; therefore, energy intensities for intake and concentrate management were assumed to be the same (as pumping is the primary energy-intensive mechanism for open-ocean intake and surface water discharge).

** Unit operation conditions: feedwater salinity of 35,000 ppm, 50% recovery, and product water salinity of 200–500 ppm. (Voutchkov 2013, Personal communication with plant employee 2017)

*** Totals may not sum due to independent rounding.

3.4. Sources for Seawater Desalination Current Typical Energy Intensity

Appendix A1 presents the CT energy intensities and energy consumption for the unit operations studied. Table 3-3 presents a summary of the main references consulted to identify CT energy intensity by unit operation. Appendix A2 provides the references used for each sub-area.

For most unit operations, multiple references were considered. As outlined in Chapter 4 of (Rao, et al. 2016), several factors will affect the energy intensity of a desalination facility, including: input and output salinity, recovery, capacity, and feedwater temperature. The scope of this report is not to estimate the energy intensity of a particular desalination facility, but to provide a national estimate of seawater desalination energy consumption based on the best available information.

Table 3-3. Main Sources Referenced in Identifying Current Typical Intensity by Seawater Desalination System Unit Operation and Total

Unit Operation	Source Abbreviation	Description
Intake, concentrate management	(DETR 1998)	This report provided the CT pump efficiency. The CT pump efficiency was calculated using a weighted average of the following two conditions: (1) an unmaintained pump configuration for 46% of U.S. potable water production from seawater, and (2) a well maintained pump for the balance (54%) of U.S. potable water production from seawater. Figure 7 of this report indicates that unmaintained pumps exhibit a 10.0%–12.5% decrease in efficiency over their lifetimes. Assuming a 10% decrease in efficiency for a 705 revolutions per minute (rpm)-rated American Marsh 480 Series and 305 MFP pump with 81.0% efficiency (American-Marsh Pumps n.d.), the pump efficiency was determined to be 72.9% for unmaintained pumps and 81% for maintained pumps.
Intake, concentrate management	(TECO Westinghouse 2017)	This report provided the CT motor efficiency. The CT motor efficiency was calculated using a weighted average of the following two conditions: (1) an EPACT/Standard/Energy Efficient 700 horsepower (hp), 1,200 rpm vertical shaft motor (nameplate efficiency of 95.0%) for 46% of potable water production from seawater and (2) a NEMA Premium Efficiency 700 hp 1,200 rpm vertical shaft motor (nameplate efficiency of 95.8%) for 54% of potable water production from seawater.
Pre-treatment	(Park and Bennett 2010)	This report provides the energy intensity values for flocculation, coagulation, and disinfection for 46% of potable water production from seawater in the United States. There were no energy numbers reported in the literature specifically for coagulation, but this report stated a combined energy intensity value of 0.12 kWh_e/m^3 for flocculation and coagulation. For more information on the reference for the energy intensity of the 54% of potable water production from seawater (SOA), please see Section 4.4.
Pre-treatment	(Shahabi, McHugh and Ho 2015)	This report provided energy intensity values for cartridge filtration. The high value of 0.02 kWh_e/m^3 was used as a conservative estimate for CT cartridge filtration.
Pre-treatment	(Kennedy/Jenks Consultants 2011)	This report provided energy intensity values for sand filtration. This reference reported a CT energy intensity of 0.26 kWh_e/m^3 for seawater pre-treatment.
Desalination	(Voutchkov 2013, Personal communication with plant employee 2017)	A wide range of values were reported in Vol. 1 (Rao, et al. 2016) for seawater reverse osmosis (SWRO) (1.58–9.00 kWh_e/m^3). An energy intensity of 4.00 kWh_e/m^3 (for an RO system with 50% recovery and feedwater salinity of 35,000 ppm) was chosen from the high value reported in Table 1.3 of reference to represent 46% of potable water production from seawater. Multiple references, such as (Voutchkov 2013), cite ~2.50 kWh_e/m^3 as SOA. A SOA energy intensity of 2.7 kWh_e/m^3 (for feedwater salinity of 35,000 ppm and 50% recovery) was chosen for the 54% of potable water production from seawater operating at SOA conditions. This energy intensity aligns with that of the RO operation at Claude "Bud" Lewis Carlsbad Desalination Facility, which has been chosen as representing SOA for this report (Personal communication with plant employee 2017). Thermal desalination is not commonly used in the United States, so only RO was considered for CT.
Post-treatment	(Dundorf, et al. 2009)	This report provides relevant information for remineralization technologies. This reference determined a remineralization energy intensity of 0.07 kWh_e/m^3 for a demonstration plant in California from 2008. The high energy intensity value for remineralization reported in this source was considered the CT energy intensity. No energy intensity values were specifically reported for fluoridation.

4. State of the Art Energy Intensity, Energy Consumption, and CO_2 Emissions for U.S. Seawater Desalination

This chapter estimates the energy savings potential if U.S. seawater desalination plants adopt the best available technologies and practices worldwide. State of the art (SOA) energy consumption is the minimum amount of energy used in a specific process when utilizing the state of the art technologies and practices. For the purposes of this report, a SOA technology has the lowest energy intensity of the reported commercially available options.

This chapter is organized as follows. A summary of the SOA energy intensities and consumption is provided first for seawater membrane and thermal systems. This is followed by a description of the technologies identified as SOA for each of the unit operations, and estimates for CO_2 emissions. It concludes with a description of the references used to determine the SOA energy intensity of each unit operation.

4.1. State of the Art Energy Intensity and Energy Consumption

Table 4-1 presents the on-site SOA energy intensities and energy consumption for the desalination system unit operations studied. The SOA energy intensities are presented as $kWh_{T,equiv}$ per m^3 potable water produced for pre-treatment, desalination process, and post-treatment. The SOA energy intensity is presented in units of $kWh_{T,equiv}$ per m^3 pumped water/concentrate per meter of TDH for intake and concentrate management. For thermal processes, it is necessary to break down the energy intensity into its electrical (kWh_e/m^3) and thermal ($kWh_{e,equiv}/m^3$) components to determine the total energy intensity ($kWh_{T,equiv}/m^3$). The thermal component is reported as an electrical equivalent by assuming an efficiency of 33% for converting thermal energy to electrical work. The on-site SOA energy consumption is presented as BBtu per year. A table presented in GWh per year for energy consumption can be found in Appendix A3. Two different types of membrane systems are presented—membrane sub-surface and membrane open-ocean—as well as one thermal system. Both membrane systems implement RO desalination with the same post-treatment (remineralization and disinfection) and concentrate management (surface water discharge), but use different intake and pre-treatment methods. Membrane sub-surface systems utilize a sub-surface intake with bag and cartridge filtration pre-treatment; while membrane open-ocean systems utilize am open-ocean intake with flocculation, coagulation, and sand and cartridge filtration. The thermal system uses MED-TVC for its desalination operation.

Table 4-1. SOA Energy Intensities and Calculated SOA Energy Consumption for Seawater Desalination Systems

Unit Operation	On-site SOA Electric Energy Intensity (kWh_e/m^3)	SOA Thermal Energy Intensity ($kWh_{e,equiv}/m^3$)*	SOA Total Energy Intensity ($kWh_{T,equiv}/m^3$)	On-site SOA Energy Consumption, Calculated (BBtu/year)
System Type: Membrane Sub-surface				
Intake** Sub-surface intake	0.0036		0.0036	3
Pre-treatment Cartridge filtration[a]	0.02		0.02	9
Desalination Reverse osmosis[b]	2.70		2.70	1,175
Post-treatment Remineralization[c] Disinfection	0.04 0.04		0.04 0.04	17 19
Concentrate Management** Surface water discharge	0.0036	N/A	0.0036	27
Total System Type: Membrane Sub-surface***				**1,251**
System Type: Membrane Open-ocean				
Intake** Open-ocean intake	0.0036		0.0036	3
Pre-treatment Flocculation Sand filtration Cartridge filtration[a]	0.01 0.13 0.02		0.01 0.13 0.02	5 57 9
Desalination Reverse osmosis[b]	2.70		2.70	1,175
Post-treatment Remineralization[c] Disinfection	0.04 0.04		0.04 0.04	17 19
Concentrate Management** Surface water discharge	0.0036	N/A	0.0036	27
Total System Type: Membrane Open-ocean***				**1,312**
System Type: Thermal				
Intake** Open-ocean intake	0.0036		0.0036	4
Pre-treatment Chlorination Media filtration[d]	0.001 0.05	N/A	0.001 0.05	0.2 22
Desalination MED-TVC[e]	1.00	10.00	11.00	4,786****
Post-treatment Remineralization[c] Disinfection	0.07 0.04	N/A	0.07 0.04	30 19

Table 4-1. SOA Energy Intensities and Calculated SOA Energy Consumption for Seawater Desalination Systems

Unit Operation	On-site SOA Electric Energy Intensity (kWh_e/m^3)	SOA Thermal Energy Intensity ($kWh_{e,equiv}/m^3$)*	SOA Total Energy Intensity ($kWh_{T,equiv}/m^3$)	On-site SOA Energy Consumption, Calculated (BBtu/year)
Concentrate Management**				
Surface water discharge	0.0036		0.0036	13
Total System Type: Thermal* **				**4,875**

State of the Art (SOA)

* $kWh_{e,equiv}$ is the equivalent amount of electrical work that could be produced from the thermal energy requirement. It is determined by assuming the efficiency of converting thermal energy to electrical work is 33%.

** To account for pump and motor efficiencies, as well as total dynamic head (TDH) loss, intake and concentrate management energy intensities were normalized per unit head loss (kWh_e/m^3-m TDH). For the SOA energy intensity, a combined system efficiency of 77.6% was applied (pump efficiency * motor efficiency = 81% * 95.8% = 77.6%) (American-Marsh Pumps n.d., TECO Westinghouse 2017). There were limited reported values in the literature for concentrate management; therefore, energy intensities for intake and concentrate management were assumed to be the same (as pumping is the primary energy-intensive mechanism for open-ocean intake and surface water discharge). Intake water was assumed to be standard seawater at 35,000 ppm. Concentrate was assumed to be diluted to 37,000 ppm to be discharged into the ocean.

*** Totals may not sum due to independent rounding.

**** In calculating the energy consumption, electrical equivalent thermal energy intensities ($kWh_{e,equiv}/m^3$) were divided by 33% to convert to thermal consumption, assuming a 33% generation, transmission, and distribution efficiency.

[a] Unit operation conditions: feedwater salinity of 40,000 ppm, 50% recovery for RO operation, and plant capacity of 35,000 m^3/day. (Shahabi, McHugh and Ho 2015)

[b] Unit operation conditions: feedwater salinity of 34,500 ppm (Virgili, Pankratz and Gasson 2017), 50% recovery, product water salinity of <500 ppm, and plant capacity of 189,300 m^3/day (Poseideon Water; San Diego County Water Authority 2016); energy intensity reference: (Personal communication with plant employee 2017).

[c] Unit operation conditions: product water salinity of 129–194 ppm. (Dundorf, et al. 2009)

[d] Single-stage, granular, gravity-fed media filtration. No specific unit operations provided by energy intensity reference.

[e] Unit operation conditions: feedwater salinity of 45,000 ppm, 33%–37.5% recovery, product water salinity of <25 ppm, and 220–250 kPa pressure. Capacity not provided (Sommariva 2010).

Table 4-2 presents a comparison of the on-site CT energy consumption and SOA energy consumption for each unit operation and as a total for the system chosen as most widely applicable in the United States—membrane open-ocean (RO desalination with an open-ocean intake). This is shown as the SOA energy savings (or *current opportunity*) and SOA energy savings percent. It is useful to consider both BBtu energy savings and energy savings percent when comparing the energy savings opportunity. Both are good measures of opportunity; however, the conclusions are not always the same. Among the processes studied, the greatest *current opportunity* in terms of percent energy savings is pre-treatment at 40% energy savings; the greatest *current opportunity* in terms of BBtu savings is desalination at 259 BBtu per year savings. A table presented in GWh per year for energy savings can be found in Appendix A3.

The *current opportunity* associated with upgrading all U.S. seawater desalination installed production capacity to SOA is 320 BBtu per year of energy, corresponding to a 28% energy savings overall (see equation in the footnote of Table 4-2 below). The *current opportunity* energy savings estimate is based on adopting available SOA technologies and practices without accounting for future gains in energy efficiency from R&D. This is a simple estimate for potential savings; it is not implied that all existing or future plants could achieve these SOA values or that the improvements would prove to be cost effective in all cases.

Table 4-2. On-site State of the Art Energy Consumption, Energy Savings, and Energy Savings Percent for Seawater Desalination Systems

Unit Operation	On-site CT Energy Consumption, Calculated (BBtu/year)	On-site SOA Energy Consumption, Calculated (BBtu/year)	SOA Energy Savings* (CT-SOA) (BBtu/year)	SOA Energy Savings Percent** (CT-SOA)/ (CT-TM)
System Type: Membrane open-ocean (Reverse osmosis)				
Intake	3	3	0.2	20%
Pre-treatment	118	70	48	40%
Desalination***	1,434	1,175	259	27%
Post-treatment	48	37	12	24%
Concentrate Management	29	27	2	20%
Total System Type: Membrane open-ocean******	**1,632**	**1,312**	**320**	**28%**

Current Typical (CT), State of the Art (SOA), Thermodynamic Minimum (TM)
* SOA energy savings is also called *Current Opportunity.*
** SOA energy savings percent is the SOA energy savings opportunity from transforming desalination system processes. Energy savings percent was calculated using TM energy consumption shown in Table 6-1 as the minimum energy consumption. The energy savings percent, with TM as the minimum, was calculated as follows: (CT-SOA)/(CT-TM)
*** Unit operation conditions: feedwater salinity of 34,500 ppm (Virgili, Pankratz and Gasson 2017), 50% recovery, product water salinity of <500 ppm, and plant capacity of 189,300 m^3/day (Personal communication with plant employee 2017).
**** Totals may not sum due to independent rounding.

The SOA energy savings percent is the percent of energy saved under SOA energy consumption compared to CT energy consumption, adjusted for the thermodynamic minimum energy consumption. Thermodynamic minimum (TM), discussed in detail in Chapter 3 of (Rao, et al. 2016) and further in Chapter 6, is considered to be the ideal case with no losses (i.e., energy input to a system is considered fully recoverable with no frictional losses—in other words, a thermodynamically reversible process). For processes where there is a separation of the components of a mixture, the TM represents the resulting change in the Gibbs free content of the components (i.e., as for the removal of sodium chloride from seawater). For processes in which mechanical (or electrical) work drives the separation, TM represents the least of amount of work from the initial to final state. The TM represents the lowest possible energy requirement for a process operating under ideal conditions: no process can ever operate below the TM. Referencing TM as the baseline in comparing bands of energy consumption and calculating energy savings percent provides the most accurate measure of achievable savings potential. The equation for calculating on-site SOA energy savings percent is:

$$SOA\ Savings\ \% = \frac{CT - SOA}{CT - TM}$$

The thermodynamic minimum work of the desalination operation will depend upon the salinity of the inlet and product water streams and on the water recovery ratio. When comparing two reported energy intensity values for the desalination operation for the purposes of understanding energy efficiency opportunity, an adjustment may be necessary to account for differences in the thermodynamic minimum if the two operations do not operate at the same conditions. Since the salinities and recoveries of the desalination operation for the CT and SOA used here are identical, there is no need to further adjust the reported energy intensity, and subtracting out the thermodynamic minimum is sufficient to isolate and compare the energy efficiency opportunity.

4.2. State of the Art Technology Selections by Unit Operation

4.2.1. Intake and Concentrate Management

Section 3.2.1. discusses the energy requirements for intake and concentrate management (pumping water), as well as the calculation approach that was taken in this report to determine energy intensity. For the SOA energy intensity, no adjustments for degradation in performance to the nameplate pump and motor efficiencies were made. The pump efficiency was assumed to be 81.0% and the motor efficiency 95.8% (American-Marsh Pumps n.d., TECO Westinghouse 2017). This results in an energy intensity of 0.0036 kWh_e/m^3-m TDH for both open-ocean and sub-surface intakes, as well as for concentrate management. For the purposes of this report, a value of one meter of TDH was assumed for all calculations.

4.2.2. Pre-treatment

For pre-treatment of a seawater membrane desalination plant using a sub-surface intake (denoted as membrane sub-surface), a cartridge filtration system with an energy intensity of 0.02 kWh_e/m^3 was found to represent the SOA. This is also assumed to be the CT energy intensity (Shahabi, McHugh and Ho 2015). There was little other information found in the available literature to suggest other commercial technologies with lower energy intensities are available. Other types of filtration, such as bag filters, could also be used to accommodate for varying intake water conditions. No energy intensity values were found for bag filtration, but it is listed in the summary tables for completeness.

A combination of flocculation, coagulation, sand filtration, and cartridge filtration was used as an SOA seawater pre-treatment process for membrane desalination systems utilizing an open-ocean intake (denoted as membrane open-ocean). It was difficult to reference an energy intensity value for coagulation specifically, but a combined flocculation and coagulation energy intensity of 0.06 kWh_e/m^3 was determined as the lowest and best available (Park and Bennett 2010). The energy intensities for sand and cartridge filtration were assumed to be 0.13 kWh_e/m^3 and 0.02 kWh_e/m^3, respectively (Kennedy/Jenks Consultants 2011, Shahabi, McHugh and Ho 2015).

For thermal seawater desalination, pre-treatment requirements are not as extensive as membrane desalination, as previously noted. Thermal pre-treatment methods encompass gravity-fed media filtration coupled with chlorination. The SOA energy intensities reported for gravity-fed media filtration and chlorination processes were 0.05 kWh_e/m^3 and 0.001 kWh_e/m^3, respectively (Voutchkov 2013, Pacific Gas & Electric 2006). Anti-scalants may be added in the desalination unit operation, but the energy intensity for this was assumed to be negligible.

4.2.3. Desalination

For membrane systems, single-pass reverse osmosis remained the SOA technology for the desalination unit operation. An energy intensity of 2.70 kWh_e/m^3 (with energy recovery) for RO for feedwater of 35,000 ppm, product water of 500 ppm, and 50% recovery was chosen as a representative estimate for SOA energy intensity, since this is the energy intensity of the desalination unit operation at the Claude “Bud” Lewis Desalination Facility in Carlsbad, California (Personal communication with plant employee 2017). This facility has been selected as representing the SOA.

For a thermal system, MED-TVC was chosen as the SOA, as it has the lowest energy intensity for thermal desalination. MED technologies are becoming more commercially available despite MSF dominating the thermal desalination market (as mentioned in Section 2.2.2.). The SOA energy intensity for MED-TVC used for the purposes of this report is 11.00 $kWh_{T,equiv}/m^3$ (1.00 kWh_e/m^3 electrical and 10.00 $kWh_{e,equiv}/m^3$ thermal) for a feedwater salinity of 45,000 ppm, 33%–37.5% recovery, product water salinity of <25 ppm, and operating pressure of 32–36 pounds per square inch (psi) (220–250 kilopascal [kPa]) (Sommariva 2010).

4.2.4. Post-treatment

As mentioned in Section 3.2.4., membrane seawater post-treatment methods require a combination of remineralization, disinfection, and fluoridation technologies, and the same post-treatment is used regardless of the type of intake. The lower of the reported values for remineralization and disinfection, approximately 0.04 kWh_e/m^3 each for a total of 0.08 kWh_e/m^3 for a product water salinity range of 129–194 ppm TDS, is used to estimate the SOA post-treatment energy intensity (Dundorf, et al. 2009, Park and Bennett 2010). No estimate was found for fluoridation; based on analysis and expert opinion, the energy intensity was assumed to be negligible.

For thermal desalination post-treatment, the same combination of remineralization, disinfection, and fluoridation technologies is utilized. However, thermal desalination systems generally require more remineralization than membrane-based systems. Accordingly, the SOA energy intensity for remineralization in thermal systems was estimated to be 0.07 kWh_e/m^3, the higher of the reported values, for a product water salinity of 129–194 ppm (Dundorf, et al. 2009). The same energy intensity used for membrane systems for disinfection (0.04 kWh_e/m^3) was used for thermal systems. With this, the total thermal SOA post-treatment unit operation energy intensity was estimated to be 0.11 kWh_e/m^3 (Dundorf, et al. 2009, Park and Bennett 2010).

4.3. State of the Art CO_2 Intensity and Emissions

Estimated CO_2 emissions consider the emissions associated with generating, transmitting, and distributing the energy consumed on site. Only CO_2 emissions associated with the U.S. electric grid and purchased steam were considered. The method for estimating CO_2 emissions from electricity was presented in Section 3.3., and the same method was used for SOA CO_2 emission estimates.

Carbon dioxide emissions from thermal energy sources were estimated by assuming that all steam and electricity consumed on site was purchased outside of plant boundaries and generated at a typical U.S. utility scale plant. The emission factor for purchased steam was calculated based on the overall CO_2 emissions per unit of steam generated in the United States in 2015 (the most recent year for which data are available) (U.S. Environmental Protection Agency 2015). This factor was then applied to the thermal component of the desalination unit operation of thermal systems in the same manner as the electricity factor.

Table 4-3 presents the CO_2 intensities based on the estimated on-site SOA energy consumption for the seawater desalination system unit operations studied. The CO_2 intensities are presented in terms of lb CO_2 per m^3 potable water produced for the pre-treatment, desalination, and post-treatment unit operations, and lb CO_2 per m^3 pumped water per m of TDH for the intake and concentrate management unit operations. Tables presented in kg $CO_2/kWh_{T,equiv}$ and emissions of kilotonnes CO_2/year can be found in Appendix A3. The SOA CO_2 emissions for these unit operations are estimated to be 1,049 thousand tons of CO_2 assuming thermal system operations; 216 thousand tons CO_2 assuming membrane sub-surface system operations; and 227 thousand tons CO_2 assuming membrane open-ocean system operations under 2016 U.S. seawater desalination installed production capacity. This corresponds to the annual emissions from 41,382 passenger vehicles for the membrane sub-surface system, 43,412 passenger vehicles for the membrane open-ocean system, and 200,893 passenger vehicles for the thermal system.

Table 4-3. Associated State of the Art CO_2 Intensities and Calculated State of the Art CO_2 Emissions for Seawater Desalination Systems

Unit Operation	On-site SOA Electric Energy Intensity (kWh_e/m^3)	SOA Thermal Energy Intensity ($kWh_{e,equiv}/m^3$)	CO_2 Electricity Emission Factor (lb $CO_2/kWh_{T,equiv}$)	CO_2 Thermal Emission Factor (lb $CO_2/kWh_{T,equiv}$)	CO_2 Emission Intensity (lb CO_2/m^3)	Capacity (million m^3)	CO_2 Emissions (Mton CO_2/yr)
System Type: Membrane Sub-surface							
Intake*	0.0036	N/A	1.18	N/A	0.0043	255	1
Pre-treatment	0.02		1.18		0.02	128	2
Desalination**	2.70		1.18		3.18	128	203
Post-treatment	0.08		1.18		0.10	128	6
Concentrate Management*	0.0036		1.18		0.0043	2,231	5
Total System Type: Membrane Sub-surface* **							**216**
System Type: Membrane Open-ocean							
Intake*	0.0036	N/A	1.18	N/A	0.0043	255	1
Pre-treatment	0.16		1.18		0.19	128	12
Desalination**	2.70		1.18		3.18	128	213
Post-treatment	0.08		1.18		0.10	128	6
Concentrate Management*	0.0036		1.18		0.0043	2,231	5
Total System Type: Membrane Open-ocean* **							**227**
System Type: Thermal (MED-TVC)							
Intake*	0.0036	N/A	1.18	N/A	0.0043	364	1
Pre-treatment	0.05		1.18		0.06	128	4
Desalination**	1.00	10.00	1.18	0.50	16.21****	128	1,033****
Post-treatment	0.11	N/A	1.18	N/A	0.13	128	9
Concentrate Management*	0.0036		1.18		0.0043	1,071	2
Total System Type: Thermal* **							**1,049**

State of the Art (SOA)

* To account for pump and motor efficiencies, as well as total dynamic head (TDH) loss, intake and concentrate management energy intensities were normalized per unit head loss (kWh_e/m^3-m TDH). For the SOA energy intensity, a combined system efficiency of 77.6% was applied (pump efficiency * motor efficiency = 81% * 95.8% = 77.6%) (American-Marsh Pumps n.d., TECO Westinghouse 2017). There were limited reported values in the literature for concentrate management; therefore, energy intensities for intake and concentrate management were assumed to be the same (as pumping is the primary energy-intensive mechanism for open-ocean intake and surface water discharge). Intake water was assumed to be standard seawater at 35,000 ppm. Concentrate was assumed to be diluted to 37,000 ppm to be discharged into the ocean.

** RO (membrane) unit operation conditions: feedwater salinity of 34,500 ppm (Virgili, Pankratz and Gasson 2017), 50% recovery, product water salinity of <500 ppm, and plant capacity of 189,300 m^3/day (Personal communication with plant employee 2017). MED-TVC (thermal) unit operation conditions: feedwater salinity of 45,000 ppm, 33%–37.5% recovery, product water salinity of <25 ppm, and 32–36 psi (220–250 kPa) pressure. Capacity not provided (Sommariva 2010).

*** Totals may not sum due to independent rounding.

**** In calculating the emissions intensity and total emissions, the thermal energy intensities ($kWh_{e,equiv}/m^3$) were divided by 33% to convert to thermal consumption, assuming a 33% generation, transmission, and distribution efficiency.

4.4. Sources for State of the Art Energy Intensity

Appendix A1 presents the on-site SOA energy intensity and consumption for the unit operations considered in this bandwidth study. The on-site SOA energy consumption values are the net energy consumed in the process using the single most efficient process and production pathway commercially available. The main published sources referenced to identify the SOA energy intensities are shown in Table 4-4.

Table 4-4. Main Sources Referenced in Identifying State of the Art Energy Intensity by Desalination System Unit Operation and System Total

Unit Operation	Source Abbreviation	Description
Intake, concentrate management	(American-Marsh Pumps n.d.)	This report provided the SOA pump efficiency. The SOA pump efficiency assumed a pump configuration for a 705 rpm-rated American Marsh 480 Series 305 MFP pump with an 81.0% efficiency.
Intake, concentrate management	(TECO Westinghouse 2017)	This report provided the SOA motor efficiency. The SOA motor configuration was based on a NEMA Premium, Max-VS Vertical Solid Shaft WPI motor. This motor is rated at a 95.8% motor efficiency.
Pre-treatment, Post-treatment	(Park and Bennett 2010)	This report provided SOA energy intensity values for disinfection, flocculation, and coagulation. Typical pre-treatment requires the combination of flocculation and coagulation. Typical post-treatment requires a disinfection step. There were no energy intensities reported in the literature specifically for coagulation, but this report provided combined energy intensities for flocculation and coagulation. Low energy intensity values were considered as SOA. No energy intensity values were specifically reported for fluoridation.
Pre-treatment	(Shahabi, McHugh and Ho 2015)	This report provided energy intensity values for cartridge filtration. Operational conditions were reported for Indian Ocean feedwaters (salinity of 40,000 ppm TDS and feedwater temperature of 30°C).
Pre-treatment	(Kennedy/Jenks Consultants 2011)	This report provided energy intensity values for sand filtration. The low values reported were used for the SOA. Dissolved air floatation (DAF) can also be considered an SOA technology, but it only operates and consumes energy in rare circumstances. Since the current report is meant to quantify energy consumption associated with typical operations, rare occurrences such as algal blooms are not accounted for in the SOA. Therefore, DAF was not considered.
Pre-treatment	(Pacific Gas & Electric 2006)	The low value for chlorination energy intensity was used for thermal SOA pre-treatment. Thermal desalination typically only requires additional chemical conditioning, opposed to additional physical treatment and screens required for membrane technologies, so chlorination was chosen to accommodate this.
Desalination (membrane)	(Personal communication with plant employee 2017)	A wide range of values were reported in Vol 1 (1.58–9.00 kWh_e/m^3) for seawater reverse osmosis (SWRO). Multiple references, such as (Voutchkov 2013), cite 2.50 kWh_e/m^3 as SOA. The Carlsbad, California, desalination facility was chosen as representing the SOA. The energy intensity of its RO operation is 2.70 kWh_e/m^3 (for feedwater salinity of 34,500 ppm (Virgili, Pankratz and Gasson 2017) and 50% recovery), and this value was chosen for the SOA of membrane systems (Personal communication with plant employee 2017).

Table 4-4. Main Sources Referenced in Identifying State of the Art Energy Intensity by Desalination System Unit Operation and System Total

Unit Operation	Source Abbreviation	Description
Desalination (thermal)	(Sommariva 2010)	MED-TVC is considered the SOA. It is commercially available and represents a significant portion of the MED technologies already implemented. According to Figure 6.10 of this reference, the low-value energy intensities were chosen as 11.00 $kWh_{T,equiv}/m^3$ (thermal 10.00 $kWh_{e,equiv}/m^3$ and electric 1.00 kWh_e/m^3) for feedwater salinity of 45,000 ppm and 33%–37.5% recovery.
Post-treatment	(Dundorf, et al. 2009)	Remineralization was selected from this report, as it is one of the most commonly implemented post-treatment technologies for seawater desalination plants. This technology is currently implemented at state of the art desalination facilities like Carlsbad. The low energy intensity value from this source (0.04 kWh_e/m^3) was used for membrane desalination post-treatment. The high value from this report (0.07 kWh_e/m^3) was used for the thermal post-treatment unit operation to account for additional remineralization requirements in thermal desalination.

5. Practical Minimum Energy Intensity, Energy Consumption, and CO_2 Emissions for U.S. Seawater Desalination

Across the globe, R&D is underway to develop new or advance existing desalination methods to improve its energy efficiency. In this chapter, the R&D energy savings made possible through R&D advancements in seawater desalination are estimated. *Practical minimum* (PM) is the minimum amount of energy required assuming the deployment of technologies currently under development and demonstrated at any physical scale worldwide, but not yet commercially available.

5.1. Practical Minimum Energy Intensity and Energy Consumption

Table 5-1 presents the on-site PM energy intensities in $kWh_{T,equiv}$ per m^3 and energy consumption in BBtu per year for the desalination system unit operations studied. The PM energy intensities for pre-treatment, desalination operation, and post-treatment are presented in units of $kWh_{T,equiv}$ per m^3 potable water produced. The PM energy intensity is presented in units of $kWh_{T,equiv}$ per m^3 pumped water/concentrate per meter of TDH for intake and concentrate management. For thermal processes, it is necessary to break down the energy intensity into its electrical (kWh_e) and thermal ($kWh_{e,equiv}$) components. The thermal component is reported as an electrical equivalent by assuming an efficiency of 33% for converting thermal energy to electrical work.

The on-site PM energy consumption is presented as BBtu per year. A table presented in GWh per year can be found in Appendix A3. Two different types of membrane systems are presented—membrane sub-surface and membrane open-ocean—as well as one thermal system. Both membrane systems implement RO desalination with the same post-treatment (remineralization and disinfection) and concentrate management (surface water discharge), but use different intake and pre-treatment methods. Membrane sub-surface systems utilize a sub-surface intake with bag and cartridge filtration pre-treatment, while membrane open-ocean systems utilize vacuum-driven microfiltration. The thermal system uses condensing MED for its desalination operation.

Table 5-1. Practical Minimum Energy Intensities and On-site Energy Consumption for U.S. Seawater Desalination Systems

Unit Operation	On-site PM Electric Energy Intensity (kWh_e/m^3)	PM Thermal Energy Intensity ($kWh_{e,equiv}/m^3$)	PM Total Energy Intensity ($kWh_{T,equiv}/m^3$)	PM Energy Consumption, Calculated (BBtu/year)
System Type: Membrane Sub-surface				
Intake* Sub-surface intake	0.0034	N/A	0.0034	3
Pre-treatment Cartridge filtration	0.02	N/A	0.02	9
Desalination Semi-batch RO**	1.48	N/A	1.48	645
Post-treatment Remineralization Disinfection	0.04 0.04	N/A	0.04 0.04	17 19
Concentrate Management Surface water discharge*	0.0034	N/A	0.0034	26
Total System Type: Membrane Sub-surface* **				**719**
System Type: Membrane Open-ocean				

Intake* Open-ocean intake	0.0034	N/A	0.0034	3
Pre-treatment Vacuum-driven microfiltration	0.13		0.13	56
Desalination Semi-batch RO**	1.48		1.48	645
Post-treatment Remineralization Disinfection	0.04 0.04		0.04 0.04	17 19
Concentrate Management Surface water discharge*	0.0034		0.0034	26
Total System Type: Membrane Open-ocean* **				**767**
System Type: Thermal				
Intake* Open-ocean intake	0.0034	N/A	0.0034	4
Pre-treatment Nanofiltration Chlorination	0.04 0.0004		0.04 0.0004	15 0.2
Desalination Condensing MED**	1.00	3.00	4.00	1,740****
Post-treatment Remineralization Disinfection	0.07 0.04	N/A	0.07 0.04	30 19
Concentrate Management Surface water discharge*	0.0034		0.0034	12
Total System Type: Thermal* **				**1,822**

Practical Minimum (PM)

* To account for pump and motor efficiencies, as well as total dynamic head (TDH) loss, intake and concentrate management energy intensities were normalized per unit head loss (kWh_e/m^3-m TDH). For the PM energy intensity, a combined system efficiency of 82% was applied (pump efficiency * motor efficiency = 85% * 97% = 82%) (Proceedings of the 6th International Conference eemods '09: Energy Efficiency in Motor Driven Systems 2009). There were limited reported values in the literature for concentrate management; therefore, energy intensities for intake and concentrate management were assumed to be the same (as pumping is the primary energy-intensive mechanism for open-ocean intake and surface water discharge). Intake water was assumed to be standard seawater at 35,000 ppm. Concentrate was assumed to be diluted to 37,000 ppm to be discharged into the ocean.

** Semi-batch RO unit operation conditions: feedwater salinity of 36,357 ppm, 42% recovery, 379 ppm product water, and plant capacity of 556 m^3/day (Gal and Efraty 2016).

Condensing MED unit operation conditions: feedwater salinity of 45,000 ppm, 33%–37.5% (35% average) recovery, product water salinity of <25 ppm, and 220–250 kPa pressure. Capacity not provided (Sommariva 2010).

*** Totals may not sum due to independent rounding.

**** In calculating the energy consumption, the thermal energy intensities ($kWh_{e,equiv}/m^3$) were divided by 33% to convert to thermal consumption, assuming a 33% generation, transmission, and distribution efficiency.

Table 5-2 presents a comparison of the on-site SOA energy consumption and PM energy consumption in BBtu per year for each unit operation and as a total for the system chosen as best representative for the United States—membrane open-ocean (RO desalination with an open-ocean intake). The SOA and PM energy consumption were used to calculate the *R&D opportunity* energy savings. A table presented in GWh per year for energy consumption can be found in Appendix A3.

Table 5-2. On-site Practical Minimum Energy Consumption, R&D Opportunity, and R&D Energy Savings Percent for U.S. Seawater Desalination Systems

Unit Operation	On-site SOA Energy Consumption, Calculated (BBtu/year)	On-site PM Energy Consumption, Calculated (BBtu/year)	R&D Opportunity (SOA-PM) (BBtu/year)	R&D Energy Savings Percent* (SOA-PM)/ (CT-TM)
System Type: Membrane Open-ocean				
Intake	3	3	0.2	19%
Pre-treatment	70	57	13	11%
Desalination**	1,175	645	529	54%
Post-treatment	37	37	0	0%
Concentrate Management	27	26	1	19%
Total System Type: Membrane Open-ocean* **	**1,312**	**767**	**544**	**47%**

State of the Art (SOA), Practical Minimum (PM), Thermodynamic Minimum (TM)
* R&D energy savings percent is the R&D energy savings opportunity from transforming desalination system processes. Energy savings percent was calculated using TM energy consumption shown in Section 6 as the minimum energy consumption. The energy savings percent, with TM as the minimum, was calculated as follows: (SOA-PM)/(CT-TM).
** Unit operation conditions: semi-batch RO, feedwater salinity of 36,357 ppm, 42% recovery, 379 ppm product water, and plant capacity of 556 m^3/day (Gal and Efraty 2016).
*** Totals may not sum due to independent rounding.

Table 5-3 presents a comparison of the on-site CT energy consumption and PM energy consumption for each unit operation and as a total for the system chosen as best representative for the United States—membrane open-ocean (RO desalination with an open-ocean intake). The data provided in Table 5-3 are presented as the PM energy savings (the difference between CT energy consumption and PM energy consumption) and PM energy savings percent. PM energy savings is equivalent to the sum of *current* and *R&D opportunity* energy savings.

It is useful to consider both BBtu energy savings and energy savings percent when comparing the energy savings opportunity. Among the processes studied, the greatest *current* plus *R&D opportunity* in terms of percent energy savings is the desalination unit operation at 81% energy savings; the greatest *current* plus *R&D opportunity* in terms of BBtu savings is also the desalination unit operation at 789 BBtu per year savings.

If U.S. seawater desalination were able to attain on-site PM energy intensities, it is estimated that 864 BBtu per year of energy could be saved from the unit operations alone compared to CT energy consumption, corresponding to 75% energy savings overall. This energy savings estimate is based on adopting available PM technologies and practices. This is a simple estimate for potential savings, it is not implied that all existing or new plants could achieve these PM energy intensity values or that the improvements would prove to be cost effective in all cases.

Table 5-3. On-site Practical Minimum Energy Consumption, Energy Savings, and Energy Savings Percent for U.S. Seawater Desalination Systems

Unit Operation	On-site CT Energy Consumption, Calculated (BBtu/year)	On-site PM Energy Consumption, Calculated (BBtu/year)	PM Energy Savings* (CT-PM) (BBtu/year)	PM Energy Savings Percent** (CT-PM)/ (CT-TM)
System Type: Membrane Open-ocean (Semi-batch RO)				
Intake	3	3	0.3	39%
Pre-treatment	118	57	61	52%
Desalination***	1,434	645	789	81%
Post-treatment	48	37	12	24%
Concentrate Management	29	26	3	39%
Total System Type: Membrane Open-ocean******	**1,632**	**767**	**864**	**75%**

Current Typical (CT), Practical Minimum (PM), Thermodynamic Minimum (TM)
* PM energy savings is the *Current Opportunity* plus the *R&D Opportunity.*
** PM energy savings percent is the PM energy savings opportunity from transforming desalination system processes. Energy savings percent was calculated using TM energy consumption shown in Section 6 as the minimum energy consumption. The energy savings percent, with TM as the minimum, was calculated as follows: (CT-PM)/(CT-TM).
*** Unit operation conditions: semi-batch RO, feedwater salinity of 36,357 ppm, 42% recovery, 379 ppm product water, and plant capacity of 556 m^3/day (Gal and Efraty 2016).
**** Totals may not sum due to independent rounding.

The PM energy savings percent is the percent of energy saved with PM energy consumption compared to CT energy consumption, while referencing the thermodynamic minimum as the baseline energy consumption. Thermodynamic minimum (TM), discussed in detail in Chapter 3 of (Rao, et al. 2016) and in Chapter 6 of this report, is considered to be the ideal case with no losses (i.e., energy input to a system that is considered fully recoverable with no frictional losses; in other words, a thermodynamically reversible process). For processes where there is a separation of the components of a mixture, the TM represents the resulting change in the Gibbs free energy of the components (i.e., as for the removal of sodium chloride from seawater). For processes in which mechanical (or electrical) work drives the separation, TM represents the least of amount of work to go from the initial to final state. The TM represents the lowest possible energy requirement for a process operating under ideal conditions: no process can ever operate below the TM. Referencing TM as the baseline in comparing bands of energy consumption and calculating energy savings percent provides the most accurate measure of achievable savings potential. The equation for calculating on-site PM energy savings percent is:

$$PM\ Savings\ \% = \frac{CT - PM}{CT - TM}$$

The thermodynamic minimum of the desalination operation will depend upon the salinity of the inlet and product water streams and the recovery. When comparing two reported energy intensity values for the desalination operation for the purposes of understanding energy efficiency opportunity, an adjustment may be necessary to account for differences in the thermodynamic minimum if the two operations do not operate at the same conditions. The conditions of the energy intensity of the semi-batch RO system as cited in this report were at a higher salinity and lower recovery than the conditions used to define the CT. In this case, the impact on the thermodynamic minimum from the increase in salinity is mostly offset by the impact from the lower recovery. The TM energy intensity is 1.06 kWh_e/m^3 at the CT and SOA conditions and 1.05 kWh_e/m^3 at the PM conditions. Since the salinities and recoveries of the desalination operation for the CT, SOA, and PM used here are within 1% of each other, no further adjustment was made to the reported energy intensity, and subtracting out the thermodynamic minimum is considered sufficient to isolate the energy efficiency opportunity across bands.

5.2. Practical Minimum Technology Selections by Unit Operation

5.2.1. Intake and Concentrate Management

Section 3.2.1. discusses the energy requirements for intake and concentrate management (pumping water), as well as the calculation approach that was taken for this report to determine energy intensity. The pump and motor efficiencies were adjusted for the PM energy efficiency, assuming that a 20% increase in pump and motor efficiency could be achieved over current SOA technologies (Proceedings of the 6th International Conference eemods '09: Energy Efficiency in Motor Driven Systems 2009). The corresponding PM pump and motor efficiencies were calculated to be 84.8% and 96.6%, respectively. This results in an energy intensity of 0.0034 kWh_e/m^3-m TDH for both open-ocean and sub-surface intakes, as well as for concentrate management. For the purposes of this report, a value of one meter of TDH was assumed for all calculations.

5.2.2. Pre-treatment

For a seawater membrane-based desalination plant using a sub-surface intake (membrane sub-surface), the cartridge filtration system is provided in Table 5-1, with an energy intensity of 0.02 kWh_e/m^3, which was also assumed to be the same as the SOA energy intensity (Shahabi, McHugh and Ho 2015). This was assumed because no significant technologies uncovered during research fitting the PM definition were found to be more energy efficient. It is likely that other pre-treatment (e.g., bag filtration) will be used along with cartridge filtration in order to protect the RO membrane; however, energy intensity data were relatively unavailable, especially for the SOA energy band definition.

As noted in Section 4.2.2., the combined SOA energy intensity of 0.16 kWh_e/m^3 for the membrane open-ocean system's (open-ocean intake) pre-treatment involves a combination of flocculation, coagulation, sand filtration, and cartridge filtration. These pre-treatment methods are considered pressure-driven pre-treatment methods. For the PM pre-treatment options, the PM technology seen as the best fit with the lowest energy intensity was vacuum-driven microfiltration (MF) pre-treatment. This vacuum-driven system is estimated to use approximately 20% less energy than pressure-driven systems (Voutchkov 2010). Therefore, the estimated PM energy intensity for membrane open-ocean pre-treatment was calculated to be 0.13 kWh_e/m^3.

Nanofiltration (NF) operated in conjunction with chlorination is the technology identified for PM thermal pre-treatment. This technology was estimated to realize 30% energy savings over gravity-fed media filtration; the savings corresponds to a PM energy intensity of 0.035 kWh_e/m^3 (Hassan 2004, Hilal, et al. 2004).

5.2.3. Desalination

Semi-batch RO was chosen as the PM technology for the desalination unit operation for membrane seawater desalination systems, as it has been tested at pilot scale and is the current lowest reported energy intensity for the desalination unit operation as reported by multiple researchers (Gal and Efraty 2016, Jacangelo, Subramani and Voutchkov 2016). The lowest PM energy intensity reported for semi-batch RO is 1.48 kWh_e /m^3 for a 556 m^3/day capacity unit (Gal and Efraty 2016). This value was reported for unit operation conditions of 42% recovery, 36,357 ppm feedwater salinity, 379 ppm product water and a pressure of 48.5 bar (Gal and Efraty 2016).

Another development for reducing the energy intensity of seawater RO membranes is to increase permeability and selectivity. However, through the transitioning from cellulose acetate to thin film composite polyamide membranes at SOA plants, much of the opportunity for increased permeability has been realized. Further R&D into increased selectivity may yield additional energy saving opportunities, depending on the end-use application (Cohen-Tanugi, et al. 2014, Shrivastava, Rosenberg and Peery 2015, Werber, Deshmukh and Elimelech 2016).

Condensing MED was selected as the PM for the thermal desalination system, as it offered the lowest referenced energy intensity for a developing technology. This process requires a lower-steam extraction pressure (which can be as low as 4.4 psi) without an additional thermo-compressor, which lowers energy consumption (Sommariva 2010). 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 45,000 ppm, 33%–37.5% recovery, and product water salinity of <25 ppm (Sommariva 2010). A corresponding GOR was not reported.

5.2.4. Post-treatment

The PM energy intensity for both thermal and membrane post-treatment was assumed to be the same as the SOA. Based on research, there was limited R&D on improving the energy efficiency of post-treatment for both thermal and membrane systems.

5.3. Practical Minimum CO_2 Intensity and Emissions

The CO_2 emissions associated with the PM energy intensity for membrane and thermal systems were estimated. Carbon dioxide emissions estimates consider the emissions associated with generating, transmitting, and distributing the energy consumed on-site. The CO_2 emissions associated with the U.S. electric grid and purchased steam were considered. The method for estimating CO_2 emissions from electricity and steam (for thermal systems) was presented in sections 3.3. and 4.3.

Table 5-4 presents the CO_2 intensities based on the estimated on-site PM energy consumption for the seawater desalination system unit operations studied. The CO_2 intensities are presented in terms of lb CO_2 per m^3 of potable water produced for the pre-treatment, desalination, and post-treatment unit operations, and lb CO_2 per m^3 pumped water per m of TDH for the intake and concentrate management unit operations. Tables presented in kg $CO_2/kWh_{T,equiv}$ and emissions of kilotonnes CO_2/year can be found in Appendix A3. The PM CO_2 emissions for these unit operations are estimated to result in 124 thousand tons of CO_2 for membrane sub-surface system operations, 133 thousand tons of CO_2 for membrane open-ocean system operations, and 377 thousand tons of CO_2 for thermal system operations under 2016 U.S. seawater desalination installed production capacity. This corresponds to the annual emissions from 23,808 passenger vehicles for membrane sub-surface systems, 25,392 passenger vehicles for membrane open-ocean systems, and 72,119 passenger vehicles for the thermal system.

Table 5-4. Associated Practical Minimum CO_2 Intensities and Emissions for Seawater Desalination Systems

Unit Operation	On-site PM Electric Energy Intensity (kWh_e/m^3)	PM Thermal Energy Intensity ($kWh_{e,equiv}/m^3$)	CO_2 Electricity Emission Factor (lb CO_2 /$kWh_{T,equiv}$)	CO_2 Thermal Emission Factor (lb CO_2 /$kWh_{T,equiv}$)	CO_2 Emission Intensity (lb CO_2 / m^3)	Capacity (million m^3)	CO_2 Emissions (Mton CO_2/year)
System Type: Membrane Sub-surface (Semi-batch RO)							
Intake*	0.0034	N/A	1.18	N/A	0.004	255	1
Pre-treatment	0.02				0.02	128	2
Desalination**	1.48				1.75	128	111
Post-treatment	0.08				0.10	128	6
Concentrate Management*	0.0034				0.004	2,231	4
Total System Type: Membrane Sub-surface* **							**124**
System Type: Membrane Open-ocean (Semi-batch RO)							
Intake*	0.0034	N/A	1.18	N/A	0.004	255	1
Pre-treatment	0.13				0.15	128	10

Table 5-4. Associated Practical Minimum CO_2 Intensities and Emissions for Seawater Desalination Systems

Unit Operation	On-site PM Electric Energy Intensity (kWh_e/m^3)	PM Thermal Energy Intensity ($kWh_{e,equiv}/m^3$)	CO_2 Electricity Emission Factor (lb CO_2 /$kWh_{T,equiv}$)	CO_2 Thermal Emission Factor (lb CO_2 /$kWh_{T,equiv}$)	CO_2 Emission Intensity (lb CO_2 / m^3)	Capacity (million m^3)	CO_2 Emissions (Mton CO_2/year)
Desalination**	1.48				1.75	128	111
Post-treatment	0.08				0.10	128	6
Concentrate Management*	0.0034				0.004	2,231	4
Total System Type: Membrane Open-ocean* **							**133**
System Type: Thermal (Condensing MED)							
Intake*	0.0034	N/A		N/A	0.004	413	1
Pre-treatment	0.04				0.04	128	3
Desalination**	1.00	3.00	1.18	0.50	5.69****	128	363****
Post-treatment	0.11	N/A		N/A	0.13	128	9
Concentrate Management*	0.0034				0.004	1,071	2
Total System Type: Thermal* **							**377**

Practical Minimum (PM)

** To account for pump and motor efficiencies, as well as total dynamic head (TDH) loss, intake and concentrate management energy intensities were normalized per unit head loss (kWh_e/m^3-m TDH). For the PM energy intensity, a combined system efficiency of 82% was applied (pump efficiency * motor efficiency = 85% * 97% = 82%) (Proceedings of the 6th International Conference eemods '09: Energy Efficiency in Motor Driven Systems 2009). There were limited reported values in the literature for concentrate management; therefore, energy intensities for intake and concentrate management were assumed to be the same (as pumping is the primary energy-intensive mechanism for open-ocean intake and surface water discharge). Intake water was assumed to be standard seawater at 35,000 ppm. Concentrate was assumed to be diluted to 37,000 ppm to be discharged into the ocean.

*** Semi-batch RO unit operation conditions: semi-batch RO, feedwater salinity of 36,357 ppm, 42% recovery, 379 ppm product water, and plant capacity of 556 m^3/day.

Condensing MED unit operation conditions: feedwater salinity of 45,000 ppm, 33%–37.5% (35% average) recovery, product water salinity of <25 ppm, and 220–250 kPa pressure. Capacity not provided (Sommariva 2010).

* Totals may not sum due to independent rounding.

**** In calculating the emissions intensity and total emissions, the electrical equivalent thermal energy intensities ($kWh_{e,equiv}/m^3$) were divided by 33% to convert to thermal consumption, assuming a 33% generation, transmission, and distribution efficiency.

5.4. Sources for Practical Minimum Energy Intensity

To estimate PM energy consumption for this bandwidth analysis, a search of R&D activities to reduce the energy intensity of desalination systems was conducted. Any relevant technology developed at lab scale (or larger) but not available at commercial scale was considered as a candidate for the PM. Technologies that have been hypothesized or modeled, but not physically developed, were not considered. This study aims at assessing the desalination system from a feasibility standpoint, e.g., identifying energy savings opportunities from applied research and technologies that are above a technology readiness level (TRL) of two (laboratory scale). This work does not address fundamental matters related to desalination which can be found in the open literature. Further, it is recognized that the scale-up and integration of PM technologies may yield different energy intensities than those reported during lab-scale demonstrations. Many of the technologies identified were disqualified from consideration due to a lack of data from which to draw energy savings conclusions.

Appendix A4 provides an example of the range of technologies considered for evaluation, and explains the calculation methodology.

In some cases, there was a limited amount of information available on technologies for specific stages (such as pre-treatment and post-treatment), requiring best engineering judgment to be used in determining the PM energy intensity. Due to a lack of supporting energy-related information on R&D technologies for post-treatment, the PM energy intensity and consumption values were calculated to be the same as the SOA energy intensity and consumption values.

Table 5-5 presents some key sources consulted to identify PM energy intensities in seawater desalination.

Table 5-5. Sources Referenced in Identifying Practical Minimum Energy Intensity by Desalination Unit Operation and Total

Unit Operation	Source Abbreviation	Description
Intake, concentrate management	(Proceedings of the 6th International Conference eemods '09: Energy Efficiency in Motor Driven Systems 2009)	This report indicated energy savings of 20%–30% of pump and motor efficiencies. For the purposes of this analysis, 20% energy savings over SOA were assumed for energy efficiency improvement potentials.
Pre-treatment	(Voutchkov 2010)	According to this reference, vacuum-driven systems may use 10% to 30% less energy than pressure-driven systems for seawater sources of medium to high turbidity and temperature between 18 and 35°C.
Pre-treatment	(Hassan 2004, Hilal, et al. 2004)	This reference provided the PM energy savings for thermal pre-treatment, which was determined to be nanofiltration (NF) pre-treatment. This NF pre-treatment lowered both the process energy consumption and water cost by about 30% or more.
Desalination (membrane)	(Gal and Efraty 2016)	The closed-circuit desalination technique was demonstrated to have higher recovery without the need for an energy recovery device (ERD). This study reported experimental trials for a Mediterranean-derived feed (TDS 33,801–37,197 ppm) for a flux, recovery and temperature range of 9.2–13.5 liter/m^2/hour, 42%–53% and 15.0–18.4°C, respectively. The PM value chosen was 1.483 kWh$_e$/m^3 for 42% recovery at 36,357 ppm feed and 379 ppm product water.
Desalination (thermal)	(Sommariva 2010)	Condensing MED was considered as a PM technology. According to Figure 6.10 of reference, the low value energy intensities were chosen as 4 kWh$_{T,equiv}$/m^3 (thermal 3 kWh$_{e,equiv}$/m^3 and electric 1 kWh$_e$/m^3).
Post-treatment	(Dundorf, et al. 2009, Park and Bennett 2010)	Limited R&D was found in the area of post-treatment, and all sources located reported either higher energy intensity values (e.g., (Shemer, Hasson and Semiat 2015)) or no energy intensity values. Therefore, no energy savings between SOA and PM were assumed.

Desalination R&D, specifically the desalination unit operation, is very active today. As a result, there were many different types of technologies that were discovered in the literature search, though not all of them had associated energy savings and they varied in the current implementation level (e.g., lab scale, pilot scale, size of pilot scale, etc.). The lower limit for on-site PM energy intensity for the desalination unit operation was the lowest referenceable value from the technologies researched that included system conditions (e.g., recovery, salinity). While full details on technologies identified are provided in Appendix A4, a summary is shown below in Table 5-6. This table provides an overview of the technologies and their energy intensities; ultimately the technology that fit the definition of PM and offered the lowest energy intensity for seawater was chosen as the basis for the membrane and thermal systems in the following section. For a different feedwater, the selection of PM would likely be different.

Semi-batch RO was chosen as the PM technology for membrane desalination systems with an energy intensity of 1.48 kWh_e/m^3, while condensing MED was chosen as the PM technology for thermal desalination systems 4.00 $kWh_{T,equiv}/m^3$ (3.00 $kWh_{e,equiv}/m^3$ thermal energy plus 1.00 kWh_e/m^3 electrical energy) (Gal and Efraty 2016, Sommariva 2010). These were the lowest energy intensity values for the technologies identified and researched with data recently available. It is recognized that many R&D technologies are tested at lower capacity scales than what is considered to be needed for fully operational commercial plants. Energy intensities will likely change with different operational scales; this analysis is based on speculative technologies but does provide a baseline from which the R&D sector can gain an understanding of the level of opportunity for the unit operation and system as a whole.

Table 5-6. Summary of Practical Minimum Energy Intensities for Desalination Unit Operation

Technology	Energy Intensity or Energy Savings Percentage Referenced	Description and Reference(s)
Membrane Desalination		
Semi-batch RO* (also referred to as *closed-circuit desalination*)	1.48 kWh_e/m^3	*Summary:* Membrane separation process using a semi-batch that recirculates concentrate back into the RO process, lowering energy consumption by staging the pressurization of the feedwater. Energy savings from semi-batch RO were reported both by (Gal and Efraty 2016) and (Jacangelo, Subramani and Voutchkov 2016). The energy intensity values from (Gal and Efraty 2016) were chosen for the PM, as they were the lowest reported in the literature. *Conditions:* 42% recovery; 36,357 ppm feed salinity; 379 ppm product salinity; 7.35 m^3/hour flow rate; 48.5 bar pressure *Reference:* (Gal and Efraty 2016)
Forward osmosis (FO)	N/A	*Summary:* Forward osmosis is a newer technology compared to RO and has recently become commercially available for limited industrial applications such as the treatment of oil- and gas-produced water and municipal wastewater. However, FO can only generate potable water from saline sources if coupled with a secondary thermal or membrane desalination process, making it more energy intensive than RO. See Section 8.2.1.2 in (Rao, et al. 2016) for more detail.
Electrodialysis (ED) and Continuous Electrodeionization (CEDI)	50% less energy	*Summary:* Desalination technique where salt ions are continuously transferred through ion exchange membranes. *Conditions:* 30% recovery; 32,000 ppm feed salinity; 475 ppm product salinity; 1.9 m^3/hour flow rate; 0.65 bar pressure drop; 75% pump efficiency *Reference*: (Knauf, et al. 2011)

Table 5-6. Summary of Practical Minimum Energy Intensities for Desalination Unit Operation

Technology	Energy Intensity or Energy Savings Percentage Referenced	Description and Reference(s)
Countercurrent membrane cascade with recycling (CMCR) (also referred to as *energy-efficient reverse osmosis* [EERO])	2.75 kWh_e/m^3	*Summary:* RO system coupled with two stages of processing utilizing a countercurrent membrane cascade with recycling (CMCR). *Conditions:* 75% recovery; 35,000 ppm feed salinity; 350 ppm product salinity; 74.1 bar pressure *Reference*: (Chong, Loo and Krantz 2014)
Batch RO	"Significantly less energy than continuous RO over a wide range of recovery ratios and source water salinities"	*Summary:* Reverse osmosis process that recirculates concentrate through the membrane module without adding additional feedwater until a desired salinity is reached. This technology has not yet been tested at a laboratory scale, and at the time of publication results were only reported using modeling and analysis. It thus did not meet the PM definitions for the purposes of this report. *Conditions:* N/A *Reference(s):* (Warsinger, et al. 2016, Werber, Deshmukh and Elimelech 2017)
High permeability membranes/ultra-permeable membranes	15% less energy for given RO plant with a given capacity and recovery	*Summary:* Increased permeability of membranes would reduce the pressure vessel requirement and as a result reduce the energy requirement for RO desalination. However, increasing membrane permeability will eventually affect the selectivity and, ultimately, quality of the product water. *Conditions:* Varies; reference used feedwater of 42,000 ppm, 42% recovery, and 300 m^2/day as a basis for calculations. *Reference:* (Cohen-Tanugi, et al. 2014)
Thermal Desalination		
Condensing MED*	4.00 $kWh_{T,equiv}/m^3$ (3.00 $kWh_{e,equiv}/m^3$ thermal + 1.00 kWh_e/m^3 electrical)	*Summary:* Thermal separation process requiring a lower steam extraction pressure compared to typical thermal units (as low as 0.3 bar), and no additional thermo-compressor, which lowers energy consumption. Significant cooling water volumes are required. *Conditions:* 33.0%–37.5% recovery; 45,000 ppm feed salinity; <25 ppm product salinity; 40 kPa steam pressure *Reference*: (Sommariva 2010)
Multi-stage flash fluidized bed evaporator	14.20 $kWh_{T,equiv}/m^3$ (11.30 $kWh_{e,equiv}/m^3$ thermal + 2.90 kWh_e/m^3 electrical)	*Summary:* Thermal process where the feedwater is heated with steam while fed at a lower pressure drop, which lowers electrical power. Significant cooling water volumes are required. *Conditions:* 80,000 m^3/day flow rate *Reference*: (Ghiazza, Borsani and Alt 2013)

Table 5-6. Summary of Practical Minimum Energy Intensities for Desalination Unit Operation

Technology	Energy Intensity or Energy Savings Percentage Referenced	Description and Reference(s)
Humidification-dehumidification desalination (HDD)	22–40 $kWh_{T,equiv}/m^3$	*Summary:* Thermal method requiring two direct contact heat exchangers (specifically for humidification and dehumidification purposes) to desalinate water. *Conditions:* 0.6% recovery; 1.7 m^3/day flow rate *Reference*: (Eslamimanesh and Hatamipour 2010, Narayan, et al. 2013)
Freeze desalination	8–12 $kWh_{T,equiv}/m^3$	*Summary:* Thermal desalination process that freezes water in order to separate saline and concentrate components (values reported for freeze concentration system with two-stage compression using tubular heat exchanger). *Conditions:* None reported *Reference*: (Rane and Padiya 2011)
Membrane distillation	5.60–13.50 $kWh_{T,equiv}/m^3$ (5.00-12.00 $kWh_{e,equiv}/m^3$ thermal + 0.60–1.50 kWh_e/m^3 electrical)	*Summary:* Thermal, membrane-based separation process using the vapor pressure difference across the membrane between water at different temperatures on either side of the membrane, a concentration gradient, or an electrical potential gradient, which drives mass transfer through a membrane (Scarab test site values). *Conditions:* 40-50% recovery *Reference*: (Camacho, et al. 2013)

* Chosen as the PM energy intensity for the desalination unit operation, as it resulted in the lowest energy intensity, which is the focus of this study.

6. Thermodynamic Minimum Energy Intensity and Energy Consumption for U.S. Seawater Desalination

Seawater desalination does not occur under theoretically ideal conditions; however, understanding the theoretical minimum amount of energy required to desalinate seawater provides a lower bound beyond which further energy savings would be thermodynamically impossible. This lower bound energy intensity can be used to establish more realistic expectations for future R&D energy savings. For a more detailed discussion on the thermodynamic minimum for desalination, please refer to Chapter 3 in the Volume 1 report (Rao, et al. 2016).

This chapter presents the thermodynamic minimum (TM) energy consumption required for the unit operations studied. TM energy consumption, which is based on change in Gibbs free energy (ΔG) calculations (for the desalination operation) and physical kinetics (for the intake and concentrate management), and assumes ideal conditions that are unachievable in real-world applications. TM energy consumption assumes that all energy is used without any losses (zero entropy generation) and that energy is ultimately conserved by the system (i.e., all energy used to produce useful work, which in this case is the removal of solutes from water). For pre- and post-treatment operations, the thermodynamic minimum was considered negligible. No desalination system unit operation can attain these values in practice. A reasonable near-term goal for energy efficiency based on today's understanding and state of research would be the practical minimum (see Chapter 5); though new technologies may eventually bring the PM closer to the TM.

6.1. Thermodynamic Minimum Energy Intensity and Energy Consumption

Table 6-1 provides the TM energy intensities in $kWh_{T,equiv}$ per m^3 and energy consumption in BBtu per year for the desalination system unit operations studied. A table presented in GWh per year can be found in Appendix A3. Ideal conditions are unrealistic goals in practice and these values serve only as a guide to estimating energy savings opportunities. The TM energy consumption was used to calculate the *current* and *R&D* energy savings percentages. Based on the definitions used in this report, if all the 2016 installed production capacity of potable water from seawater desalination occurred at TM energy intensity, then there would be 100% energy savings.

Table 6-1. On-site Thermodynamic Minimum Energy Consumption for Seawater Desalination Systems

Unit Operation	On-site TM Energy Intensity ($kWh_{T,equiv}/m^3$)	On-site TM Energy Consumption, Calculated (BBtu/year)
System Type: Membrane Sub-surface and Open-ocean		
Intake*	0.0028	1
Pre-treatment	0.00	0
Desalination @ CT and SOA conditions**	1.06	135
Desalination @ PM conditions***	1.05	134
Post-treatment	0.00	0
Concentrate Management*	0.0028	6
Total System Type: Membrane Sub-surface and Open-ocean******		**142**
System Type: Thermal (MED)		
Intake*	0.0028	1
Pre-treatment	0.00	0
Desalination*****	1.20	153
Post-treatment	0.00	0
Concentrate Management*	0.0028	6
Total System Type: Thermal******		**160**

Thermodynamic minimum (TM)

* To account for pump and motor efficiencies, as well as total dynamic head (TDH) loss, intake and concentrate management energy intensities were normalized per unit head loss (kWh_e/m^3-m TDH). For the TM energy intensity, a combined system efficiency of 100% was assumed. There were limited reported values in the literature for concentrate management; therefore, energy intensities for intake and concentrate management were assumed to be the same (as pumping is the primary energy-intensive mechanism for open-ocean intake and surface water discharge). Intake water was assumed to be standard seawater at 35,000 ppm. Concentrate was assumed to be diluted to 37,000 ppm to be discharged into the ocean.
** Unit operation conditions: 50% recovery of 0 ppm product water from 35,000 ppm and 25˚C feedwater (CT and SOA conditions)
*** Unit operation conditions: 42% recovery of 0 ppm product water from 36,357 ppm and 25˚C feedwater (PM conditions)
**** Totals may not sum due to independent rounding.
***** Unit operation conditions: 35% recovery of 0 ppm product water from 45,000 ppm and 25˚C feedwater (SOA and PM thermal conditions)

6.2. Thermodynamic Minimum Energy Intensity by Unit Operation

The thermodynamic minimum energy intensity was calculated for each sub-process. The TM energy intensity calculation is path independent (state function), and depends only on the difference between the starting and ending material and energy content. It would not change if the process had greater or fewer process steps.

In this report, TM energy consumption is referenced as the baseline (or minimum amount of energy) when calculating the absolute energy savings potential. The equations used to determine the absolute energy savings for SOA and PM are as follows:

$$SOA\ Savings\ \% = \frac{CT - SOA}{CT - TM}$$

$$PM\ Savings\ \% = \frac{CT - PM}{CT - TM}$$

For the purposes of this report, this percent energy savings approach results in more realistic and comparable energy savings estimates from energy efficiency improvements. Using zero as the baseline (or minimum amount of energy) would exaggerate the total bandwidth to which SOA energy savings and PM energy savings are compared to determine the energy savings percent. When TM energy consumption is referenced as the baseline, SOA energy savings and PM energy savings are relatively more comparable, resulting in more accurate energy savings percentages.

Further, when comparing two reported energy intensity values for the desalination operation for the purposes of understanding energy efficiency opportunity, an adjustment may be necessary to account for differences in the thermodynamic minimum if the two operations do not operate at the same conditions. For example, the thermal (1.20 $kWh_{T,equiv}/m^3$) and the membrane technologies (1.05 and 1.06 $kWh_{T,equiv}/m^3$) differ by approximately 12% due to the different salinity and recovery operating conditions. A direct comparison between the SOA and/or PM energy intensity for the thermal and membrane systems may exaggerate the relative energy efficiency at which each process produces potable water because it will not take into account the impact of the different operating conditions on the energy requirements. Subtracting out the thermodynamic minimum and comparing across technologies factors out differing operating conditions and provides a better comparison of energy saving opportunities.

The TM for the intake and concentrate management was calculated based on the energy required to move water. The equation found in Section 3.2.1. was used for the TM, assuming a motor and pump efficiency of 100%.

The TM for the pre- and post-treatment was considered to be negligible. This is reasoned because neither of these steps would be required in the ideal case where water with only dissolved salts (such as seawater as assumed in this report for the TM) is used to produce pure (0 ppm) water (as assumed in this report for the TM). In practice, energy is required for these steps because the intake water is not pure seawater and 0 ppm product water would not meet drinking water requirements.

The TM for the desalination operation considered its dependency on feedwater and product water salinity and recovery. Several references, as cited in Chapter 3 of the Volume 1 report, provide relations for estimating the thermodynamic minimum. Three of these references were used in the analysis for this report: (Mistry, et al. 2011, Nayar, et al. 2016, Sharqawy, Lienhard and Zubair 2010). These references provided the equations and seawater properties used to calculate the thermodynamic minimum for the desalination operation for the conditions specified.

The TM calculation approach adopted here is independent of the desalination process chosen. However, the ability to operate at the reversible limit cited here is not the same for each desalination process. For a treatment on the entropy generation associated with each of the various components (i.e., pumping, expanding, compressing) of a desalination system, see (Lienhard, et al. 2017, Mistry, et al. 2011). The consideration of where entropy is generated within each system will allow researchers to better understand the sources and magnitudes of entropy generation by process within a desalination system, and potentially develop techniques/processes to lower the entropy generation. This additional analysis was not within the scope of the present work.

7. U.S. Seawater Desalination Current and R&D Opportunity Analysis

7.1. Current and R&D Energy Reduction Opportunities

Table 7-1 presents the *current opportunity* and *R&D opportunity* energy savings in BBtu per year for the systems and unit operations studied for producing potable water at municipal scale from seawater within the boundaries considered for this study. A table presented in GWh per year for energy consumption can be found in Appendix A3. Each row in Table 7-1 shows the opportunity bandwidth for an individual unit operation as well as for the whole desalination system. As previously noted, the energy savings opportunities presented reflect the estimated production of potable water from seawater desalination in baseline year of 2016 and are adjusted for the TM.

As shown in Figure 7-1, two hypothetical opportunity bandwidths for energy savings are estimated for the system chosen as best representative for the United States—membrane open-ocean (RO desalination with an open-ocean intake) as defined in Chapter 2. To complete the unit operations studied, the analysis shows the following:

- *Current Opportunity:* 320 BBtu per year of energy savings over current operations could be obtained if state of the art technologies and practices are deployed.
- *R&D Opportunity:* 544 BBtu per year of additional energy savings could be attained in the future if applied R&D technologies under development worldwide are deployed (i.e., reaching the practical minimum).

Figure 7-1 also shows the estimated *current* and *R&D* energy savings opportunities for individual desalination system unit operations for the membrane open-ocean intake system. The area between *R&D opportunity* and *impractical* is shown as a dashed line with color fading because the PM energy savings impacts are based on research at the laboratory scale as made public at the time of this publication; emerging technologies being investigated through modeling and theoretical calculations may eventually bring the PM energy consumption further into the faded region and closer to the TM energy consumption. From the unit operations studied, the greatest *current* and *R&D* energy savings opportunity for seawater desalination comes from upgrading the desalination unit operation—this is largely because a significant amount of energy consumed in seawater desalination occurs in this step.

If a “leap-frog” of technology were to occur, whereby U.S. seawater desalination facilities were to implement all identified PM technologies and practices directly without implementing SOA technologies and practices first, the resulting energy savings (*PM Energy Savings*) would be 864 BBtu per year.

Table 7-1. Current and R&D Opportunity for Seawater Desalination

Unit Operation	Current Opportunity (CT-SOA) (BBtu/year)	R&D Opportunity (SOA-PM) (BBtu/year)
System Type: Membrane Sub-surface (Reverse osmosis)		
Intake	0.2	0.2
Pre-treatment	0	0
Desalination*	259	530
Post-treatment	12	0
Concentrate Management	2	1
Total System: Membrane sub-surface**	**272**	**531**
System Type: Membrane Open-ocean (Reverse osmosis)		
Intake	0.2	0.2
Pre-treatment	48	13
Desalination*	259	530
Post-treatment	12	0
Concentrate Management	2	1
Total System: Membrane Open-ocean**	**320**	**544**
System Type: Thermal (MED)		
Intake	N/A	0.2
Pre-treatment		7
Desalination***		3,045
Post-treatment		0
Concentrate Management		1
Total System: Thermal**	**N/A**	**3,053**
U.S. Total "Best" Fit: Membrane Open-ocean	**320**	**544**

Current typical (CT), state of the art (SOA), practical minimum (PM)
* Unit operation conditions: CT and SOA: RO-based system at 50% recovery of 500 ppm product water from 35,000 ppm feedwater (Voutchkov 2013, Personal communication with plant employee 2017). PM: semi-batch RO-based system at 42% recovery of 379 ppm product water from 36,357 ppm feedwater (Gal and Efraty 2016).
** Totals may not sum due to independent rounding.
*** Unit operation conditions: SOA technology is MED-TVC, PM technology is condensing MED; feedwater salinity of 45,000 ppm, 33%–37.5% (35% average) recovery, product water salinity of <25 ppm, and 220–250 kPa pressure. Capacity not provided (Sommariva 2010).

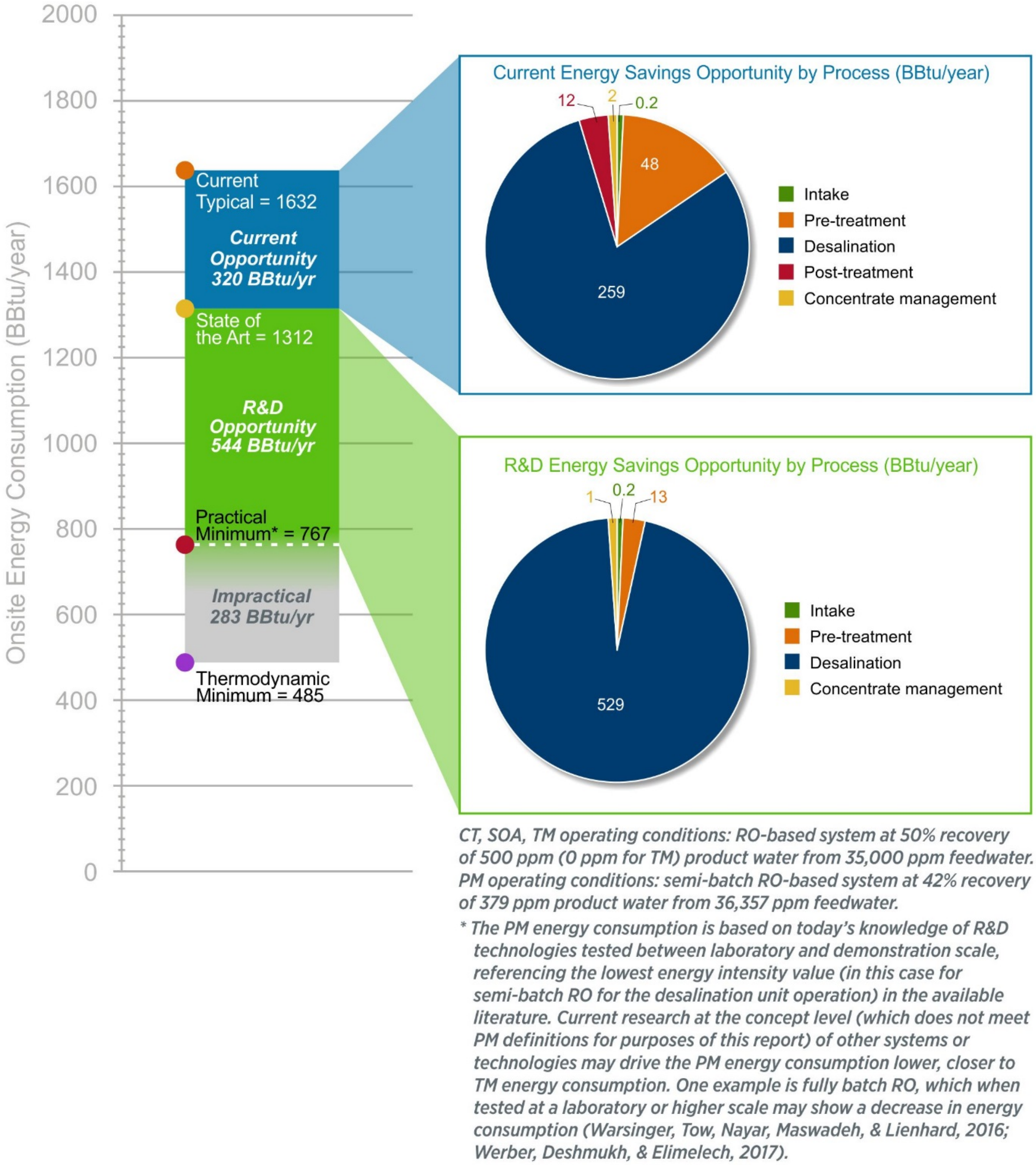

Figure 7-1. Current and R&D energy savings opportunities for open-ocean intake RO desalination system
Source: EERE

Figure 7-2 compares the on-site energy consumption for membrane and thermal seawater desalination. As noted, the difference between membrane sub-surface and membrane open-ocean are the intake and pre-treatment methods utilized. Membrane sub-surface intake and pre-treatment processes are sub-surface intake and cartridge filtration, respectively. Membrane open-ocean intake and pre-treatment processes are open-ocean intake and flocculation, coagulation, sand filtration, and cartridge filtration pre-treatment, respectively. As a point of reference, the energy consumption for sourcing the same volume of water from freshwater instead would be 127 BBtu (37 GWh), assuming a national energy intensity for freshwater extraction, conveyance, and treatment of 0.29 kWh_e/m^3. This national average varies throughout the United States; in Southern California, it is 2.6 kWh_e/m^3, and the resulting energy consumption for sourcing the same volume of potable water but from freshwater in Southern California is 1,136 BBtu (333 GWh).

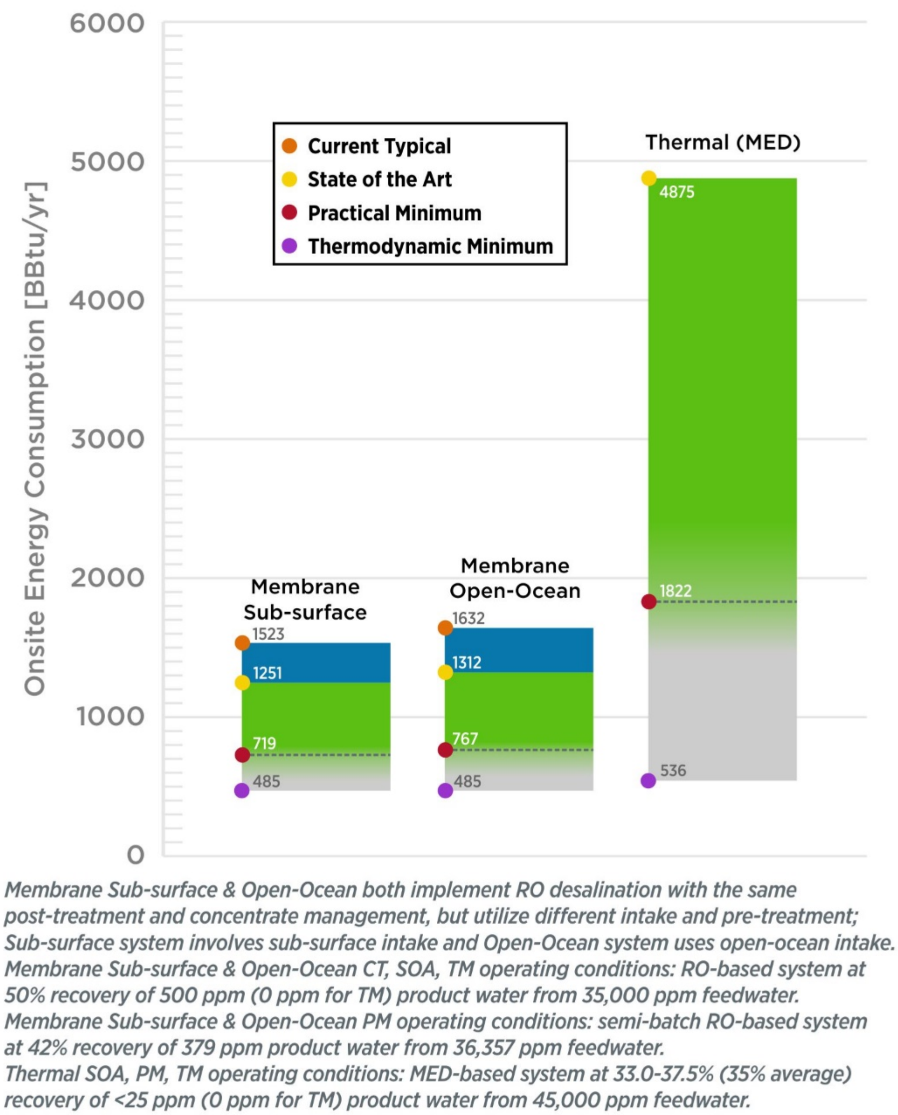

Figure 7-2. Current and R&D energy savings opportunities in U.S. seawater membrane and thermal desalination systems for the unit operations studied

Source: EERE

Note: Membrane Sub-surface and Membrane Open-Ocean both implement RO desalination with the same post-treatment (remineralization and disinfection) and concentrate management (surface water discharge), but they use different intake and pre-treatment methods. Membrane Sub-surface utilizes sub-surface intake with cartridge and bag filtration pre-treatment, while Membrane Open-Ocean utilizes open-ocean intake with flocculation, coagulation, and sand and cartridge filtration. The thermal system does not have a CT value as it is not currently used for seawater desalination in the United States.

As previously mentioned, CT for thermal was not considered in this analysis because there are no known thermal seawater desalination installations in the U.S in 2016 (the baseline year for this report). However, while the energy consumption of thermal systems is significantly higher than membrane systems, use of waste heat from other processes and/or renewable thermal energy may provide a low-cost and clean source of energy to power thermal desalination plants. Figure 7-3 describes the breakout of thermal desalination energy savings by electrical and fuel sources. This indicates that energy savings in thermal desalination are heavily reliant on minimizing consumption of fuel sources. Fuel sources in thermal desalination accounted for approximately 89% the total energy savings for the R&D opportunity (SOA-PM).

Realizing deeper energy savings beyond the PM levels (*impractical* bandwidth in this report) would require fundamental R&D. The term *impractical* is used because the PM energy consumption is based on today's knowledge of R&D technologies tested between laboratory and demonstration scale; further decreases in energy intensity have not been displayed at any physical scale. However, decreasing the PM energy consumption with future R&D efforts in desalination may be possible. Fully batch RO is one example of a desalination technology that has shown energy savings potential based on models, but no physical demonstration of these energy savings has been made public. When tested at a laboratory or higher scale, fully batch RO may show a decrease in energy consumption over the technology chosen for the PM in this report (semi-batch RO), but this would be dependent on overcoming any challenges associated with scale-up and integration with the rest of the desalination system (Warsinger, et al. 2016, Werber, Deshmukh and Elimelech 2017).

Decreasing beyond the TM energy consumption is not possible. The TM energy intensity represented here is a lower level that will apply to any technology seeking to achieve the desired output product (e.g., potable water). The TM energy consumption is based on ideal conditions that are typically unattainable in commercial applications. It was used as the baseline for calculating the energy savings potentials (instead of zero) to provide more accurate targets of energy savings opportunities.

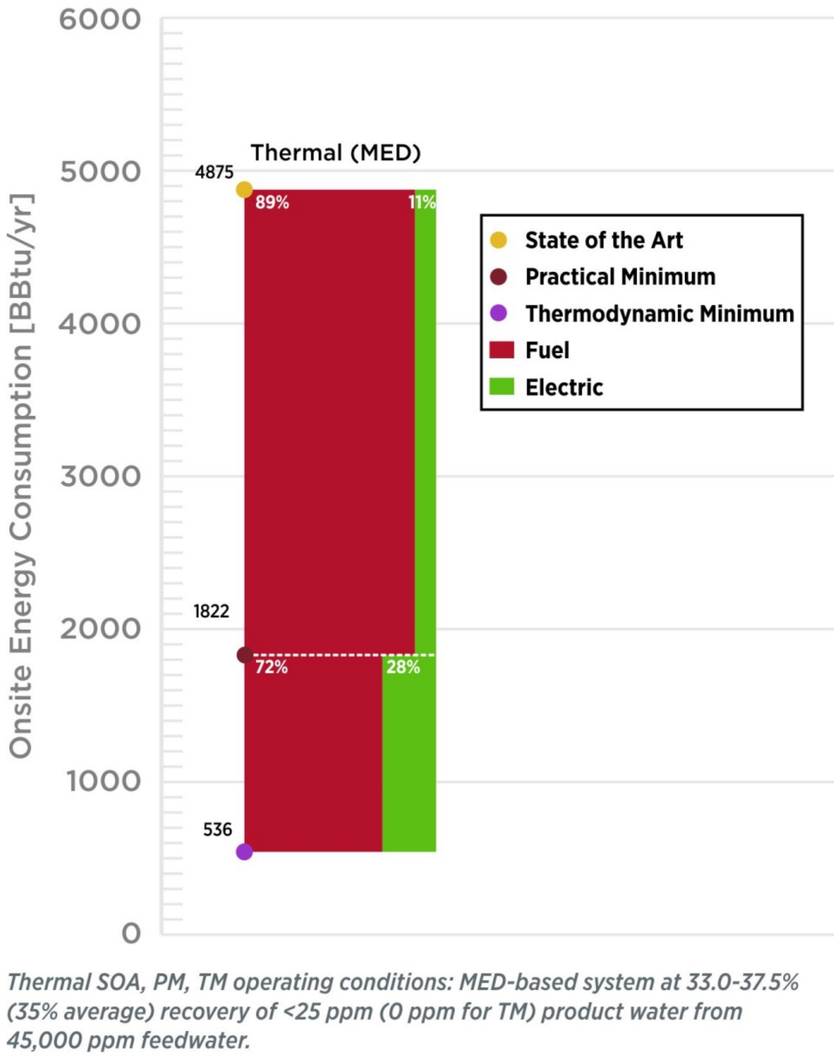

Figure 7-3. R&D energy savings opportunities in U.S. seawater thermal desalination systems for unit operations studied broken out by thermal and electric energy source
Source: EERE

7.2. CO_2 Emissions for CT, SOA, and PM Energy Consumption

Table 7-2 shows CO_2 emissions associated with the CT, SOA, and PM energy consumption for seawater desalination systems. As described in previous chapters, the CO_2 emissions are calculated based on the energy intensities (and energy sources) for each unit operation. Because CO_2 reductions were not studied in detail (aside from the reduction in CO_2 directly related to the reduction in energy intensity), comparisons across bands should not be considered either current or R&D opportunity emissions savings. This study focused on energy reduction opportunities; it did not comprehensively consider other CO_2 reduction opportunities (e.g., integration of renewable energy, waste heat utilization).

Table 7-2. Summary of Associated CO_2 Emissions for Seawater Desalination Systems

Unit Operation	CT CO_2 Emissions (Mton CO_2/year)	SOA CO_2 Emissions (Mton CO_2/year)	PM CO_2 Emissions (Mton CO_2/year)
System Type: Membrane Sub-surface			
Intake	1	1	1
Pre-treatment	2	2	2
Desalination*	248	203	111
Post-treatment	8	6	6
Concentrate Management	5	5	4
Total System: Membrane Sub-surface**	**263**	**216**	**124**
System Type: Membrane Open-ocean			
Intake	1	1	1
Pre-treatment	20	12	10
Desalination*	248	203	111
Post-treatment	8	6	6
Concentrate Management	5	5	4
Total System: Membrane Open-ocean**	**282**	**227**	**133**
System Type: Thermal			
Intake	N/A	1	1
Pre-treatment	N/A	4	3
Desalination***	N/A	1,033	363
Post-treatment	N/A	9	9
Concentrate Management	N/A	2	2
Total System: Thermal**	**N/A**	**1,049**	**377**
U.S. Total "Best" Fit: Membrane Open-ocean	**282**	**227**	**133**

Current typical (CT), state of the art (SOA), practical minimum (PM)
* Unit operation conditions: CT and SOA: RO-based system at 50% recovery of 500 ppm product water from 35,000 ppm feedwater (Voutchkov 2013, Personal communication with plant employee 2017). PM: semi-batch RO-based system at 42% recovery of 379 ppm product water from 36,357 ppm feedwater (Gal and Efraty 2016).
** Totals may not sum due to independent rounding.
*** Unit operation conditions: SOA technology is MED-TVC, PM technology is condensing MED; feedwater salinity of 45,000 ppm, 33%–37.5% (35% average) recovery, product water salinity of <25 ppm, and 220–250 kPa pressure. Capacity not provided (Sommariva 2010).

8. Estimated Reduction in Total Cost of Water Attributable to SOA and PM Energy Intensity Reductions

Energy intensities and energy saving opportunities for membrane and thermal desalination technologies are discussed in detail in this bandwidth study. This section builds on the findings of this report and determines cost savings associated with these energy saving opportunities.

Several factors influence the cost of water produced through desalination. Major cost categories for determining unit production cost of water in dollars per cubic meter are discussed in the Volume 1 report (Rao, et al. 2016). The energy intensity of desalination has declined significantly in recent years due to technological advancements. These have likely led to energy cost reductions after normalizing for changes in energy unit costs (e.g., $/kWh$_e$) over time. However, cost categories such as annualized capital cost, raw materials, and energy remain significant contributors to the cost of potable water production through desalination. Energy cost alone makes up 44% (membrane) to 50% (thermal) of the total cost of water produced at typical seawater desalination plants (PIER 2011). Other cost components of desalination systems are shown in Figure 8-1, but are beyond the scope of this work. This bandwidth study focuses only on the cost savings resulting from the energy intensity reductions associated with each of the identified bands.

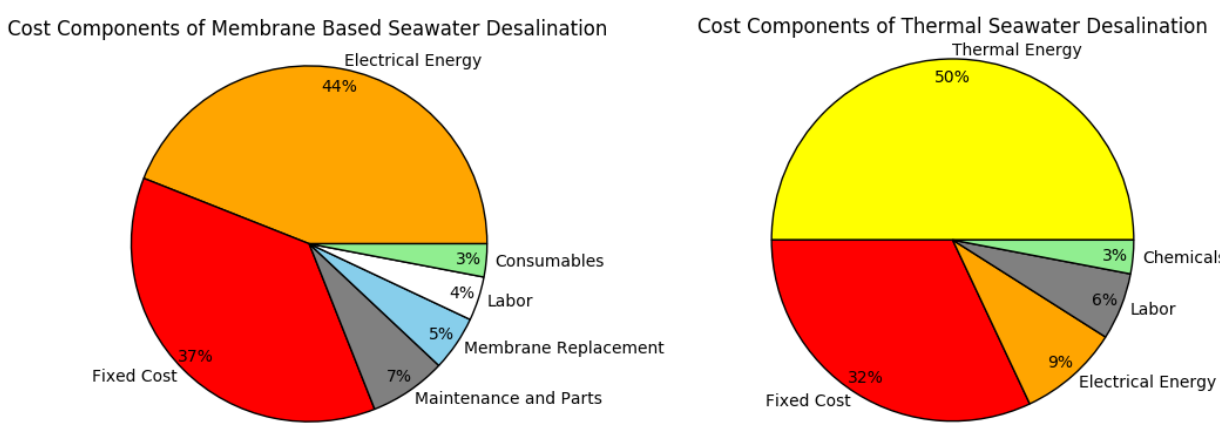

Figure 8-1. Cost components of membrane - (left) and thermal - (right) based seawater desalination systems
Source: (Public Interest Energy Research 2011)

Table 8-1 summarizes energy intensity and estimated energy saving opportunities per unit of potable water production in the United States under different technology bands for membrane and thermal systems.

Table 8-1. Energy Intensity and Energy Saving Opportunities for Seawater Desalination Systems

Technology Band	Energy Intensity ($kWh_{T,equiv}/m^3$)	Opportunity Band	Estimated Energy Saving Opportunity* ($kWh_{T,equiv}/m^3$)	Estimated Energy Saving Opportunity* (%)
System Type: Membrane Open-ocean (Reverse Osmosis)				
CT	3.68	N/A	N/A	N/A
SOA	2.95	Current (CT-SOA)	0.73	28%
PM	1.70	R&D (SOA-PM)	1.25	47%
TM	1.07	TM (PM-TM)	0.64	25%

Table 8-1. Energy Intensity and Energy Saving Opportunities for Seawater Desalination Systems

Technology Band	Energy Intensity ($kWh_{T,equiv}/m^3$)	Opportunity Band	Estimated Energy Saving Opportunity* ($kWh_{T,equiv}/m^3$)	Estimated Energy Saving Opportunity* (%)
System Type: Membrane Open-ocean (Reverse Osmosis)				
System Type: Thermal				
CT	N/A	N/A	N/A	N/A
SOA	11.17	Current (CT-SOA)	N/A	N/A
PM	4.16	R&D (SOA-PM)	7.01	70%
TM	1.21	TM (PM-TM)	2.95	30%

* The energy savings percent, with TM as the minimum was calculated as follows:
Membrane: Current = (CT-SOA)/(CT-TM), R&D = (SOA-PM)/(CT-TM), TM = (SOA-TM)/(CT-TM)
Thermal: R&D = (SOA-PM)/(SOA-TM), TM = (SOA-TM)/(SOA-TM)

Reductions in energy cost of water for CT, PM, and TM are then calculated assuming 44% energy cost for membrane and 50% for thermal technologies. A summary of percent energy cost savings estimated for each opportunity band is presented in Table 8-2. The selected open-ocean membrane system can reduce its energy cost by a total of 33% through realizing current (12%) and R&D (21%) opportunities. Thermal technologies can observe a higher energy cost reduction of 35% through adopting R&D technologies.

Table 8-2. Energy Cost Savings Opportunities for Seawater Desalination Systems

Opportunity Band	Cost Savings Opportunity Fraction of Energy Cost x Energy Saving Opportunity (%)
System Type: Membrane Open-ocean	
Current Opportunity (CT-SOA)	12%
R&D Opportunity (SOA-PM)	21%
TM Opportunity (PM-TM)*	11%
System Type: Thermal	
Current Opportunity (CT-SOA)	N/A
R&D Opportunity (SOA-PM)	35%
TM Opportunity (PM-TM)*	15%

* Cost savings beyond the PM technology band is not achievable due to thermodynamic limitations but is provided here for reference.

Impact of energy cost savings on the total cost of water can be determined for membrane technologies by assuming a representative cost of $1.78/m^3 (cost of water produced at Claude “Bud” Lewis Carlsbad desalination plant) (Personal communication with plant employee 2017). Therefore, the energy cost share of the cost of water (“energy cost of water”) for the SOA technology would be $0.78/m^3. Total cost of water for other technology bands could then be calculated using the energy saving percentages calculated in Table 8-2. Energy and total cost of water for different technology bands are summarized in Table 8-3.

Table 8-3. Energy and Total Cost of Water Production Through Seawater Desalination Systems Using RO Membranes with Open Ocean Intake

Technology Band	Energy Cost of Water ($/m³)	Total Cost of Water ($/m³)
CT	0.89	2.00
SOA	0.78	1.78
PM	0.61	1.41
TM*	0.56	1.26

* Cost savings beyond the PM technology band is not achievable due to thermodynamic limitations but is provided here for reference.

Another variable that can have a significant impact on the unit production cost of water is the price of energy, especially electricity. The price of electricity varies by location and can range from $0.003/kWh$_e$ (Kansas Electric Power Cooperative) to $1.00/kWh$_e$ (Plumas-Sierra Rural Electric Cooperative). Therefore, a desalination plant in San Diego Gas and Electric’s territory (with an industrial electricity rate of $0.18/kWh$_e$) will observe double the cost savings per unit of water compared to a plant operating in Tampa Electric Company’s territory (with an industrial electricity rate of $0.09/kWh$_e$) (U.S. Energy Information Administration 2017a). In general, energy cost savings calculated in this section and presented in Table 8-3 are strong functions of the energy prices. Fluctuations in future energy prices can have a significant impact on the results of this simple analysis.

9. Seawater Desalination Uptake Scenarios

In 2016, less than 0.5% of U.S. municipal potable water was sourced from seawater. As water costs from freshwater sources continue to rise and options for freshwater supply are exhausted in some areas of the United States, regions may look to alternate freshwater sources, including seawater, to diversify their water supply portfolio. This chapter seeks to provide a better understanding of the energy consumption implications of increasing the uptake of seawater desalination in the United States. It investigates two scenarios, with the energy consumption evaluated at multiple uptake conditions for each. The scenarios are:

1) Supplying the public water demand for all of the continental United States' counties with desalinated water from U.S. coastal areas, and
2) Supplying all water-stressed regions (as defined later in this section) of the continental United States with desalinated water from U.S. coastal areas.

Each scenario evaluates the energy consumption implication at uptake volumes corresponding to public water demand within prescribed distances and elevations from a coastline.

Only seawater from the Atlantic Ocean, Pacific Ocean, and Gulf of Mexico are considered. The energy requirements evaluated are to: (1) desalinate seawater and (2) pump the product potable water to water demand locations throughout the continental United States. This section presents methods used to estimate these energy requirements as well as the energy consumption corresponding to the two scenarios. Appendix 5 provides sensitivity analysis for several key assumptions for parameters used in the method.

9.1. Methods

The energy requirements estimated in this section are for (1) desalinating seawater, and (2) pumping product potable water to public water demand locations throughout the continental United States. In all of the scenarios, the water demand used for each county equals the 2010 Public Water Demand as reported by the U.S. Geological Survey (U.S. Geological Survey 2017d). The SOA desalination energy intensities for Membrane open-ocean systems presented in this bandwidth report were used to determine desalination energy requirements by multiplying the intensity (after converting to $kWh_{T,equiv}$/gallon) by water demand (gallons per day). The SOA energy intensity was used rather than the CT or PM because it was assumed that any near future municipal scale desalination facilities in the United States will be designed similar to the facility in Carlsbad, California. This facility operates at SOA conditions, as defined in this report. Further, it was assumed that all seawater desalination facilities are located at the coast and that potable water is conveyed to each county. This minimizes feedwater and concentrate pumping requirements. Once within the county, the energy requirement to integrate the water into the existing water system and distribute it to each service location was not evaluated.

Pumping energy requirements for conveying desalinated water to each location within the continental United States are location-specific due to each county's water demand, distance, and net elevation above sea level. Because the pumping energy requirements are not presented elsewhere in the bandwidth report, this section focuses on estimating pumping energy requirements.

As a simplification for the scenarios, each county's water demand was located at the county's geographic centroid. This assumption set the distance and elevation used in the pumping load calculations. Each county's geographic centroid was calculated using ArcGIS software, which produces the latitude and longitude coordinates for each county centroid. ArcGIS software was also used to calculate the shortest distance between each county's centroid and the nearest coastal area. Because many of the shortest distances between counties and coasts would cross Mexico or Canada, the ArcGIS produced distances that do not cross either of these two countries.

Each county's latitude and longitude coordinates were then entered into a U.S. Geological Survey (USGS) web page that provides the elevation for each centroid coordinate (U.S. Geological Survey 2017b). However, the centroid of each county might not align with the population concentration and consequently the location of the water demand. The most significant example is Los Angeles county, where the county centroid is in the mountains surrounding the City of Los Angeles at 4,550 foot elevation, while the city center is located at 215 foot elevation. In all of the scenarios, Los Angeles' elevation was adjusted to 215 foot above sea level. The appendix presents the sensitivity analysis for the elevation and distance to coastal regions for each county's water demand. See Appendix A5.

Pumping energy was estimated using engineering equations with variables defined in Table 9-1. First, the velocity of water flow through a pipe was assumed to be two feet per second (Lindeburg 2013). This velocity and the volume of flow in cubic-feet per second determine pipe diameters. Once a pipe diameter was estimated for each county's water demand, a Reynolds Number was calculated and used in conjunction with a relative roughness to determine a Moody friction factor unique to the county's pipe size and flow rate. A relative roughness factor reflects various pipe materials that affect the frictional and pressure losses as water is pumped through the pipe. The total work performed by pumps is the sum of friction pressure losses (friction head) and work required to overcome elevation changes (elevation head). Lastly, the pump work was converted into a pumping electric load (kW) and pumping electric energy required (kWhe) using pumping and motor efficiency factors. An individual pumping electric load was determined for each county's centroid. Appendix A5 presents key parameter sensitivity scenarios to evaluate the effect of different assumptions on the pumping energy requirements.

Since the second scenario constitutes a sub-set of the regions from the first scenario, the method and parameter sensitivities are applicable to both scenarios.

Table 9-1. Parameters and Equations Used to Determine Pumping Energy Consumption for Each County under Each Scenario

Variable	Variable Units
Flow (potable water being pumped)	ft^3/s
Velocity (of potable water in pipes)	ft/s
Static Head (elevation relative to sea level)	ft
Distance (between coasts and potable water demand)	ft
Specific Roughness (specific to pipe material; Plain Cast Iron = 0.0008)	ft
Viscosity (water at 70° F and atmospheric pressure = 0.0000141)	ft^2/s
Gravitational Constant = 32.2	$lb_m\text{-}ft/lb_f\text{-}s^2$
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	
Equation 1 $$Diameter = 2 \times \sqrt{\frac{Flow}{Velocity} \times \frac{1}{\pi}}$$	ft^2
Equation 2 $$\text{Relative Roughnes} = \frac{\text{Specific Roughness}}{\text{Diameter}}$$	ft
Equation 3	N/A

$$\text{Reynolds Number} = \text{Diameter} \times \frac{\text{Velocity}}{\text{Viscocity}}$$	
Equation 4 $$\text{Friction Head} = \frac{\text{Moody Friction Factor} \times \text{Distance} \times \text{Velocity}^2}{2 \times \text{Diameter} \times \text{Gravitational Constant}}$$	ft
Equation 5 $$\text{Total Pump Head} = \mathit{Friction\ Head} + \mathit{Elevation\ Head}$$	ft
Equation 6 $$\text{Pump Horsepower} = \frac{\text{Total Pump Head} \times \text{Flow Rate}}{3956}$$	hp
Equation 7 $$\text{Pumping Electric Load} = \frac{\text{Pump Horsepower} \times 0.7457}{\mathit{Pump\ Efficiency} \times \mathit{Motor\ Efficiency}}$$	kW
Equation 8 $$\text{Pumping Electric Energy} = \text{Pumping Electric Load} \times 8760$$	kWh_e
Equation 9 $$\text{Total Electric Energy} = \text{Desalination Electrical Energy} + \text{Pumping Electric Energy}$$	kWh_e

9.2. Scenario Results

Figure 9-1 and Figure 9-2 show the cumulative energy requirements and water demand on a county-by-county basis under scenarios 1 and 2, respectively. The left Y-axis shows cumulative energy consumption, in TWh per year, and the right Y-axis is the percent of 2017's net grid supplied electricity that the cumulative energy requirement represents. All of the energy consumption in the scenarios is site electricity. The X-axis is the cumulative water flow in millions of gallons per day (MGD). Each "step" in the plots represents a separate county, and all of the counties are sorted from shortest to longest distance between coasts and county centroid (water demand location).

9.2.1. Scenario 1: Seawater Desalination Supplying Public Water Demand throughout the Continental United States

Scenario 1 estimates the total energy requirements for supplying public potable water demand with desalinated seawater for all populations living within 25 miles and 250 miles of a coastline, as well the entire continental United States. Figure 9-1 shows Scenario 1 results.

The black plot in the figure shows the total energy required for both desalination energy (assuming SOA energy intensity) and potable water pumping energy, and the red plot shows the total energy required for potable water pumping alone. Three vertical blue lines indicate distances from coasts. Approximately 8,000 MGD of public water demand is within 25 miles of a coast; 25,000 MGD is within 250 miles of a coast; and the remainder is within 1,060 miles of a coast. The energy requirements under this scenario would require approximately 38 TWh for populations within 25 miles of a coastline (equating to 1% of 2017 U.S. electricity consumption), 132 TWh for those 250 miles of coastline (3.4%), and 246 TWh (6.3%) for the entire continental United States. On average, the total pumping energy is roughly 30% of the total energy including desalination energy for all of the desalinated seawater supply for the entire continental United States: 20% for seawater supply within 250 miles of a coast; and 10% for seawater supply within 25 miles of a coast. As can be seen, mass uptake of seawater desalination would require significant expansion of current U.S. electricity supplies.

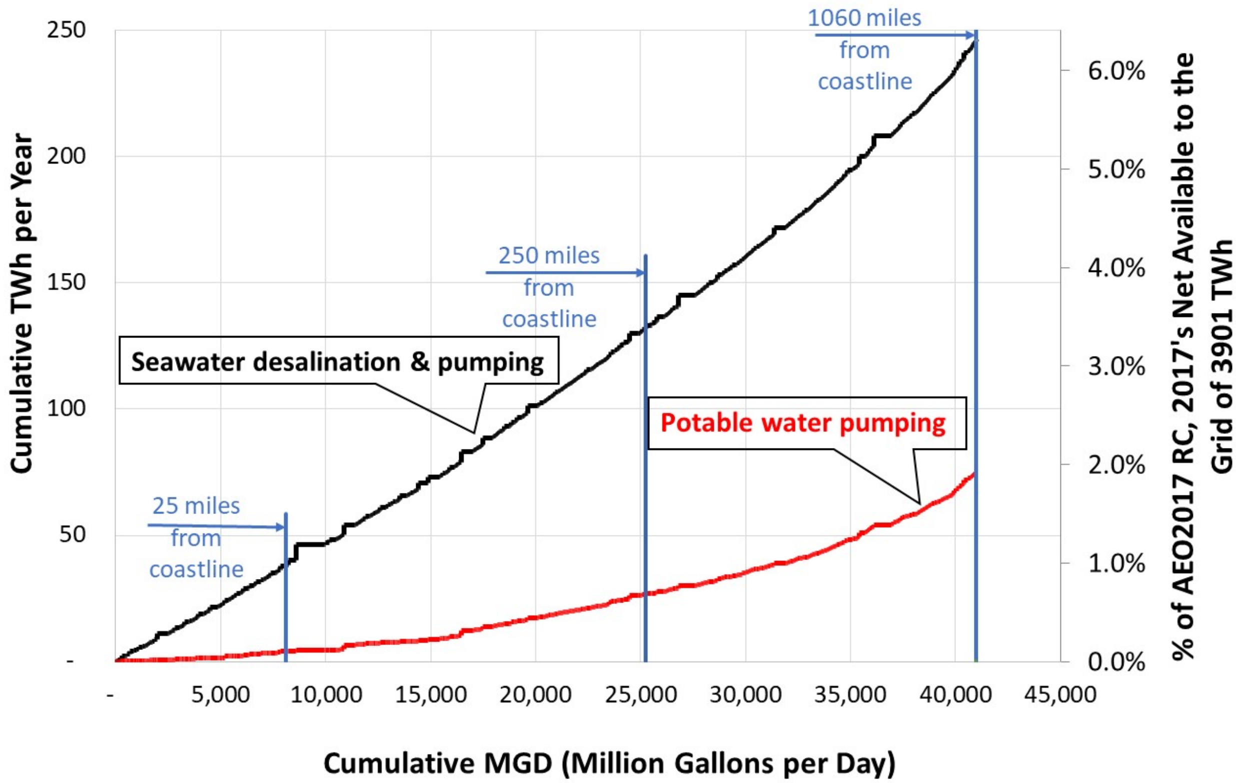

Figure 9-1. Scenario 1: Desalination and pumping energy required to supply all continental U.S. public water demand with desalinated seawater
Source: LBNL

Desalination energy requirements scale by the volume of water demanded at each county, while pumping energy is not only a function of water demanded at each county, but also the water's piping distance and elevation gain. For this reason, counties at the right end of the plots have larger pumping energy requirements per gallon of water than those on the left side of the plots. Table 9-2 shows the scenario results.

Table 9-2. Scenario 1: All Counties Scenario Result

	Distance from Coastline	25 Miles	250 Miles	Entire Continental United States
Scenario 1: All Counties	Desalination System Energy Requirement (TWh)	34	105	171
	Potable Water Conveyance Pumping Energy Requirement (TWh)	4	27	75
	Total (Desalination System + Potable Water Conveyance Pumping) Energy Requirement (TWh)	38	132	246
	% of 2017 U.S. electricity consumption	1%	3.4%	6.3%
	Desalination System Energy Percent of Total Energy	89%	80%	69%

9.2.2. Scenario 2: Seawater Desalination Supplying Public Water Demand in Water-Stressed Areas in the Continental United States

An alternative scenario assumes that desalinated water from coastal regions only supplies water to water-stressed counties within the continental United States. For this report, water stress is determined using the Water Supply Stress Index (WaSSI). This index is a ratio of a region's water demand to its water availability:

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

For this report, a WaSSI greater than one is defined as denoting water stress. At these values, the region uses more water than is available.

The *WaSSI Ecosystems Services Model* from North Carolina State University, the U.S. Department of Agriculture, and the U.S. Forest Service calculate this index at the smallest hydrological units, as defined by the USGS (North Carolina State University, US Department of Agriculture, and the US Forest Service 2017). This unit divides the continental United States into 2,264 "watersheds." These data are used to estimate a long-term WaSSI over the period from 1985 to 2010 for each county. In instances where a county had multiple watersheds within it, the average WaSSI of all watersheds within the county is used. Figure 9-2 shows the resulting WaSSI for each county.

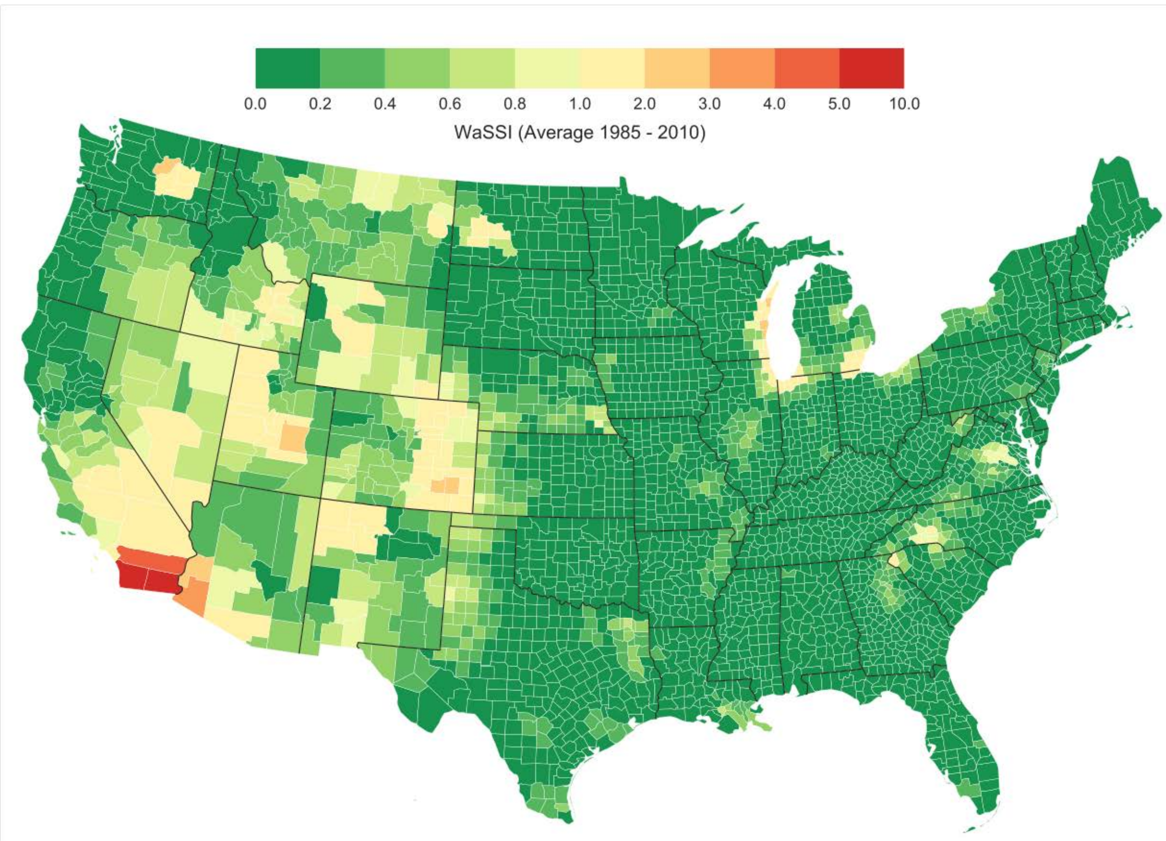

Figure 9-2. WaSSI metric for each continental U.S. county (counties with WaSSI>1 are considered water-stressed for the purposes of this report)
Source: LBNL utilizing data from the WaSSI Ecosystems Services Model by North Carolina State University, U.S. Department of Agriculture, and U.S. Forest Service

Using this method, 85 counties are defined in this report as "water stressed" corresponding to approximately 13% of total U.S. public water demand. Figure 9-3 shows the energy consumption associated with supplying water-stressed counties within 25 miles and 250 miles from a coastline, as well as throughout the continental United States.

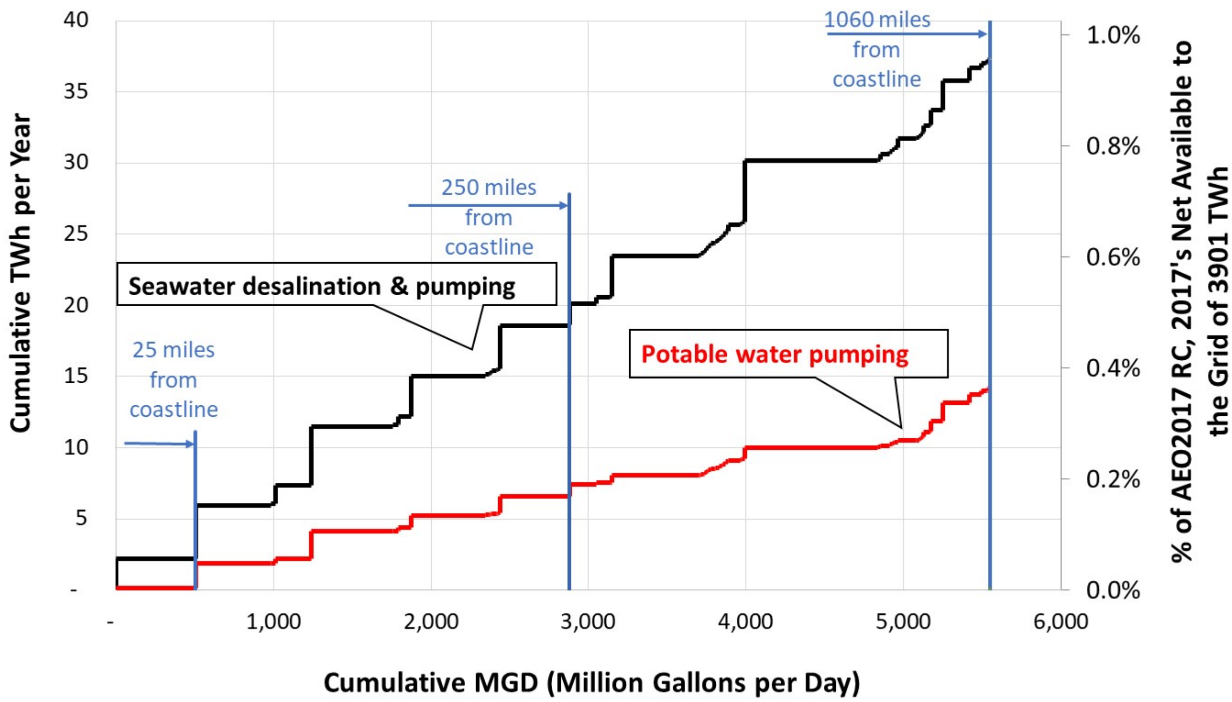

Figure 9-3. Scenario 2: Desalination and pumping energy required to meet public water demand using seawater in counties with WaSSI>1 within the continental United States
Source: LBNL

As Figure 9-3 shows, only supplying desalinated water to water-stressed counties within the continental United States dramatically reduces the electricity requirement from 246 TWh to 37 TWh, or 0.9% of 2017's 3,901 TWh electric demand. Table 9-3 shows the scenario results.

Table 9-3. Scenario 2: Water-Stressed Counties Scenario Result

	Distance from Coastline	25 Miles	250 Miles	Entire Continental United States
Scenario 2: Water-Stressed Counties	Desalination System Energy Requirement (TWh)	2	12	23
	Potable Water Conveyance Pumping Energy Requirement (TWh)	0.1	7	14
	Total (Desalination System + Potable Water Conveyance Pumping) Energy Requirement (TWh)	2	19	37
	% of 2017 U.S. electricity consumption	0.1%	0.5%	1.0%
	Desalination System Energy Percent of Total Energy	94%	65%	62%

10. Summary and Conclusion

This report analyzed the energy savings potential for U.S. seawater desalination systems for potable water production at municipal scales (defined here as serving more than 10,000 people) through advanced technology adoption. The system analyzed included the following operations: intake, pre-treatment, desalination, post-treatment, and concentrate management. The estimated energy consumption and potential energy savings were evaluated at four bands and two bandwidths, respectively. The four bands corresponded to the energy consumption: at typically installed conditions (current typical [CT]), associated with application of best available technologies and practices (state of the art [SOA]) and pre-commercial technologies (practical minimum [PM]), and at the thermodynamic limit (thermodynamic minimum [TM]). The two bandwidths correspond to the energy savings resulting from widespread adoption of best available technologies (current opportunity) and application of technologies under development (R&D opportunity).

The analysis method used in this report adopted the approach used in previous U.S. Department of Energy (DOE) bandwidth studies. It is a well-tested methodology developed by DOE for evaluating the energy savings potential through technology adoption for several traditional manufacturing sectors. Underlying the methodology is a deep investigation and vetting of the available literature and data (i.e., journals, government reports, white papers, case studies) to determine the various bands. The focus of this report is energy reduction potential; all technology selections for each band were based on lowest energy intensity for a given process. In reality, several other factors must be considered when selecting technologies for a given application, including cost (first time and operating), availability, reliability, and environmental impact.

This report is intended to be read using *Volume 1: Survey of Available Information in Support of the Energy-Water Bandwidth Study of Desalination Systems* (Rao, et al. 2016) as a reference. Unlike other Bandwidth Studies, this study was broken into two parts. The Volume 1 report is intended to provide foundational information on conducting analysis of desalination systems and the results from reviewing the available (as of 2016) literature on energy reduction potential. This Volume 2 report further vets and uses the information in the Volume 1 report to evaluate seawater desalination systems.

The analysis results found that there is significant potential for reducing the energy consumption of U.S. seawater desalination systems over current operations. For the system identified as the most broadly applicable in the United States (membrane based with open-ocean intake), the current opportunity was found to be 28% of the estimated 2016 energy consumption for seawater desalination systems in the United States, and the R&D opportunity was 47%. Direct adoption of technologies under development presuming successful scale-up (i.e., current opportunity plus R&D opportunity) would result in a 75% reduction over 2016 energy consumption levels. The vast majority of the opportunity lies within the desalination stage; tests of the technology identified as achieving the PM (semi-batch RO) operated at approximately 70% of the CT energy intensity and 60% of the SOA energy intensity.

Thermal-based desalination systems were also evaluated. The PM energy consumption for a thermal-based system was found to be higher than the CT energy consumption for a membrane-based system, indicating that even with further R&D, the energy requirement for thermal technologies is unlikely to fall below that of membrane technologies for seawater desalination. However, taking advantage of waste heat and renewable energy may lead to opportunities to reduce the costs and CO_2 emissions of seawater desalination systems.

This report expanded upon the bandwidth study approach and estimated CO_2 emissions based on each energy consumption band. For the membrane open-ocean system, the CO_2 emissions corresponding to CT conditions at 2016 production capacities were 282 Mton/year (256 kilotonnes/year). This corresponds to the annual emissions from slightly more than 54,000 passenger vehicles. At PM conditions and 2016 production capacities, the CO_2 emissions were estimated to be 133 Mton/year (120 kilotonnes/year), corresponding to the annual emissions from slightly more than 25,000 passenger vehicles.[8] It was not within the scope of this report

[8] Passenger vehicle equivalency determined using information from the EPA: https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator

to evaluate CO_2 emissions reduction potential for seawater desalination systems. The values presented here reflect the impact that advanced energy efficient technology adoption would have on CO_2 emissions.

This report expanded upon previous Bandwidth Studies by considering the reduction in product water cost attributable to the energy intensity reductions associated with each band. The simple analysis approach adopted here showed a 33% reduction in overall water costs associated with implementation of PM technologies against CT operations in 2016.

This report identifies semi-batch RO technologies as the PM technology for membrane systems. The desalination operations offer the largest opportunity for energy reductions. Adoption of semi-batch RO would result in 90% of the current opportunity plus R&D opportunity identified in this report (assuming successful scale-up). The operation constituting the next largest portion of the energy savings identified in this report is pre-treatment, which represents 8% of the current opportunity plus R&D opportunity. Additional research is required before semi-batch RO is a viable option for desalination facilities. Primarily, results at larger scales are required, and methods for reducing manufacturing and/or equipment costs will improve cost-effectiveness.

Improvements in pumping systems, including advanced motor, pump, and drive technologies as well as improvements in piping design, will yield benefits throughout the water-energy nexus, including seawater desalination facilities. In general this report likely underestimates the energy consumption and reduction potential of seawater and concentrate conveyance pumping by normalizing the respective energy intensity to one meter of TDH. One meter corresponds to low frictional losses and pressure head. However, this simplification was deemed necessary by the authors in order to arrive at national estimates of energy consumption and reduction potential. The actual TDH for any given facility will be site specific.

This report also evaluated the energy consumption impact from increased uptake of seawater desalination for municipal potable water in the United States. As of 2016, seawater desalination represented a small fraction of potable water supply in the United States. However, with increasing concerns over freshwater availability and ongoing efforts to improve water system management and resource allocation, regional planners and technology developers are considering seawater desalination as a means to diversify the portfolio of water supplies for a given region. The analysis results found that the electrical energy intensity associated with seawater desalination will result in needing to add significant grid capacity should seawater desalination become more widespread. If all water-stressed counties were to be provided 100% of their municipal potable water through seawater desalination, electricity production would need to increase by 1% over estimated 2017 U.S. electric grid production. Realistically, communities would seek a diversified water source portfolio and consider other options as well—conservation, reuse, and brackish water desalination. Seawater desalination would not supply 100% of a county's water supply. As seen in Carlsbad, California, seawater desalination can be part of the mix that provides a region with greater water resiliency.

As depicted in Figure 1-2, there are many applications of desalination technologies. This report considered one application—the treatment of seawater for municipal potable water. To conduct an in-depth analysis of energy saving technologies, the number of applications was restricted. The application selected for this report is an important option to consider as part of a portfolio approach for meeting increased water demands due to growing populations and standards of living in the near future.

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Appendix A1. Master Seawater Desalination Summary Table

Table A1-1. U.S. Installed Production Capacity of Membrane Seawater Desalination Unit Operations in 2016 with Energy Intensity Estimates and Calculated On-site Energy Consumption for the Four Bandwidth Measures

Unit operation	Installed Production Capacity (million m^3)	Calculated On-site Energy Intensity ($kWh_{T,equiv}/m^3$)*				Calculated On-site Energy Consumption (BBtu/year)			
		CT	SOA	PM	TM	CT	SOA	PM	TM
Intake									
Open ocean intake/sub-surface intake	255	0.0038**	0.0036**	0.0034**	0.0028**	3	3	3	2
Pre-treatment									
Flocculation	128	0.06	0.01		0	27	5		0
Cartridge filtration	128	0.02	0.02		0	9	9		0
Sand filtration	128	0.19	0.13		0	82	57		0
Vacuum-driven microfiltration	128	N/A	N/A	0.13	0	N/A	N/A	57	0
Desalination									
Reverse osmosis	128	3.30	2.70	1.48	1.06	1,434	1,175	645	461
Post-treatment									
Remineralization	128	0.05	0.04	0.04	0	23	17	17	0
Disinfection	128	0.06	0.04	0.04	0	25	19	19	0
Concentrate Management									
Surface water discharge	2,231	0.0038**	0.0036**	0.0034**	0.0028**	29	27	26	21

The four bandwidth measures are current typical (CT), state of the art (SOA), practical minimum (PM), and thermodynamic minimum (TM).

* $kWh_{T,equiv}$ = kilowatt-hour of total electrical equivalent energy ($kWh_{e,equiv}$ + kWh_e)

** To account for pump and motor efficiencies, as well as total dynamic head (TDH) loss, intake and concentrate management energy intensities were normalized per unit head loss (kWh_e/m^3-m TDH). For the CT energy intensity, a combined system efficiency of 69.3% was applied (pump efficiency * motor efficiency = 72.9% * 95% = 69.3%) (DETR 1998, U.S. Department of Energy 2014b). For the SOA energy intensity, a combined system efficiency of 77.6% was applied (pump efficiency * motor efficiency = 81% * 95.8% = 77.6%) (American-Marsh Pumps n.d., TECO Westinghouse 2017). For the PM energy intensity, a combined system efficiency of 82% was applied (pump efficiency * motor efficiency = 85% * 97% = 82%) (Proceedings of the 6th International Conference eemods '09: Energy Efficiency in Motor Driven Systems 2009). There were limited reported values in the literature for concentrate management; therefore, energy intensities for intake and concentrate management were assumed to be the same (as pumping is the primary energy-intensive mechanism for open-ocean intake and surface water discharge). Intake water was assumed to be standard seawater at 35,000 ppm. Concentrate was assumed to be diluted to 37,000 ppm to be discharged into the ocean.

Table A1-2. Thermal Seawater Desalination Unit Operation Energy Intensity Estimates and Calculated On-site Energy Consumption for the Four Bandwidth Measures at 2016 U.S. Membrane Seawater Desalination Capacity Volume

Unit Operation	Installed Production Capacity* (million m^3)	On-site Energy Intensity ($kWh_{T,equiv}/m^3$)**				Calculated On-site Energy Consumption (BBtu/year)			
		CT*	SOA	PM	TM	CT*	SOA	PM	TM
Intake						*N/A*	*4*	*4*	*3*
Open ocean intake	364	N/A	0.0036***	0.0034***	0.0028***	N/A	4	4	3
Pre-treatment		*N/A*	*0.05*	*0.04*	*0.00*	*N/A*	*22*	*15*	*0*
Filtration	128		0.05	0.04	0.00		22	15	0
Chlorination	128		0.001	0.0004	0.00		0.2	0.2	0
Desalination		*N/A*	*11.00*	*4.00*	*1.20*	*N/A*	*4,786*** ***	*1,740*** ***	*522*** ***
MED-TVC	128		11.00	N/A	1.20		4,786	N/A	522
Condensing MED	128		N/A	4.00	1.20		N/A	1,740	522
Post-treatment		N/A	*0.11*	*0.11*	*0.00*	N/A	*50*	*50*	*0*
Remineralization	128		0.07	0.07	0.00		30	30	0
Disinfection	128		0.04	0.04	0.00		19	19	0
Concentrate Management						*N/A*	*13*	*12*	*10*
Surface water discharge	1,071	N/A	0.0036***	0.0034***	0.0028***	N/A	13	12	10

The four bandwidth measures are current typical (CT), state of the art (SOA), practical minimum (PM), and thermodynamic minimum (TM).
* Thermal desalination was not utilized in the United States for seawater in 2016, so a CT was not calculated. The installed production capacity for membrane seawater desalination (RO) was applied to the energy intensity estimates for thermal desalination to arrive at the calculated on-site energy consumption numbers for comparison purposes.
** $kWh_{T,equiv}$ = kilowatt-hour of total electrical equivalent energy ($kWh_{e,equiv}$ + kWh_e)
*** To account for pump and motor efficiencies, as well as total dynamic head (TDH) loss, intake and concentrate management energy intensities were normalized per unit head loss (kWh_e/m^3-m TDH). For the CT energy intensity, a combined system efficiency of 69.3% was applied (pump efficiency * motor efficiency = 72.9% * 95% = 69.3%) (DETR 1998, TECO Westinghouse 2017). There were limited reported values in the literature for concentrate management; therefore, energy intensities for intake and concentrate management were assumed to be the same (as pumping is the primary energy-intensive mechanism for open-ocean intake and surface water discharge).
**** In calculating the energy consumption, the thermal energy intensities ($kWh_{e,equiv}/m^3$) were divided by 33% to convert to thermal consumption, assuming a 33% generation, transmission, and distribution efficiency.

Appendix A2. References for Capacity, CT, SOA, PM, and TM

Table A2-1. References for Membrane Seawater Desalination Production Volumes and Energy Intensities

Unit Operation	Installed Production Capacity Reference(s)	CT Energy Intensity Reference(s)	SOA Energy Intensity Reference(s)	PM Energy Intensity Reference(s)	TM Energy Intensity Reference(s)
Intake					
Sub-surface intake	(Global Water Intelligence 2017)	(DETR 1998, U.S. Department of Energy 2014b)	(American-Marsh Pumps n.d., TECO Westinghouse 2017)	(Proceedings of the 6th International Conference eemods '09: Energy Efficiency in Motor Driven Systems 2009)	Internal calculations
Open ocean intake	(Global Water Intelligence 2017)	(DETR 1998, U.S. Department of Energy 2014b)	(American-Marsh Pumps n.d., TECO Westinghouse 2017)	(Proceedings of the 6th International Conference eemods '09: Energy Efficiency in Motor Driven Systems 2009)	Internal calculations
Pre-treatment					
Flocculation	(Global Water Intelligence 2017)	(Park and Bennett 2010)	(Park and Bennett 2010)	N/A	Set to zero due to minimal chemical conversions
Sand filtration	(Global Water Intelligence 2017)	(Kennedy/Jenks Consultants 2011)	(Kennedy/Jenks Consultants 2011)	N/A	Set to zero due to minimal chemical conversions
Cartridge filtration	(Global Water Intelligence 2017)	(Shahabi, McHugh and Ho 2015)	(Shahabi, McHugh and Ho 2015)	N/A	Set to zero due to minimal chemical conversions
Vacuum-driven microfiltration	(Global Water Intelligence 2017)	N/A	N/A	(Voutchkov 2010)	Set to zero due to minimal chemical conversions
Desalination					
Reverse osmosis	(Global Water Intelligence 2017)	(Voutchkov 2013, Personal communication with plant employee 2017)	(Personal communication with plant employee 2017)	(Gal and Efraty 2016)	(Mistry and Lienhard V 2013)
Post-treatment					
Remineralization	(Global Water Intelligence 2017)	(Dundorf, et al. 2009)	(Dundorf, et al. 2009)	(Dundorf, et al. 2009)	Set to zero due to minimal chemical conversions
Disinfection	(Global Water Intelligence 2017)	(Park and Bennett 2010)	(Park and Bennett 2010)	(Park and Bennett 2010)	Set to zero due to minimal chemical conversions

Table A2-1. References for Membrane Seawater Desalination Production Volumes and Energy Intensities

Unit Operation	Installed Production Capacity Reference(s)	CT Energy Intensity Reference(s)	SOA Energy Intensity Reference(s)	PM Energy Intensity Reference(s)	TM Energy Intensity Reference(s)
Concentrate Management					
Surface water discharge	(Global Water Intelligence 2017, Mickley 2006)	(DETR 1998, U.S. Department of Energy 2014b)	(American-Marsh Pumps n.d., TECO Westinghouse 2017)	(Proceedings of the 6th International Conference eemods '09: Energy Efficiency in Motor Driven Systems 2009)	Internal calculations

The four bandwidth measures are current typical (CT), state of the art (SOA), practical minimum (PM), and thermodynamic minimum (TM).

Table A2-2. References for Thermal Seawater Desalination Production Volumes and Energy Intensities

Unit Operation	Installed Production Capacity Reference(s)	CT Energy Intensity Reference(s)	SOA Energy Intensity Reference(s)	PM Energy Intensity Reference(s)	TM Energy Intensity Reference(s)
Intake					
Open ocean intake	(Global Water Intelligence 2017)	N/A	(American-Marsh Pumps n.d., TECO Westinghouse 2017)	(Proceedings of the 6th International Conference eemods '09: Energy Efficiency in Motor Driven Systems 2009)	Set to zero due to minimal chemical conversions
Pre-treatment					
Chlorination	(Global Water Intelligence 2017)	N/A	(Voutchkov 2013)	(Hassan 2004, Hilal, et al. 2004)	Set to zero due to minimal chemical conversions
Media filtration	(Global Water Intelligence 2017)	N/A	(Pacific Gas & Electric 2006) (single-stage, granular, gravity-fed)	(Hassan 2004, Hilal, et al. 2004) (nanofiltration)	Set to zero due to minimal chemical conversions
Desalination					
Multi-effect distillation-Thermal Vapor Compression (MED-TVC)	(Global Water Intelligence 2017)	N/A	(Sommariva 2010)	(Sommariva 2010)	(Mistry and Lienhard V 2013)
Post-treatment					
Remineralization	(Global Water Intelligence 2017)	N/A	(Dundorf, et al. 2009)	(Dundorf, et al. 2009)	Set to zero due to minimal chemical conversions
Disinfection	(Global Water Intelligence 2017)	N/A	(Park and Bennett 2010)	(Park and Bennett 2010)	Set to zero due to minimal chemical conversions
Concentrate Management					
Surface water discharge	(Global Water Intelligence 2017, Mickley 2006)	N/A	(American-Marsh Pumps n.d., TECO Westinghouse 2017)	(Proceedings of the 6th International Conference eemods '09: Energy Efficiency in Motor Driven Systems 2009)	Set to zero due to minimal chemical conversions

The four bandwidth measures are current typical (CT), state of the art (SOA), practical minimum (PM), and thermodynamic minimum (TM)

Appendix A3. Seawater Desalination Figures and Data Tables (Scientific Units)

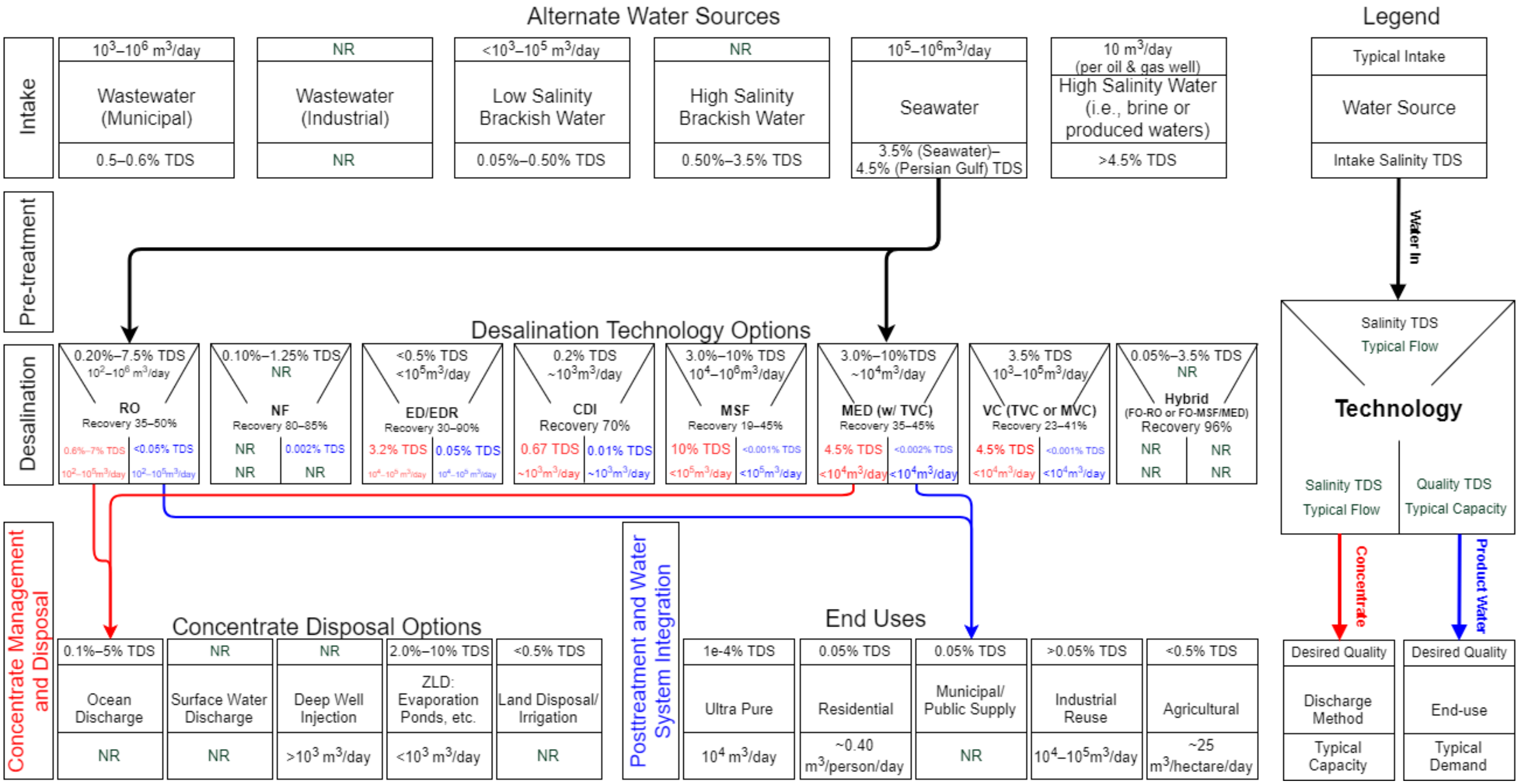


Figure A3-1. Technology choices for desalination are dependent on water source, product water end-use, and contaminant disposal options (scientific units)
Source: LBNL

All the values included in this figure are typical intake, plant, and end use capacities. Thermal process flows do not include cooling water. For an alternate water source to match a technology option or a technology option to match a concentrate disposal or end-use option, the output salinity and capacity range of the first should overlap with the input salinity and capacity range of the second. For this report, one water source (seawater) was selected for one end use (municipal scale potable water) and one concentrate disposal option (ocean), as shown by the arrows. Although many desalination technologies can be used for this pathway, reverse osmosis and multi-effect distillation were selected for this report based on their relatively low energy intensity and, in the case of reverse osmosis, its common usage in the United States. Salinities are represented with the units of % TDS. Percent TDS can be converted to ppm using the following conversion: 1 % = 10,000 ppm. Sources: (Rao, et al. 2016) (Alameddine and El-Fadel 2006) (Imbrogno and Belfort 2016) (Jenkins, et al. 2012) (Lenntech 2017) (U.S. Geological Survey 2017a) (U.S. Geological Survey 2017c) (McIlvaine and Bagga 2017) (Wu, Tam and Wong 2008) (Clark and Veil 2009).

A3.1. Current Typical

Table A3-1. On-site Current Typical Energy Intensity and Calculated On-site Energy Consumption and Primary Energy Consumption for U.S. Seawater Desalination for Municipal Potable Water Production in 2016 (GWh/year)

Unit Operation	On-site CT Energy Intensity ($kWh_{T,equiv}/m^3$)	Capacity (million m^3/year)	On-site CT Energy Consumption, Calculated (GWh/year)	Off-site Losses, Calculated* (GWh/year)	Primary CT Energy Consumption, Calculated* (GWh/year)
System Type: Membrane Sub-surface					
Intake[a]					
Sub-surface intake	0.0038	255	1	2	3
Pre-treatment					
Bag filtration	[b]	128	[b]	[b]	[b]
Cartridge filtration[c]	0.02	128	3	5	8
Desalination					
Reverse osmosis[d]	3.3	128	420	845	1,266
Post-treatment					
Remineralization	0.05	128	7	14	21
Disinfection	0.06	128	7	15	22
Fluoridation	[b]	128	[b]	[b]	[b]
Concentrate management[a]					
Surface water discharge	0.0038	2,231	9	17	26
Total System Type: Membrane Sub-surface**			**446**	**898**	**1,344**
System Type: Membrane Open-ocean					
Intake[a]					
Open-ocean intake	0.0038	255	1	2	3
Pre-treatment					
Flocculation	0.06	128	8	16	23
Coagulation	[b]	[b]	[b]	[b]	[b]
Sand filtration	0.19	128	27	49	73
Cartridge filtration[c]	0.02	128	3	5	8
Desalination					
Reverse osmosis[d]	3.3	128	420	845	1,266
Post-treatment					
Remineralization	0.05	128	7	14	21
Disinfection	0.06	128	7	15	22
Fluoridation	[b]	128	[b]	[b]	[b]
Concentrate management[a]					
Surface water discharge	0.0038	2,231	9	17	26
Total System Type: Membrane Open-ocean**			**478**	**962**	**1,441**

Current typical (CT)
* Accounts for off-site electricity and steam generation and transmission losses. Off-site electrical losses are based on a 33% grid generation efficiency.
** Totals may not sum due to independent rounding.

[a] To account for pump and motor efficiencies, as well as total dynamic head (TDH) loss, intake and concentrate management energy intensities were normalized per unit head loss (kWh_e/m^3-m TDH). For the CT energy intensity, a combined system efficiency of 69.3% was applied (pump efficiency * motor efficiency = 72.9% * 95% = 69.3%) (DETR 1998, U.S. Department of Energy 2014b). There were limited reported values in the literature for concentrate management; therefore, energy intensities for intake and concentrate management were assumed to be the same (as pumping is the primary energy-intensive mechanism for open-ocean intake and surface water discharge). Intake water was assumed to be standard seawater at 35,000 ppm. Concentrate was assumed to be diluted to 37,000 ppm to be discharged into the ocean.
[b] No values were determined specifically for coagulation or bag filtration in the pre-treatment unit operation, or for fluoridation process in post-treatment, due to lack of referenceable energy intensity data.
[c] Unit operation conditions: feedwater salinity of 40,000 ppm, 50% recovery for RO operation, and plant capacity of 35,000 m^3/day (Shahabi, McHugh and Ho 2015).
[d] Unit operation conditions: feedwater salinity of 35,000 ppm, 50% recovery, and product water salinity of 200–500 ppm. Capacity not provided (Personal communication with plant employee 2017, Voutchkov, Desalination Engineering: Planning and Design 2013).

Table A3-2. Associated Current Typical CO_2 Emissions for U.S. Seawater Desalination for Municipal Water Production in 2016 (kilotonne CO_2/year)

Unit Operation	On-site CT Energy Intensity ($kWh_{T,equiv}/m^3$)	Capacity (million m^3/year)	CO_2 Emission Factor (kg $CO_2/kWh_{T,equiv}$)	CO_2 Emission Intensity (kg CO_2/m^3)	Total CO_2 Emissions (kilotonne CO_2/year)
System Type: Membrane Sub-surface (Reverse osmosis)					
Intake*	0.0038	255	0.53	0.002	1
Pre-treatment	0.02	128	0.53	0.01	1
Desalination**	3.30	128	0.53	1.76	225
Post-treatment	0.11	128	0.53	0.06	8
Concentrate management*	0.0038	2,231	0.53	0.002	5
Total System Type: Membrane Sub-surface* **					**239**
System Type: Membrane Open-ocean (Reverse osmosis)					
Intake*	0.0038	255	0.53	0.002	1
Pre-treatment	0.27	128	0.53	0.14	18
Desalination**	3.30	128	0.53	1.76	225
Post-treatment	0.11	128	0.53	0.06	8
Concentrate management*	0.0038	2,231	0.53	0.002	5
Total System Type: Membrane Open-ocean* **					**256**

Current typical (CT)
* To account for pump and motor efficiencies, as well as total dynamic head (TDH) loss, intake and concentrate management energy intensities were normalized per unit head loss (kWh_e/m^3-m TDH). For the CT energy intensity, a combined system efficiency of 69.3% was applied (pump efficiency * motor efficiency = 72.9% * 95% = 69.3%) (DETR 1998, U.S. Department of Energy 2014b). There were limited reported values in the literature for concentrate management; therefore, energy intensities for intake and concentrate management were assumed to be the same (as pumping is the primary energy-intensive mechanism for open-ocean intake and surface water discharge).
** Unit operation conditions: feedwater salinity of 35,000 ppm, 50% recovery, and product water salinity of 200–500 ppm. Capacity not provided (Personal communication with plant employee 2017, Voutchkov 2013).
*** Totals may not sum due to independent rounding.

A3.2. State of the Art

Table A3-3. SOA Energy Intensities and Calculated SOA Energy Consumption for Seawater Desalination Systems (GWh/year)

Unit Operation	On-site SOA Electric Energy Intensity (kWh_e/m^3)	SOA Thermal Energy Intensity ($kWh_{e,equiv}/m^3$)*	SOA Total Energy Intensity ($kWh_{T,equiv}/m^3$)	On-site SOA Energy Consumption, Calculated** (GWh/year)
System Type: Membrane Sub-surface				
Intake***				
Sub-surface intake	0.0036	N/A	0.0036	1
Pre-treatment				
Cartridge filtration[a]	0.02		0.02	3
Desalination				
Reverse osmosis[b]	2.70		2.70	344
Post-treatment				
Remineralization[c]	0.04		0.04	5
Disinfection	0.04		0.04	6
Concentrate Management***				
Surface water discharge	0.0036		0.0036	8
Total System Type: Membrane Sub-surface**				**366**
Intake***				
Open-ocean intake	0.0036	N/A	0.0036	1
Pre-treatment				
Flocculation	0.01		0.01	1
Sand filtration	0.13		0.13	17
Cartridge filtration[a]	0.02		0.02	3
Desalination				
Reverse osmosis[b]	2.70		2.70	344
Post-treatment				
Remineralization[c]	0.04		0.04	5
Disinfection	0.04		0.04	6
Concentrate Management***				
Surface water discharge	0.0036		0.0036	8
Total System Type: Membrane Open-ocean**				**384**
System Type: Thermal				
Intake***				
Open-ocean intake	0.0036	N/A	0.0036	1
Pre-treatment				
Chlorination	0.001		0.001	0.07
Media filtration[d]	0.05		0.05	6
Desalination				
MED-TVC[e]	1.00	10.00	11.00	1,403****

Table A3-3. SOA Energy Intensities and Calculated SOA Energy Consumption for Seawater Desalination Systems (GWh/year)

Unit Operation	On-site SOA Electric Energy Intensity (kWh_e/m^3)	SOA Thermal Energy Intensity ($kWh_{e,equiv}/m^3$)*	SOA Total Energy Intensity ($kWh_{T,equiv}/m^3$)	On-site SOA Energy Consumption, Calculated** (GWh/year)
Post-treatment		N/A		
Remineralization[c]	0.07		0.07	9
Disinfection	0.04		0.04	6
Concentrate Management***				
Surface water discharge	0.0036		0.0036	4
Total System Type: Thermal**				**1,429**

State of the art (SOA)

* $kWh_{e,equiv}$ is the equivalent amount of electrical work that could be produced from the thermal energy requirement. It is determined by assuming the efficiency of converting thermal energy to electrical work is 33%.
** Totals may not sum due to independent rounding.
*** To account for pump and motor efficiencies, as well as total dynamic head (TDH) loss, intake and concentrate management energy intensities were normalized per unit head loss (kWh_e/m^3-m TDH). For the SOA energy intensity, a combined system efficiency of 77.6% was applied (pump efficiency * motor efficiency = 81% * 95.8% = 77.6%) (American-Marsh Pumps n.d., TECO Westinghouse 2017). There were limited reported values in the literature for concentrate management; therefore, energy intensities for intake and concentrate management were assumed to be the same (as pumping is the primary energy-intensive mechanism for open-ocean intake and surface water discharge). Intake water was assumed to be standard seawater at 35,000 ppm. Concentrate was assumed to be diluted to 37,000 ppm to be discharged into the ocean.
**** In calculating the energy consumption, electrical equivalent thermal energy intensities ($kWh_{e,equiv}/m^3$) were divided by 33% to convert to thermal consumption, assuming a 33% generation, transmission, and distribution efficiency.
[a] Unit operation conditions: feedwater salinity of 40,000 ppm, 50% recovery for RO operation, and plant capacity of 35,000 m^3/day (Shahabi, McHugh and Ho 2015).
[b] Unit operation conditions: feedwater salinity of 34,500 ppm (Virgili, Pankratz and Gasson 2017), 50% recovery, and product water salinity of <500 ppm, plant capacity of 189,300 m^3/day (Personal communication with plant employee 2017).
[c] Unit operation conditions: product water salinity of 129–194 ppm (Dundorf, et al. 2009).
[d] Single-stage, granular, gravity-fed media filtration. No specific unit operations provided by energy intensity reference.
[e] Unit operation conditions: feedwater salinity of 45,000 ppm, 33%–37.5% recovery, product water salinity of <25 ppm, and 220–250 kPa pressure. Capacity not provided (Sommariva 2010).

Table A3-4. On-site State of the Art Energy Consumption, Energy Savings, and Energy Savings Percent for Seawater Desalination Systems (GWh/year)

Unit Operation	On-site CT Energy Consumption, Calculated (GWh/year)	On-site SOA Energy Consumption, Calculated (GWh/year)	SOA Energy Savings* (CT-SOA) (GWh/year)	SOA Energy Savings Percent** (CT-SOA)/ (CT-TM)
System Type: Membrane open-ocean (Reverse osmosis)				
Intake	1.0	0.9	0.1	20%
Pre-treatment	34	21	14	40%
Desalination***	420	344	76	27%
Post-treatment	14	11	3	24%
Concentrate Management	8.5	8.1	0.4	20%
Total System Type: Membrane open-ocean******	**478**	**384**	**94**	**28%**

Current Typical (CT), State of the Art (SOA), Thermodynamic Minimum (TM)
* SOA energy savings is also called *Current Opportunity.*
** *SOA energy savings percent* is the SOA energy savings opportunity from transforming desalination system processes. Energy savings percent was calculated using TM energy consumption shown in Table 6-1 as the minimum energy consumption. The energy savings percent, with TM as the minimum, was calculated as follows: (CT-SOA)/(CT-TM).
*** Unit operation conditions: feedwater salinity of 34,500 ppm (Virgili, Pankratz and Gasson 2017), 50% recovery, product water salinity of <500 ppm, and plant capacity of 189,300 m^3/day (Personal communication with plant employee 2017).
**** Totals may not sum due to independent rounding.

Table A3-5. Associated State of the Art CO_2 Intensities and Calculated State of the Art CO_2 Emissions for Seawater Desalination Systems (kilotonne CO_2/year)

Unit Operation	On-site SOA Electric Energy Intensity (kWh_e/m^3)	SOA Thermal Energy Intensity ($kWh_{e,equiv}/m^3$)	CO_2 Electricity Emission Factor (kg $CO_2/kWh_{T,equiv}$)	CO_2 Thermal Emission Factor (kg $CO_2/kWh_{T,equiv}$)	CO_2 Emission Intensity (kg CO_2/m^3)	Capacity (million m^3)	CO_2 Emissions (kilotonne CO_2/yr)
System Type: Membrane Sub-surface							
Intake*	0.0036	N/A	0.53	N/A	0.002	255	0.5
Pre-treatment	0.02		0.53		0.01	128	1
Desalination**	2.70		0.53		1.44	128	184
Post-treatment	0.08		0.53		0.04	128	6
Concentrate Management*	0.0036		0.53		0.002	2,231	4
Total System Type: Membrane Sub-surface***							**196**
System Type: Membrane Open-ocean							
Intake*	0.0036	N/A	0.53	N/A	0.002	255	0.5
Pre-treatment	0.16		0.53		0.09	128	11
Desalination**	2.70		0.53		1.44	128	184
Post-treatment	0.08		0.53		0.04	128	6

Table A3-5. Associated State of the Art CO_2 Intensities and Calculated State of the Art CO_2 Emissions for Seawater Desalination Systems (kilotonne CO_2/year)

Unit Operation	On-site SOA Electric Energy Intensity (kWh_e/m^3)	SOA Thermal Energy Intensity ($kWh_{e,equiv}/m^3$)	CO_2 Electricity Emission Factor (kg $CO_2/kWh_{T,equiv}$)	CO_2 Thermal Emission Factor (kg $CO_2/kWh_{T,equiv}$)	CO_2 Emission Intensity (kg CO_2/m^3)	Capacity (million m^3)	CO_2 Emissions (kilotonne CO_2/yr)
Concentrate Management*	0.0036		0.53		0.002	2,231	4
Total System Type: Membrane Open-ocean* **							**206**
System Type: Thermal (MED-TVC)							
Intake*	0.0036	N/A	0.53	N/A	0.002	364	1
Pre-treatment	0.05		0.53		0.03	128	3
Desalination**	1.00	10.00	0.53	0.23	7.35****	128	937
Post-treatment	0.11	N/A	0.53	N/A	0.06	128	7
Concentrate Management*	0.0036		0.53		0.002	1,071	2
Total System Type: Thermal* **							**951**

State of the art (SOA)
* To account for pump and motor efficiencies, as well as total dynamic head (TDH) loss, intake and concentrate management energy intensities were normalized per unit head loss (kWh_e/m^3-m TDH). For the SOA energy intensity, a combined system efficiency of 77.6% was applied (pump efficiency * motor efficiency = 81% * 95.8% = 77.6% (American-Marsh Pumps n.d., TECO Westinghouse 2017)). There were limited reported values in the literature for concentrate management; therefore, energy intensities for intake and concentrate management were assumed to be the same (as pumping is the primary energy-intensive mechanism for open-ocean intake and surface water discharge). Intake water was assumed to be standard seawater at 35,000 ppm. Concentrate was assumed to be diluted to 37,000 ppm to be discharged into the ocean.
** RO (membrane) unit operation conditions: feedwater salinity of 34,500 ppm (Virgili, Pankratz and Gasson 2017), 50% recovery, product water salinity of <500 ppm, and plant capacity of 189,300 m^3/day (Personal communication with plant employee 2017). MED (thermal) unit operation conditions: feedwater salinity of 45,000 ppm, 33%–37.5% recovery, product water salinity of <25 ppm, 220–250 kPa pressure. Capacity not provided (Sommariva 2010).
*** Totals may not sum due to independent rounding.
**** In calculating the emissions intensity and total emissions, the thermal energy intensities ($kWh_{e,equiv}/m^3$) were divided by 33% to convert to thermal consumption, assuming a 33% generation, transmission, and distribution efficiency.

A3.3. Practical Minimum

Table A3-6. Practical Minimum Energy Intensities and On-site Energy Consumption for U.S. Seawater Desalination Systems (GWh/year)

Unit Operation	On-site PM Electric Energy Intensity (kWh_e/m^3)	PM Thermal Energy Intensity ($kWh_{e,equiv}/m^3$)	PM Total Energy Intensity ($kWh_{T,equiv}/m^3$)	PM Energy Consumption, Calculated* (GWh/year)
System Type: Membrane Sub-surface				
Intake** Sub-surface intake	0.0034	N/A	0.0034	1
Pre-treatment Cartridge filtration	0.02		0.02	3
Desalination Semi-batch RO***	1.48		1.48	189

Post-treatment Remineralization Disinfection	0.04 0.04		0.04 0.04	5 6
Concentrate Management Surface water discharge**	0.0034		0.0034	8
Total System Type: Membrane Sub-surface*				**211**
System Type: Membrane Open-ocean				
Intake** Open-ocean intake	0.0034	N/A	0.0034	1
Pre-treatment Vacuum-driven microfiltration	0.13		0.13	17
Desalination Semi-batch RO***	1.48		1.48	189
Post-treatment Remineralization Disinfection	0.04 0.04		0.04 0.04	5 6
Concentrate Management Surface water discharge**	0.0034		0.0034	8
Total System Type: Membrane Open-ocean*				**225**
System Type: Thermal				
Intake** Open-ocean intake	0.0034	N/A	0.0034	1
Pre-treatment Nanofiltration Chlorination	0.04 0.0004		0.04 0.0004	4 0.05
Desalination Condensing MED***	1.00	3.00	4.00	510****
Post-treatment Remineralization Disinfection	0.07 0.04	N/A	0.07 0.04	9 6
Concentrate Management Surface water discharge**	0.0034		0.0034	8
Total System Type: Thermal*				**538**

Practical Minimum (PM)
* Totals may not sum due to independent rounding.
** To account for pump and motor efficiencies, as well as total dynamic head (TDH) loss, intake and concentrate management energy intensities were normalized per unit head loss (kWh_e/m^3-m TDH). For the PM energy intensity, a combined system efficiency of 82% was applied (pump efficiency * motor efficiency = 85% * 97% = 82%) (Proceedings of the 6th International Conference eemods '09: Energy Efficiency in Motor Driven Systems 2009). There were limited reported values in the literature for concentrate management; therefore, energy intensities for intake and concentrate management were assumed to be the same (as pumping is the primary energy-intensive mechanism for open-ocean intake and surface water discharge). Intake water was assumed to be standard seawater at 35,000 ppm. Concentrate was assumed to be diluted to 37,000 ppm to be discharged into the ocean.
*** Semi-batch RO nit operation conditions: feedwater salinity of 36,357 ppm, 42% recovery, 379 ppm product water, and plant capacity of 556 m^3/day (Gal and Efraty 2016).
Condensing MED unit operation conditions: feedwater salinity of 45,000 ppm, 33%–37.5% (35% average) recovery, product water salinity of <25 ppm, and 220–250 kPa pressure. Capacity not provided (Sommariva 2010).
**** In calculating the energy consumption, the thermal energy intensities ($kWh_{e,equiv}/m^3$) were divided by 33% to convert to thermal consumption, assuming a 33% generation, transmission, and distribution efficiency.

Table A3-7. On-site Practical Minimum Energy Consumption, R&D Opportunity, and R&D Energy Savings Percent for U.S. Seawater Desalination Systems (GWh/year)

Unit Operation	On-site SOA Energy Consumption, Calculated (GWh/year)	On-site PM Energy Consumption, Calculated (GWh/year)	R&D Opportunity (SOA-PM) (GWh/year)	R&D Energy Savings Percent* (SOA-PM)/ (CT-TM)
System Type: Membrane Open-ocean (Semi-batch RO)				
Intake	0.9	0.9	0.05	19%
Pre-treatment	21	17	4	11%
Desalination**	344	189	155	54%
Post-treatment	11	11	0	0%
Concentrate Management	8	8	0.4	19%
Total System Type: Membrane Open-ocean* **	**384**	**225**	**160**	**47%**

State of the Art (SOA), Practical Minimum (PM), Thermodynamic Minimum (TM)
* *R&D energy savings percent* is the R&D energy savings opportunity from transforming desalination system processes. Energy savings percent was calculated using TM energy consumption shown in Chapter 6 as the minimum energy consumption. The energy savings percent, with TM as the minimum, was calculated as follows:
(SOA-PM)/(CT-TM).
** Unit operation conditions: semi-batch RO, feedwater salinity of 36,357 ppm, 42% recovery, 379 ppm product water, and plant capacity of 556 m^3/day (Gal and Efraty 2016).
*** Totals may not sum due to independent rounding.

Table A3-8. On-site Practical Minimum Energy Consumption, Energy Savings, and Energy Savings Percent for U.S. Seawater Desalination Systems (GWh/year)

Unit Operation	On-site CT Energy Consumption, Calculated (GWh/year)	On-site PM Energy Consumption, Calculated (GWh/year)	PM Energy Savings* (CT-PM) (GWh/year)	PM Energy Savings Percent** (CT-PM)/ (CT-TM)
System Type: Membrane Open-ocean (Semi-batch RO)				
Intake	1	1	0.2	39%
Pre-treatment	34	17	38	52%
Desalination***	420	189	231	81%
Post-treatment	14	11	3	24%
Concentrate Management	9	8	1	39%
Total System Type: Membrane Open-ocean** **	**478**	**225**	**253**	**75%**

Current Typical (CT), Practical Minimum (PM), Thermodynamic Minimum (TM)
* *PM energy savings* is the *Current Opportunity* plus the *R&D Opportunity.*
** *PM energy savings percent* is the PM energy savings opportunity from transforming desalination system processes. Energy savings percent was calculated using TM energy consumption shown in Chapter 6 as the minimum energy consumption. The energy savings percent, with TM as the minimum, was calculated as follows:
(CT-PM)/(CT-TM).
*** Unit operation conditions: semi-batch RO, feedwater salinity of 36,357 ppm, 42% recovery, 379 ppm product water, and plant capacity of 556 m^3/day (Gal and Efraty 2016).
**** Totals may not sum due to independent rounding.

Table A3-9. Associated Practical Minimum CO_2 Intensities and Emissions for Seawater Desalination Systems (kilotonne CO_2/year)

Unit Operation	On-site PM Electric Energy Intensity (kWh_e/m^3)	PM Thermal Energy Intensity ($kWh_{e,equiv}/m^3$)	CO_2 Electricity Emission Factor (kg CO_2 /$kWh_{T,equiv}$)	CO_2 Thermal Emission Factor (kg $CO_2/kWh_{T,equiv}$)	CO_2 Emission Intensity (kg CO_2/ m^3)	Capacity (million m^3)	CO_2 Emissions (kilotonne CO_2/year)
System Type: Membrane Sub-surface (Semi-batch RO)							
Intake*	0.0034	N/A	0.53	N/A	0.002	255	0.5
Pre-treatment	0.02				0.01	128	1
Desalination**	1.48				0.79	128	101
Post-treatment	0.08				0.04	128	6
Concentrate Management*	0.0034				0.002	2,231	4
Total System Type: Membrane Sub-surface* **							**113**
System Type: Membrane Open-ocean (Semi-batch RO)							
Intake*	0.0034	N/A	0.53	N/A	0.002	255	0.5
Pre-treatment	0.13				0.07	128	9
Desalination**	1.48				0.79	128	101
Post-treatment	0.08				0.04	128	6
Concentrate Management*	0.0034				0.002	2,231	4
Total System Type: Membrane Open-ocean* **							**120**
System Type: Thermal (Condensing MED)							
Intake*	0.0034	N/A	0.53	N/A	0.002	364	1
Pre-treatment	0.04		0.53		0.02	128	2
Desalination**	1.00	3.00	0.53	0.23	2.58****	128	329****
Post-treatment	0.11	N/A	0.53	N/A	0.06	128	7
Concentrate Management*	0.0034		0.53		0.002	1,071	2
Total System Type: Thermal* **							**341**

Practical Minimum (PM)

* To account for pump and motor efficiencies, as well as total dynamic head (TDH) loss, intake and concentrate management energy intensities were normalized per unit head loss (kWh_e/m^3-m TDH). For the PM energy intensity, a combined system efficiency of 82% was applied (pump efficiency * motor efficiency = 85% * 97% = 82%) (Proceedings of the 6th International Conference eemods '09: Energy Efficiency in Motor Driven Systems 2009). There were limited reported values in the literature for concentrate management; therefore, energy intensities for intake and concentrate management were assumed to be the same (as pumping is the primary energy-intensive mechanism for open-ocean intake and surface water discharge). Intake water was assumed to be standard seawater at 35,000 ppm. Concentrate was assumed to be diluted to 37,000 ppm to be discharged into the ocean.

** Semi-batch RO unit operation conditions: semi-batch RO, feedwater salinity of 36,357 ppm, 42% recovery, 379 ppm product water, and plant capacity of 556 m^3/day (Gal and Efraty 2016).

Condensing MED unit operation conditions: feedwater salinity of 45,000 ppm, 33%–37.5% (35% average) recovery, product water salinity of <25 ppm, and 220–250 kPa pressure. Capacity not provided (Sommariva 2010).

*** Totals may not sum due to independent rounding.

**** In calculating the emissions intensity and total emissions, the electrical equivalent thermal energy intensities ($kWh_{e,equiv}/m^3$) were divided by 33% to convert to thermal consumption, assuming a 33% generation, transmission, and distribution efficiency.

A3.4. Thermodynamic Minimum

Table A3-10. On-site Thermodynamic Minimum Energy Consumption for Seawater Desalination Systems (GWh/year)

Unit Operation	On-site TM Energy Intensity ($kWh_{T,equiv}/m^3$)	On-site TM Energy Consumption, Calculated (GWh/year)
System Type: Membrane Sub-surface and Open-ocean		
Intake*	0.0028	0.7
Pre-treatment	0	0
Desalination**	1.06	135
Desalination***	1.05	134
Post-treatment	0	0
Concentrate Management*	0.0028	6.3
Total System Type: Membrane Sub-surface and Open-ocean****		**142**
System Type: Thermal (MED)		
Intake*	0.0028	0.7
Pre-treatment	0	0
Desalination*****	1.20	153
Post-treatment	0	0
Concentrate Management*	0.0028	6.3
Total System Type: Thermal****		**160**

Thermodynamic minimum (TM)

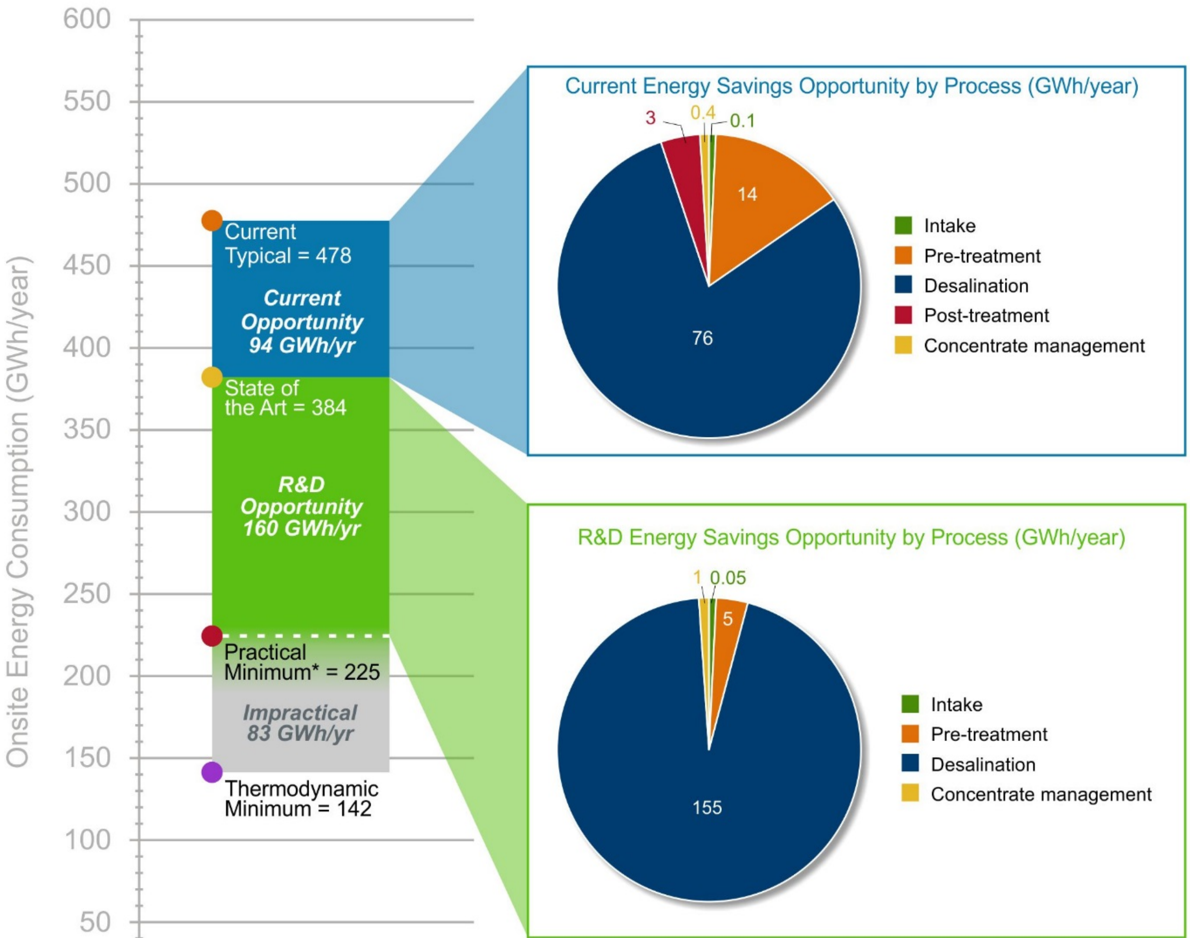
* To account for pump and motor efficiencies, as well as total dynamic head (TDH) loss, intake and concentrate management energy intensities were normalized per unit head loss (kWh_e/m^3-m TDH). For the TM energy intensity, a combined system efficiency of 100% was assumed. There were limited reported values in the literature for concentrate management; therefore, energy intensities for intake and concentrate management were assumed to be the same (as pumping is the primary energy-intensive mechanism for open-ocean intake and surface water discharge). Intake water was assumed to be standard seawater at 35,000 ppm. Concentrate was assumed to be diluted to 37,000 ppm to be discharged into the ocean.
** Unit operation conditions: 50% recovery of 0 ppm product water from 35,000 ppm and 25^{0}C feedwater (CT and SOA conditions)
*** Unit operation conditions: 42% recovery of 0 ppm product water from 36,357 ppm and 25^{0}C feedwater (PM conditions)
**** Totals may not sum due to independent rounding.
***** Unit operation conditions: 35% recovery of 0 ppm product water from 45,000 ppm and 25^{0}C feedwater (SOA and PM thermal conditions)

A3.5. Summary

Table A3-11. Current and R&D Opportunity for Seawater Desalination (GWh/year)

Unit Operation	Current Opportunity (CT-SOA) (GWh/year)	R&D Opportunity (SOA-PM) (GWh/year)
System Type: Membrane Sub-surface (Reverse osmosis)		
Intake	0.1	0.05
Pre-treatment	0	0
Desalination*	76	155
Post-treatment	3	0
Concentrate Management	0.4	0.4
Total System: Membrane Sub-surface**	**80**	**156**
System Type: Membrane Open-ocean (Reverse osmosis)		
Intake	0.1	0.05
Pre-treatment	14	4
Desalination*	76	155
Post-treatment	3	0
Concentrate Management	0.4	0.4
Total System: Membrane Open-ocean**	**94**	**160**
System Type: Thermal (MED)		
Intake	N/A	0.07
Pre-treatment		2
Desalination***		893
Post-treatment		0
Concentrate Management		0.2
Total System: Thermal**	**N/A**	**895**
U.S. Total "Best" Fit: Membrane Open-ocean	**94**	**160**

Current typical (CT), state of the art (SOA), practical minimum (PM)
* Unit operation conditions: CT and SOA: RO-based system at 50% recovery of 500 ppm product water from 35,000 ppm feedwater (Voutchkov 2013). PM: semi-batch RO-based system at 42% recovery of 379 ppm product water from 36,357 ppm feedwater (Gal and Efraty 2016).
** Totals may not sum due to independent rounding.
*** Unit operation conditions: SOA technology is MED-TVC, PM technology is condensing MED; feedwater salinity of 45,000 ppm, 33%–37.5% (35% average) recovery, product water salinity of <25 ppm, and 220–250 kPa pressure. Capacity not provided (Sommariva 2010).



CT, SOA, TM operating conditions: RO-based system at 50% recovery of 500 ppm (0 ppm for TM) product water from 35,000 ppm feedwater.
PM operating conditions: semi-batch RO-based system at 42% recovery of 379 ppm product water from 36,357 ppm feedwater.

** The PM energy consumption is based on today's knowledge of R&D technologies tested between laboratory and demonstration scale, referencing the lowest energy intensity value (in this case for semi-batch RO for the desalination unit operation) in the available literature. Current research at the concept level (which does not meet PM definitions for purposes of this report) of other systems or technologies may drive the PM energy consumption lower, closer to TM energy consumption. One example is fully batch RO, which when tested at a laboratory or higher scale may show a decrease in energy consumption (Warsinger, Tow, Nayar, Maswadeh, & Lienhard, 2016; Werber, Deshmukh, & Elimelech, 2017).*

Figure A3-2. Current and R&D energy savings opportunities for open-ocean intake RO desalination system (GWh/year)
Source: EERE

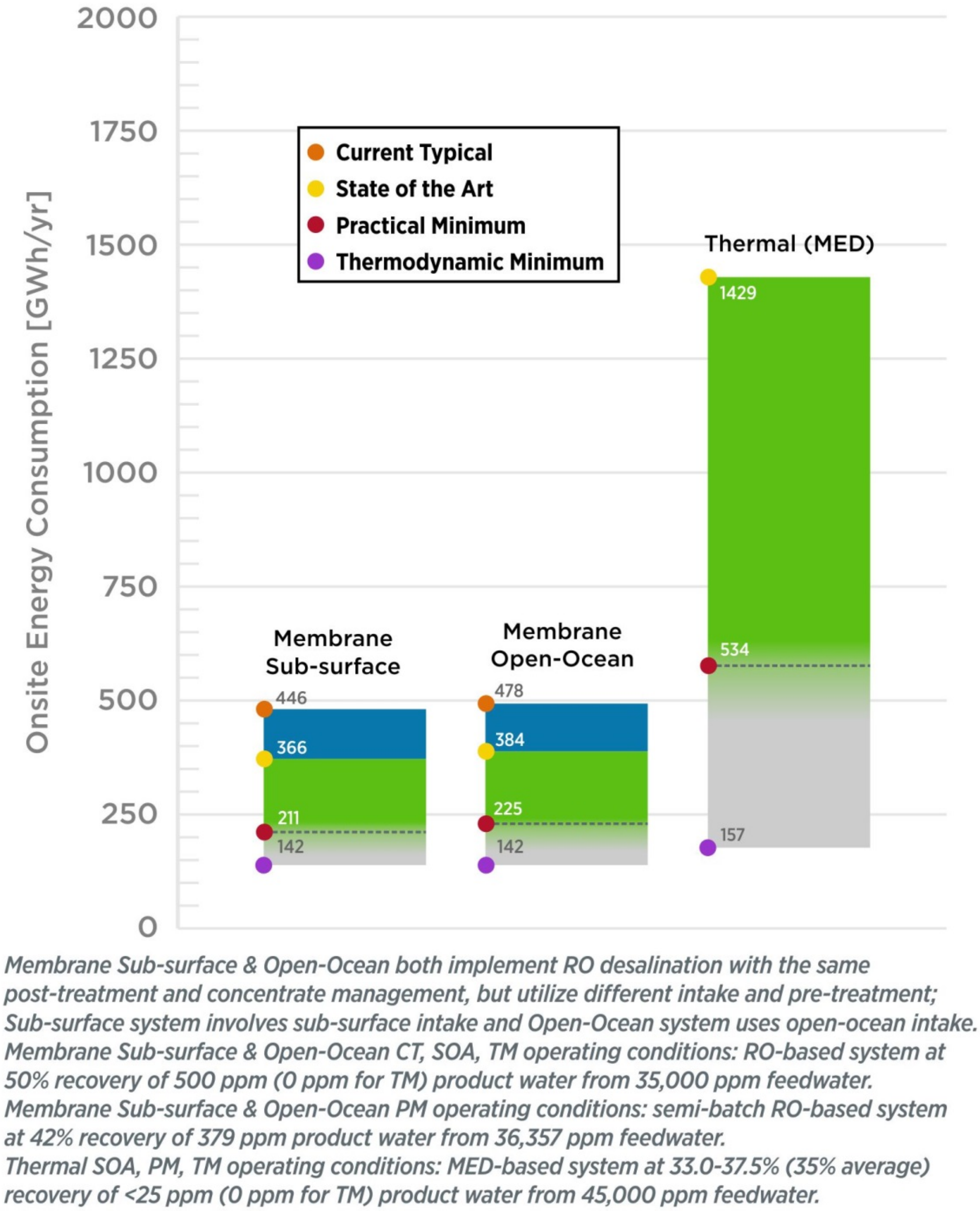


Figure A3-3. Current and R&D energy savings opportunities in U.S. seawater membrane and thermal desalination systems for unit operations studied (GWh/year)
Source: EERE

Note: Membrane #1 and Membrane #2 both implement RO desalination with the same post-treatment (remineralization and disinfection) and concentrate management (surface water discharge), but use different intake and pre-treatment methods. Membrane #1 utilizes sub-surface intake with cartridge and bag filtration pre-treatment, while membrane #2 utilizes open-ocean intake with flocculation, coagulation, and sand and cartridge filtration. The thermal (MED) system does not have a CT value, as it is not currently used for seawater desalination in the United States.

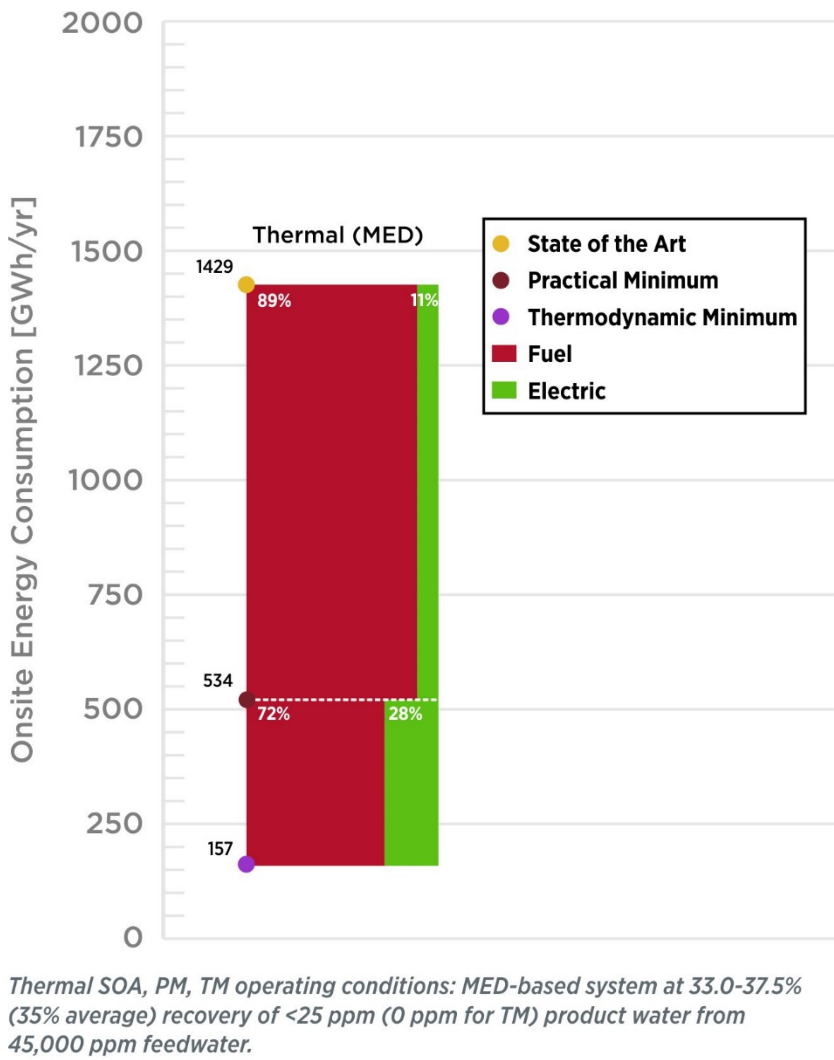


Figure A3-4. R&D energy savings opportunities in U.S. seawater thermal desalination systems for unit operations studied broken out by thermal and electric energy source (GWh/year)
Source: EERE

Table A3-12. Summary of Associated CO_2 Emissions for Seawater Desalination Systems

Unit Operation	CT CO_2 Emissions (kilotonne CO_2/year)	SOA CO_2 Emissions (kilotonne CO_2/year)	PM CO_2 Emissions (kilotonne CO_2/year)
System Type: Membrane Sub-surface			
Intake	1	0.5	0.5
Pre-treatment	1	1	1
Desalination*	225	184	101
Post-treatment	8	6	6
Concentrate Management	5	4	4
Total System: Membrane Sub-surface**	**239**	**196**	**113**
System Type: Membrane Open-ocean			
Intake	1	0.5	0.5
Pre-treatment	18	11	9
Desalination*	225	184	101
Post-treatment	8	6	6
Concentrate Management	5	4	4
Total System: Membrane Open-ocean**	**256**	**206**	**120**
System Type: Thermal			
Intake	N/A	1	1
Pre-treatment	N/A	3	2
Desalination***	N/A	937	329
Post-treatment	N/A	7	7
Concentrate Management	N/A	2	2
Total System: Thermal**	**N/A**	**951**	**341**
U.S. Total "Best" Fit: Membrane Open-ocean	**256**	**206**	**120**

Current typical (CT), state of the art (SOA), practical minimum (PM)
* Unit operation conditions: CT and SOA: RO-based system at 50% recovery of 500 ppm product water from 35,000 ppm feedwater (Voutchkov 2013, Personal communication with plant employee 2017). PM: semi-batch RO-based system at 42% recovery of 379 ppm product water from 36,357 ppm feedwater (Gal and Efraty 2016).
** Totals may not sum due to independent rounding.
*** Unit operation conditions: SOA technology is MED-TVC, PM technology is condensing MED; feedwater salinity of 45,000 ppm, 33%–37.5% (35% average) recovery, product water salinity of <25 ppm, and 220–250 kPa pressure. Capacity not provided (Sommariva 2010).

Appendix A4. Practical Minimum Energy Intensity Calculation and Example Technologies Considered

To estimate PM energy consumption for this bandwidth analysis, a broad search of R&D activities in the seawater desalination industry was conducted. A large number and range of potential technologies were identified. If more than one technology was considered for a particular process, the technology that resulted in the lowest energy intensity was selected for the PM energy intensity. The on-site PM energy intensity and consumption values are shown in Table A4-1 below.

Table A4-1. Calculated PM Energy Consumption for Seawater Desalination

Unit Operation	On-site PM Energy Intensity ($kWh_{T,equiv}/m^3$) [Btu/m^3]	On-site PM Energy Consumption, Calculated* (GWh/year) [BBtu/year]
Membrane Sub-surface		
Intake** Sub-surface intake	0.0034 [12]	1 [3]
Pre-treatment Cartridge filtration	0.02 [68]	3 [9]
Desalination Semi-batch RO***	1.48 [5,060]	189 [645]
Post-treatment		
Remineralization	0.04 [136]	5 [17]
Disinfection	0.04 [150]	6 [19]
Concentrate Management** Surface water discharge	0.0034 [12]	8 [26]
Total System Type: Membrane Sub-surface*		**211*** **[719]***
Membrane Open-ocean		
Intake** Open-ocean intake	0.0034 [12]	1 [3]
Pre-treatment Vacuum-driven microfiltration	0.13 [445]	17 [57]
Desalination		
Semi-batch RO***	1.48 [5,060]	189 [645]
Post-treatment		
Remineralization	0.04 [136]	5 [17]
Disinfection	0.04 [150]	6 [19]
Concentrate Management** Surface water discharge	0.0034 [12]	8 [26]
Total System Type: Membrane Open-ocean*		**225*** **[767]***
Thermal		
Intake** Open-ocean intake	0.0034 [12]	1 [4]

Table A4-1. Calculated PM Energy Consumption for Seawater Desalination

Unit Operation	**On-site PM Energy Intensity** ($kWh_{T,equiv}/m^3$) [Btu/m^3]	**On-site PM Energy Consumption, Calculated*** (GWh/year) [BBtu/year]
Pre-treatment		
Nanofiltration	0.04 [119]	4 [15]
Chlorination	0.0004 [1]	0.05 [0.2]
Desalination		
Condensing MED***	4.00 [13,649]	510 [1,740]
Post-treatment		
Remineralization	0.07 [239]	9 [30]
Disinfection	0.04 [150]	6 [19]
Concentrate Management** Surface water discharge	0.0034 [12]	4 [12]
Total System Type: Thermal*		**534 [1,822]**

Practical minimum (PM)
* Totals may not sum due to independent rounding.
** To account for pump and motor efficiencies, as well as total dynamic head (TDH) loss, intake and concentrate management energy intensities were normalized per unit head loss (kWh_e/m^3-m TDH). For the PM energy intensity, a combined system efficiency of 82% was applied (pump efficiency * motor efficiency = 85% * 97% = 82%) (Proceedings of the 6th International Conference eemods '09: Energy Efficiency in Motor Driven Systems 2009). There were limited reported values in the literature for concentrate management; therefore, energy intensities for intake and concentrate management were assumed to be the same (as pumping is the primary energy-intensive mechanism for open-ocean intake and surface water discharge). Intake water was assumed to be standard seawater at 35,000 ppm. Concentrate was assumed to be diluted to 37,000 ppm to be discharged into the ocean.
*** Semi-batch RO unit operation conditions: feedwater salinity of 36,357 ppm, 42% recovery, 379 ppm product water, and plant capacity of 556 m^3/day (Gal and Efraty 2016).
Condensing MED unit operation conditions: feedwater salinity of 45,000 ppm, 33%–37.5% (35% average) recovery, product water salinity of <25 ppm, and 220–250 kPa pressure. Capacity not provided (Sommariva 2010).

The PM energy intensity for seawater desalination was determined based on the technologies outlined in Table A4-2. The Applicability column indicates the Unit Operation/process where the technology is considered for application. The percent savings over the PM baseline was estimated, and a brief explanation provided. Some technologies in Table A4-2 were considered but not included in the final PM model (in most of the cases the savings estimates were conservative compared to SOA energy intensity).

In some cases, there was a limited amount of information available on technologies for specific stages (such as pre-treatment and post-treatment), requiring best engineering judgment to be used in determining the PM energy intensity. For post-treatment, the PM energy intensity and consumption values were calculated to be the same as the SOA energy intensity and consumption values based on best engineering judgment.

Table A4-2. Details of PM Technologies Considered

Technology Name	Description	Applicability	Energy Savings Estimate	PM Energy Intensity ($kWh_{T,equiv}/m^3$)	Included in PM model?	Reason for Excluding (if applicable)	Reference
High-efficiency pump and motor systems	Highest practical minimum efficiency pumps and motors have an energy efficiency improvement potential of 20%–30%	Intake/concentrate management	20%	0.0034	Yes		(Proceedings of the 6th International Conference eemods '09: Energy Efficiency in Motor Driven Systems 2009)
Vacuum-driven microfiltration	Pre-treatment technique using the same devices (MF or UF) at lower pressures	Pre-treatment (membrane)	20%	0.13	Yes		(Voutchkov 2010)
Nanofiltration	Filtration technique which utilizes a nano-porous membrane	Pre-treatment (thermal)	30%	0.04	Yes		(Hassan 2004, Hilal, et al. 2004)
Semi-batch reverse osmosis	Membrane separation process using an semi-batch that recirculates concentrate back into the RO process, lowering energy consumption	Desalination (membrane)	41%	1.48	Yes		(Gal and Efraty 2016)
Two-stage reverse osmosis	Membrane separation process using an additional stage within the RO process, lowering energy consumption	Desalination (membrane)	15%	2.13	No	The two-stage RO process described is theoretical analysis.	(Werber, Deshmukh and Elimelech 2017)

Technology Name	Description	Applicability	Energy Savings Estimate	PM Energy Intensity ($kWh_{T,equiv}/m^3$)	Included in PM model?	Reason for Excluding (if applicable)	Reference
Condensing MED	Thermal separation unit that requires a lower steam extraction pressure compared to typical thermal units (as low as 0.3 bar), and also does not require an additional thermo-compressor unlike the MED-TVC unit.	Desalination (thermal)		4.00	Yes		(Sommariva 2010)
Second pass RO for B and Cl removal	Post-treatment technique using a second treatment process for further water desalination	Post-treatment	0.50 kWh_e/m^3	0.50	No	Reduced post-treatment requirements from upstream processes like desalination are not a technological improvement.	(Shaffer, et al. 2012)
Calcium based post-treatment	Post-treatment methods utilizing limestone dissolution, source water blending, or direct chemical dosage to treat desalinated water	Post-treatment	None reported	None reported	No	Energy values calculated from reported cost data do not exhibit energy savings.	(Shemer, Hasson and Semiat 2015)
Magnesium based post-treatment	Post-treatment methods utilizing dolomite dissolution, ion exchange, or magnesium oxide dissolution to treat desalinated water	Post-treatment	None reported	None reported	No	Energy values calculated from reported cost data do not exhibit energy savings.	(Shemer, Hasson and Semiat 2015)

Microfiltration (MF), ultrafiltration (UF), boron (B), chlorine (Cl)

A4.1. PM Technologies Considered

Table A4-3 provides a more comprehensive list of the technologies considered in studying R&D technology opportunities for seawater desalination.

Table A4-3. Seawater Desalination System R&D Technologies Considered for PM Energy Intensity Analysis

Technology Name	Description	Applicability	Explanation of Energy Savings Assumptions	Percent Savings Estimate (%) or Energy Intensity ($kWh_{T,equiv}/m^3$)	Conditions* (Salinity, Flow Rate, Recovery, Pressure, etc.)	References
Intake						
Increased plant size/intake	Increased water intake as a strategy for lowering energy and capital costs	Intake	From Table 1 of source: 1-(2.99/3.96) = 24.5%	24.5%	Flow rate: 50 MGD	(Kim, et al. 2011)
Variable speed drives (VFDs)	matching pump and motors to match energy demand, lowering energy consumption	Intake	The use of VFDs is estimated to reduce energy use by as much as 50% because VFDs match the motor speed to the specific energy demands needed	50.0%	None reported	(Water Research Foundation n.d.)
Axial piston pump-axial piston motor (APP-APM)	combined hybrid pump configuration using a water hydraulic axial piston pump with an energy-recovery motor	Intake	Some of the advantages of the APP—APM system are reduced power consumption approximately 50% compared with APP alone	50.0%	Flow rate: 476 m^3/day Pressure: 5,516–8,274 kPa Efficiency: 94%	(MacHarg 2007)
Pre-treatment						
Ultrafiltration (UF)	Filtration technique which utilizes a finely-pored (0.01–0.05 µm) membrane	Pre-treatment	0.07 kWh_e/m^3 after accounting for pumps and air scouring	0.07 $kWh_{T,equiv}/m^3$	Flow rate: 416,000 m^3 seawater/day	(Al-Sarkal and Arafat 2013, Lau, et al. 2014)
Nanofiltration (NF)	Filtration technique which utilizes a nano-porous membrane	Pre-treatment	"The net effect of this NF pre-treatment, which, unlike the UF treatment, it succeeded in changing the seawater feed chemistry, mainly by the removal of hardness ions and reduction of feed TDS, was to increase SWRO	30.0%	Conditions from Hassan 2004: Recovery: 65% Flow rate: 10.0–13.3 m^3/hour Pressure: 30 bar	(Hassan 2004, Hilal, et al. 2004)

			potable water yield by 40%–100% and recovery from 20%–35% without NF pre-treatment to 50%–70% with NF feed pre-treatment. Furthermore, this NF pre-treatment lowered both the process energy consumption and water cost by about 30% or better." Hassan 2004			
Center Port Pressure Vessel Energy Savings Patented by Protec Arisawa	Patented filtration technique which utilizes a nano-porous membrane	Pre-treatment	Reduces feed pumping energy consumption for energy savings 35%-40% over conventional nanofiltration	37.5%	Recovery: 85% Feed pressure: 53–55 psi	(Protec Arisawa 2017)
Vacuum-driven MF pre-treatment	pre-treatment technique using the same devices (MF or UF) at lower pressures	Pre-treatment	"The vacuum-driven systems may use 10% to 30% less energy than pressure-driven systems for water sources of medium to high turbidity and temperature between18 and 35°C."	20.0%	Temperature: 18–35°C	(Voutchkov 2010)
Desalination						
Fouling resistant membranes	Improves the membrane product lifetime by resisting natural buildup of unwanted particles in the membrane	Membrane desalination	"Technical-economic research showed that fouling resistant membranes…may allow savings of 25% in energy consumption…"	25.0%	None reported	(Van der Bruggen and Vandecasteele 2002)
Thin film composite nano-membranes (TFN)	Desalination process using nano-sized pores coupled with an RO configuration	Membrane desalination	Savings based on SEC values for conventional, one- and two-pass RO system configuration (4% for one-pass, 10% for two-pass)	10.0%	Salinity in; 33,935 ppm Flow rate: 22.7 m^3/hour	(Subramani, Voutchkov and Jacangelo 2014)
Aquaporin membranes	Biomimetic membranes for RO and FO separation processes can be used to capture undesirable species prior to membrane separation	Membrane desalination	Estimated 15% total energy savings potential (page 19 of source)	15%	None reported	(Perry 2017)

Ultra-permeable membranes	Increased permeability of membranes would reduce the pressure vessel requirement and as a result reduce the energy requirement for RO desalination	Membrane desalination	Assumes the 15% reduction in the energy consumption of the RO stage would only result in a reduction in the total SWRO energy cost	15.0%	Salinity in: 42,000 ppm Flow rate: 300 m^3/day (per vessel) Inlet pressure: 70 bar	(Cohen-Tanugi, et al. 2014)
Electrodialysis (ED) and Continuous Electro-deionization (CEDI)	Desalination technique where salt ions are continuously transferred through ion exchange membranes (Singapore case study). Actual seawater was treated to a drinking water quality standard.	Membrane desalination	Greater than 50% reduction of energy from existing best available technology (3.4–4.8 kWh_e/m^3) At start-up, the pilot was achieving 1.85 kWh_e/m^3 (inclusive of pumping, pre-treatment, desalting, and post-treatment)	50%	Recovery: 30% Flow rate: 1.9 m^3/hour Salinity in: 32,000 ppm Salinity out: 475 ppm Pressure drop: 0.65 bar Pump efficiency: 75%	(Knauf, et al. 2011)
Freeze desalination	Thermal desalination process that freezes water in order to separate saline and concentrate components	Thermal desalination	"Freeze concentration system with two stage compression using tubular heat exchanger…8–12 $kWh_{T,equiv}/m^3$"	None	None reported	(Rane and Padiya 2011)
Humidification-dehumidification desalination (HDD)	Thermal method requiring two direct contact heat exchangers (specifically for humidification and dehumidification purposes) to desalinate water	Thermal desalination	N/A	None	Recovery: 0.6% Flow rate: 1.7 m^3/day output	(Eslamimanesh and Hatamipour 2010)
Condensing MED	Unit that requires a lower steam extraction pressure compared to typical thermal units (as low as 0.3 bar). Steam can be extracted from a back pressure steam turbine within a combined cycle. Also, it does not require an additional thermo-compressor unlike the MED-TVC unit, which would increase the energy consumption. Decreased steam extraction pressure	Thermal desalination	Reference provides energy intensity of technology	Electric: 1 kWh_e/m^3 Thermal: 3 $kWh_{e,equiv}/m^3$ Total: 4 $kWh_{T,equiv}/m^3$	Salinity in: 45,000 ppm Salinity out: <25 ppm TDS product Recovery: 33%–37.5% Pressure: 40 kPa	(Sommariva 2010)

	and discarded thermo-compressor enables significant energy savings.					
Recovery of retrograde soluble solute for forward osmosis water treatment	Technology to desalinate seawater based on a diol acting as a osmotic agent	Membrane desalination	Seawater desalination using 87.5% less electrical energy than current RO membrane systems	87.5%	None reported	(Valladares Linares, et al. 2014)
Coupled freezing-melting (FM process w/RO	Desalination technique combining RO and FM technologies to minimize concentrate disposal	Thermal desalination	Assuming intake flow rates of 200 m^3/hour, "the combined system can reduce the energy consumption by about 13%…compared to…RO plants…"	13.0%	Flow rate: 200 m^3/hour	(Rahman, Ahmed and Chen 2007)
Pressure center and Double Work Exchanger Energy Recovery (DWEER)	Separation of trains from pumping section and energy recovery system coupled with a positive displacement pump for the concentrate stream	Membrane desalination	"Namely, 10%–15% below the contractual specific energy of 3.9 $kWh_{T,equiv}$/ m^3 ± 5% of with reduced consumption in winter time at cold water temperatures of 15 deg. C were achieved."	12.50%	Recovery: 48% Pressure: 70 bar	(Taub 2007)
Three-stage energy efficient reverse osmosis (EERO)	RO system coupled with two stages of processing utilizing a countercurrent membrane cascade with recycling (CMCR)	Membrane desalination	"The 3-stage EERO process can achieve a recovery of 75% at a net SEC of 2.746 kWh_e/m^3, which represents an 11.0% reduction in the SEC relative to SSRO for the same recovery."	2.75 $kWh_{T,equiv}$ /m^3	Recovery: 75% Salinity in: 35,000 ppm Salinity out: 350 ppm Pressure: 74.1 bar	(Chong, Loo and Krantz 2014)
Hybrid FO-RO system	Hybrid system that couples forward and reverse osmosis processes during desalination	Membrane desalination	"Estimated energy requirements are estimated between 5.68 to 11.36 $kWh_{T,equiv}$/kgal (0.24 to 0.48 $kWh_{T,equiv}$/bbl)"	5.68–11.36 $kWh_{T,equiv}/m^3$	Recovery: 96% Salinity in: 500–35,000 ppm	(Colorado School of Mines 2009)
Mechanical vapor compression (MVC)	Vapor compression relying on the heat generated by the mechanical compression of water vapor to evaporate sea or brackish water	Thermal desalination	8–14 $kWh_{T,equiv}/m^3$ required, but no thermal energy required	100% thermal savings; increased electrical energy	Recovery: 40%–50%	(Camacho, et al. 2013)
Membrane distillation (MD)	A thermal, membrane-based separation process using the vapor pressure difference across the membrane between water	Thermal desalination	Scarab test site (solar-powered MD); 0.6–1.5 kWh_e/m^3 required, 5–12 $kWh_{e,equiv}/m^3$ required	-20% to 50% thermal savings; -50% to 40% electrical	Flow rate: 1-2 m^3/day GOR: 0.78	(Camacho, et al. 2013)

	at different temperatures on either side of the membrane, a concentration gradient or an electrical potential gradient, which drives mass transfer through a membrane			savings (values compared to SOA value for MED-TVC from (Sommariva 2010))		
Multi-effect distillation (MED)	A thermal separation process that evaporates seawater films in contact with a heat transfer surface at each individual stage.	Thermal desalination	Low value reported in literature as 1 kWh_e/m^3 and 3 $kWh_{e,equiv}/m^3$; so 0% electric savings, but 70% thermal savings compared to MED-TVC low value in (Sommariva 2010)	-70% thermal savings; -0% electrical savings (values compared to SOA value for MED-TVC from (Sommariva 2010)	Recovery: 33.0%–37.5% Salinity in: 45,000 ppm Steam pressure: 0.35–0.50 bar abs	(Sommariva 2010)
Two-stage Reverse Osmosis (RO)	Membrane separation process using an additional stage within the RO process, lowering energy consumption	Membrane desalination	For example, two-stage RO would save…15% energy…over one-stage seawater RO at 50% recovery.	15%	Recovery: 50%	(Werber, Deshmukh and Elimelech 2017)
Semi-batch Reverse Osmosis (RO)	Membrane separation process using an semi-batch that recirculates concentrate back into the RO process, lowering energy consumption	Membrane desalination	For example, semi-batch RO, would save 13%…energy…over one-stage seawater RO at 50% recovery.	13%	Recovery: 50%	(Werber, Deshmukh and Elimelech 2017)
Closed-circuit desalination (also referred to as semi-batch RO)	Seawater desalination under closed-circuit desalination conditions with a unit comprising four modules, each of four Qfx-SW-400-ES nanoH2O elements, with seawater feed in the cited (parentheses) ranges of salinity (33,801–37,197 ppm), flux (9.2–13.4 liter/m^2/hour), recovery (42%–53%), and temperature (15.0–18.4 °C).	Membrane desalination	Assumed the value of 1.483 kWh_e/m^3 for 42% recovery at 36,357 ppm feed. Source also provides 1.775 kWh_e/m^3 for 53% recovery at 33,913 ppm feed	1.483 $kWh_{T,equiv}/m^3$	Recovery: 42.0% Salinity in: 36,357 ppm Salinity out: 379 ppm Flow rate: 7.35 m^3/hour Pressure: 48.5 bar	(Gal and Efraty 2016)

Post-treatment						
Second pass RO for B and Cl removal	Post-treatment technique using a second treatment process for further water desalination	Post-treatment	0.5 kWh_e/m^3 (second pass); 0.3–1.1 kWh_e/m^3 (pre- and post-treatment chemicals)	0.5 $kWh_{T,equiv}/m^3$; 0.7 $kWh_{T,equiv}/m^3$	None reported	(Shaffer, et al. 2012)
Pelton turbine ERD	Post-treatment method to recover energy in concentrate disposal via turbine	Post-treatment	Energy consumed by Pelton turbine was -26.02%, implying energy recovered	26.0%	Flow rate: 1.0 m^3/hour permeate; 1.22 m^3/hour concentrate Pressure: 63 bar (Pelton turbine), 64 bar (high pressure pumping)	(V. G. Gude 2011)
Pressure exchanger (PX) ERD	Post-treatment method to recover energy in concentrate disposal via reduction of high-pressure pumping	Post-treatment	1-(3.71/6.26) = 40.75%	40.8%	Flow rate: 1.0 m^3/hour permeate; 1.22 m^3/hour concentrate Pressure: 4 bar (circulation pump), 64 bar (high-pressure pumping)	(V. G. Gude 2011)
Calcium based post-treatment	Post-treatment methods utilizing limestone dissolution, source water blending, or direct chemical dosage to treat desalinated water	Post-treatment	None reported	None reported	None reported	(Shemer, Hasson and Semiat 2015)
Magnesium based post-treatment	Post-treatment methods utilizing dolomite dissolution, ion exchange, or magnesium oxide dissolution to treat desalinated water	Post-treatment	None reported	None reported	None reported	(Shemer, Hasson and Semiat 2015)
Degasification	Post-treatment method to remove dissolved gases like	Post-treatment (more likely for	None reported	None reported	None reported	(R. W. Beck, Inc. 2004)

	hydrogen sulfide from the product water	brackish water)				
Concentrate Management						
Chemical and concentrate discharge	Concentrate management method to further process unwanted products in water	Concentrate management	Post-treatment chemicals dosing: 2.4 kWh_e/day (0.100 kWh_e/m^3) Treated water pumping: 8.2 kWh_e/day (0.342 kWh_e/m^3) Concentrate discharge: 2.2 kWh_e/day (0.092 kWh_e/m^3) Filters backwashing/cleaning: 4.0 kWh_e/day (0.083 kWh_e/m^3) Post-treatment total: 0.525 kWh_e/m^3 Concentrate discharge: 0.092 kWh_e/m^3	0.092 $kWh_{T,equiv}/m^3$	Flow rate: 1.0 m^3/hour permeate; 1.22 m^3/hour concentrate Pressure: 2 bar Pump efficiency: 80% Motor efficiency: 92%	(V. G. Gude 2011)
Vibratory shear-enhanced processing (VSEP)	Concentrate disposal technique using low-velocity, meandering flow across a membrane with high shear	Concentrate management	1-(0.07/0.23) = 69.6% energy savings – 0.23 $kWh_{T,equiv}/m^3$ for distribution energy [Kim et al. (2011)]	69.6%	None reported	(Masnoon and Glucina 2011)
Wind-aided intensified evaporation	Concentrate disposal method in which water is pumped onto fabrics to provide additional surface area for evaporation	Concentrate management	None reported	None reported	None reported	(Hoque, Alexander and Gurian 2008, Morillo, et al. 2014)

Practical minimum (PM), * As provided by reference(s)

Appendix A5. Parameter Sensitivity Analysis for Seawater Desalination Uptake Scenarios

This appendix presents parameter sensitivity analysis for seawater desalination uptake scenarios. Alternative scenarios test how sensitive Scenario 1 (presented in section 9. in the main body of the report) results are to key parameters used to estimate the total energy requirement for supplying desalinated seawater to all counties in the continental United States. The total energy requirement results for Scenario 1 reflect a number of key parameter assumptions as defined in Table A5-1.

Table A5-1. Key Parameters for Parameter Sensitivity Scenarios

Parameter	Scenario 1 Assumption	Parameter Units
Desalination Energy Intensity	Reverse Osmosis State of the Art (SOA) with open-ocean intake	kWh_e/gal
Potable Water Demand	USGS Public Supply Intake	MGD
Potable Water Pumping Distance	Straight line minimum	mile
Potable Water Pumping Elevation	USGS county centroid	ft
Potable Water Pipe Flow Rate	2	ft/s
Pipe Material	Plain Cast Iron	
Potable Water Pump Efficiency	90%	
Potable Water Pump Motor Efficiency	95%	

The following sections present alternative scenarios resulting from varying each of the parameter assumptions listed in Table A5-1. Each section contains a figure that compares the Scenario 1 results (black plot) to the alternative scenario results (red plots). In all of the figures, the left Y-axis shows cumulative energy consumption, in TWh per year, and the right Y-axis is the percent of 2017's net grid supplied electricity that the cumulative energy requirement represents. All of the energy in the scenarios are end-use electricity. The X-axis is the cumulative water flow in millions of gallons per day (MGD). Each "step" in the plots represents a separate county and all of the counties are sorted from shortest to longest distance between coasts and county centroid (water demand location).

Each section also contains a table showing Scenario 1 and the alternative scenario results for counties within 25 miles, 250 miles, and all distances; broken out by desalination energy, potable water conveyance pumping energy, total energy; and the ratios of total energy to 2017 U.S. electricity consumption, and desalination energy's percent of total energy.

A5.1. Parameter Sensitivity Scenario: Desalination SOA Energy Intensity versus TM Energy Intensity

Figure A5-1 shows the result of lowering the desalination energy requirement from state of the art (SOA) in Scenario 1 to the thermodynamic minimum (TM). As presented in the main body of the report, state of the art (SOA) desalination energy intensity is 0.0114 kWh/gal (3 kWh/m^3) of desalinated water; and the thermodynamic minimum is 0.004 kWh/gal (1.1 kWh/m^3) of desalinated water. Water pumping assumptions are the same in both plots in Figure A5-1.

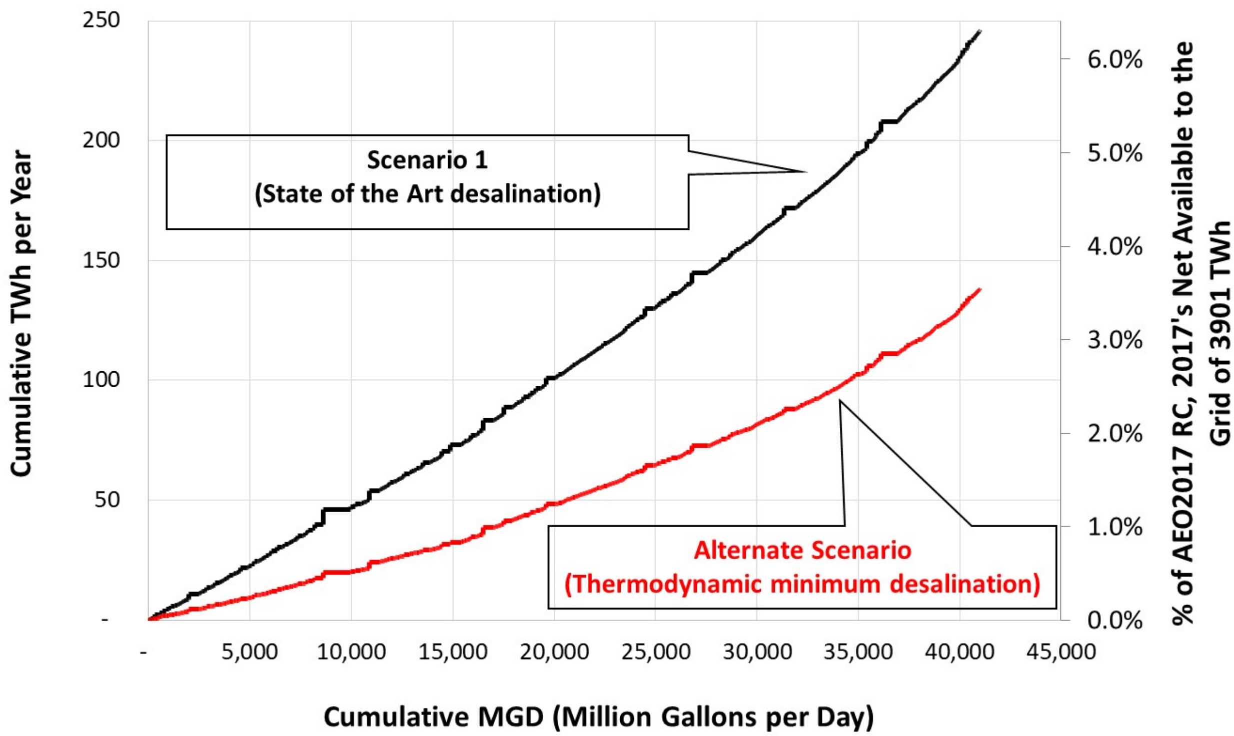


Figure A5-1. Parameter sensitivity scenario: Desalination SOA energy intensity versus TM energy intensity
Source: LBNL

Decreasing the desalination energy requirement from SOA to TM reduces the total energy requirement from 246 TWh to 138 TWh, as shown in Table A5-2.

Table A5-2. Desalination SOA Energy Intensity versus TM Energy Intensity Scenario Results

	Scenario 1 (State of the Art desalination)			Alternate Scenario (Thermodynamic minimum desalination)		
Distance from Coastline (miles)	25	250	All	25	250	All
Desalination Energy Requirement (TWh)	34	105	171	12	39	63
Potable Water Pumping Energy Requirement (TWh)	4	27	75	4	27	75
Total (desalination + potable water pumping) Energy Requirement (TWh)	38	132	246	16	65	138
% of 2017 U.S. electricity consumption	1.0%	3.4%	6.3%	0.4%	1.7%	3.5%
Desalination % of Total	89%	80%	69%	76%	59%	46%

A5.2. Parameter Sensitivity Scenario: USGS Public Water Intake versus USGS Total Water Intake

Figure A5-2 shows the result when each county's water demand is set at the USGS total water intake levels. The USGS total water intake includes all water demand (e.g., public, thermoelectric cooling, industrial, commercial, domestic, agriculture, and mining). Supplying the total intake demand to each county increases the cumulative million gallons per day from 41,000 MGD to 350,000 MGD and increases the total energy requirement from 233 TWh per year to over 2,000 TWh per year—an order of magnitude increase in required energy.

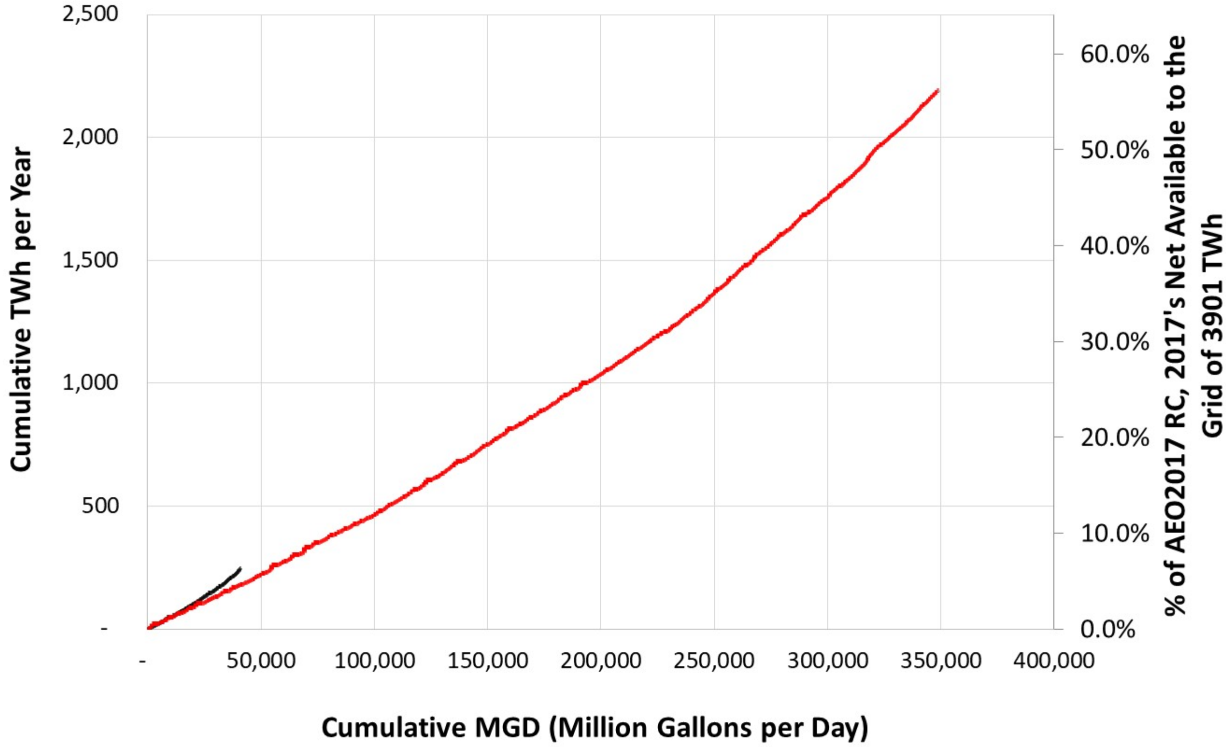


Figure A5-2. Parameter sensitivity scenario: USGS public water intake versus USGS total water intake
Source: LBNL

Table A5-3. USGS Public Water Intake versus USGS Total Water Intake Scenario Results

	Scenario 1 (USGS Public Water Intake)			Alternate Scenario (USGS Total Water Intake)		
Distance from Coastline (miles)	25	250	All	25	250	All
Desalination Energy Requirement (TWh)	34	105	171	260	738	1,454
Potable Water Pumping Energy Requirement (TWh)	4	27	75	22	166	738
Total (desalination + potable water pumping) Energy Requirement (TWh)	38	132	246	282	904	2,192
% of 2017 U.S. electricity consumption	1.0%	3.4%	6.3%	7.2%	23.2%	56.2%
Desalination % of Total	89%	80%	69%	92%	82%	66%

A5.3. Parameter Sensitivity Scenario: USGS Public Water Intake versus 20% of USGS Public Water Intake

Each county's water demand is set at 20% of the USGS public water demand levels in the following sensitivity scenario figure (Figure A5-3). The red plot shows the energy requirements for the much smaller public water demand at each county in the continental United States. Supplying 20% of the public water demand for each county decreases the cumulative million gallons per day from 41,000 MGD to 8,200 MGD and decreases the total energy requirement from 233 TWh per year to 55 TWh per year. Smaller water demand volumes reduce pipe diameters, which will increase friction losses and increase pumping loads. Thus, although the water demand is 20%, the total energy requirement is 22% of Scenario 1's total energy requirement. This scenario could represent seawater desalination uptake as a means of providing water resiliency and complementing freshwater sources.

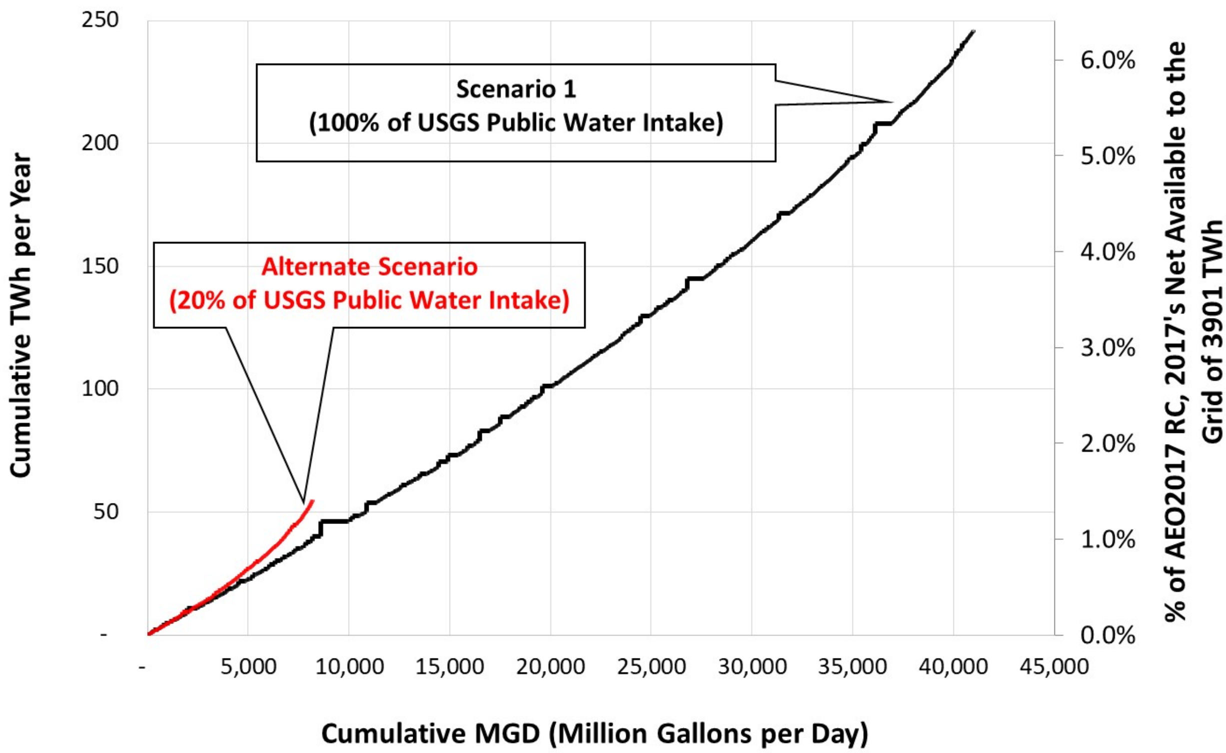


Figure A5-3. Parameter sensitivity scenario: USGS public water intake versus 20% of USGS public water intake
Source: LBNL

Table A5-4. USGS Public Water Intake versus 20% of USGS Public Water Intake Scenario Results

	Scenario 1 (100% of USGS Public Water Intake)			Alternate Scenario (20% of USGS Public Water Intake)		
Distance from Coastline (miles)	25	250	All	25	250	All
Desalination Energy Requirement (TWh)	34	105	171	7	21	34
Potable Water Pumping Energy Requirement (TWh)	4	27	75	1	6	21
Total (desalination + potable water pumping) Energy Requirement (TWh)	38	132	246	8	27	55
% of 2017 U.S. electricity consumption	1.0%	3.4%	6.3%	0.2%	0.7%	1.4%
Desalination % of Total	89%	80%	69%	89%	77%	62%

A5.3. Parameter Sensitivity Scenario: Shortest Pumping Distance versus 50% Greater Pumping Distances

Figure A5-4 shows the result of increasing each county's Scenario 1 water pumping distance by 50% in the alternative pumping distance scenario.

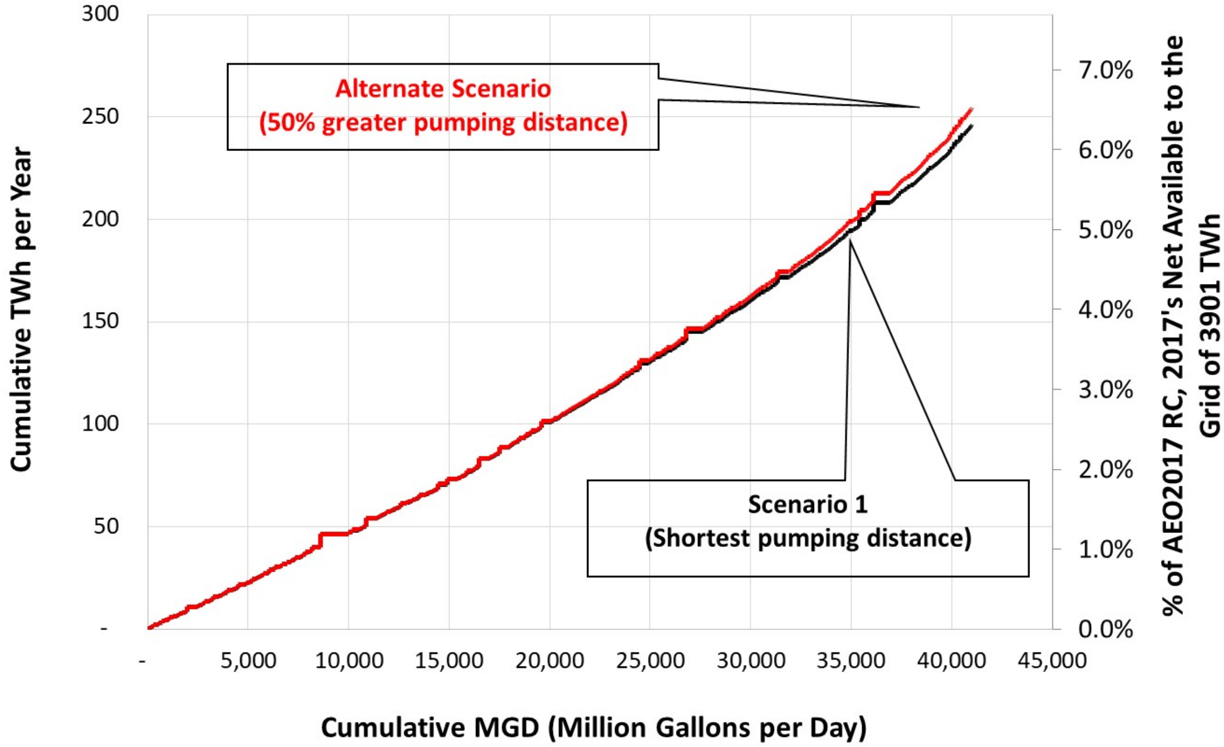


Figure A5-4. Parameter sensitivity scenario: Shortest pumping distance versus 50% greater pumping distances
Source: LBNL

Increasing the water pumping distance by 50% increases the total energy requirement from 246 TWh to 254 TWh, as shown in Table A5-5.

Table A5-5. Shortest Pumping Distance versus 50% Greater Pumping Distances Scenario Results

	Scenario 1 (Shortest pumping distance)			Alternate Scenario (50% greater pumping distance)		
Distance from Coastline (miles)	25	250	All	25	250	All
Desalination Energy Requirement (TWh)	34	105	171	34	105	171
Potable Water Pumping Energy Requirement (TWh)	4	27	75	4	28	84
Total (desalination + potable water pumping) Energy Requirement (TWh)	38	132	246	38	133	254
% of 2017 U.S. electricity consumption	1.0%	3.4%	6.3%	1.0%	3.4%	6.5%
Desalination % of Total	89%	80%	69%	89%	79%	67%

A5.4. Parameter Sensitivity Scenario: County Centroid Elevations versus 50% Higher Elevations

Figure A5-5 shows the result of increasing each county's Scenario 1 water demand pumping elevation above sea level by 50% in the alternative pumping elevation scenario.

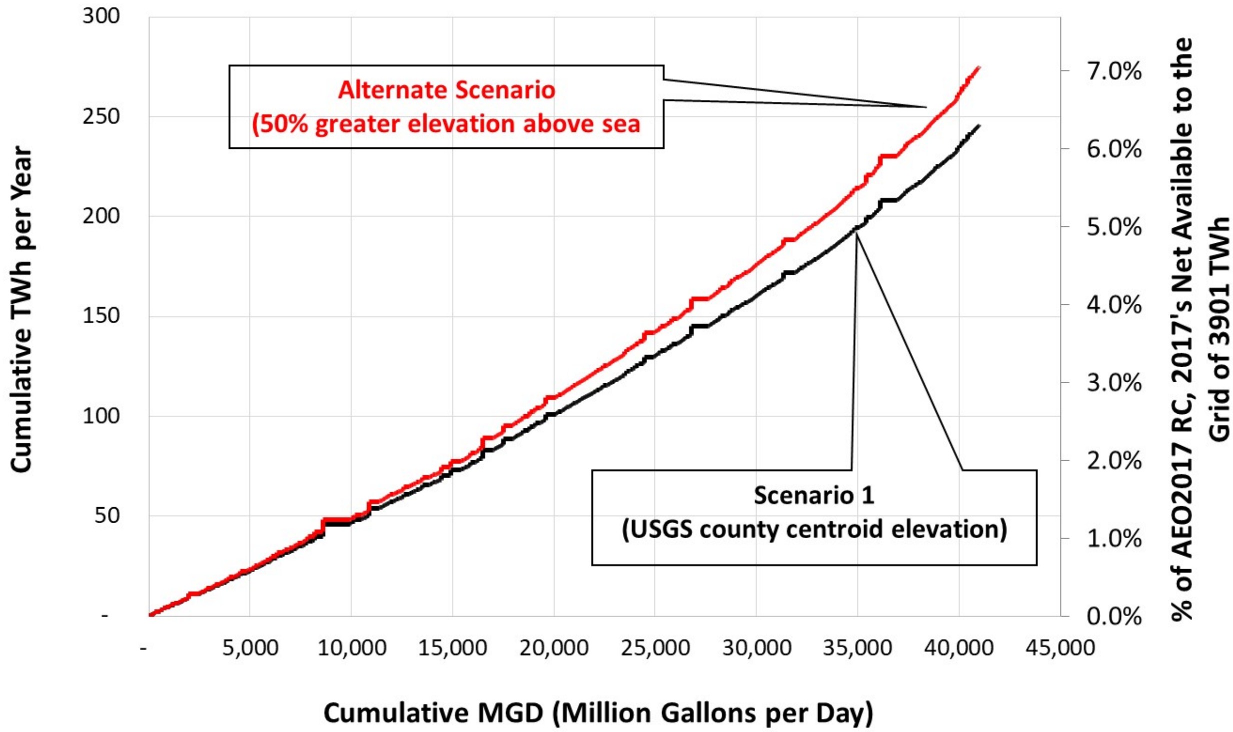


Figure A5-5. Parameter sensitivity scenario: County centroid elevations versus 50% higher elevations
Source: LBNL

Increasing each county's pumping elevation above sea level by 50% increases the total energy requirement from 246 TWh to 275 TWh, as shown in Table A5-6.

Table A5-6. County Centroid Elevations versus 50% Higher Elevations Scenario Results

	Scenario 1 (USGS county centroid elevation)			Alternate Scenario (50% greater elevation above sea level)		
Distance from Coastline (miles)	25	250	All	25	250	All
Desalination Energy Requirement (TWh)	34	105	171	34	105	171
Potable Water Pumping Energy Requirement (TWh)	4	27	75	6	39	104
Total (desalination + potable water pumping) Energy Requirement (TWh)	38	132	246	40	144	275
% of 2017 U.S. electricity consumption	1.0%	3.4%	6.3%	1.0%	3.7%	7.1%
Desalination % of Total	89%	80%	69%	85%	73%	62%

A5.5. Parameter Sensitivity Scenario: Piping Water Flow Velocity, 2 Feet per Second versus 3 Feet per Second

Figure A5-6 shows the result of increasing the piping water flow velocity for each county's water supply from 2 feet per second (Scenario 1) to 3 feet per second in the alternative piping water flow velocity sensitivity scenario.

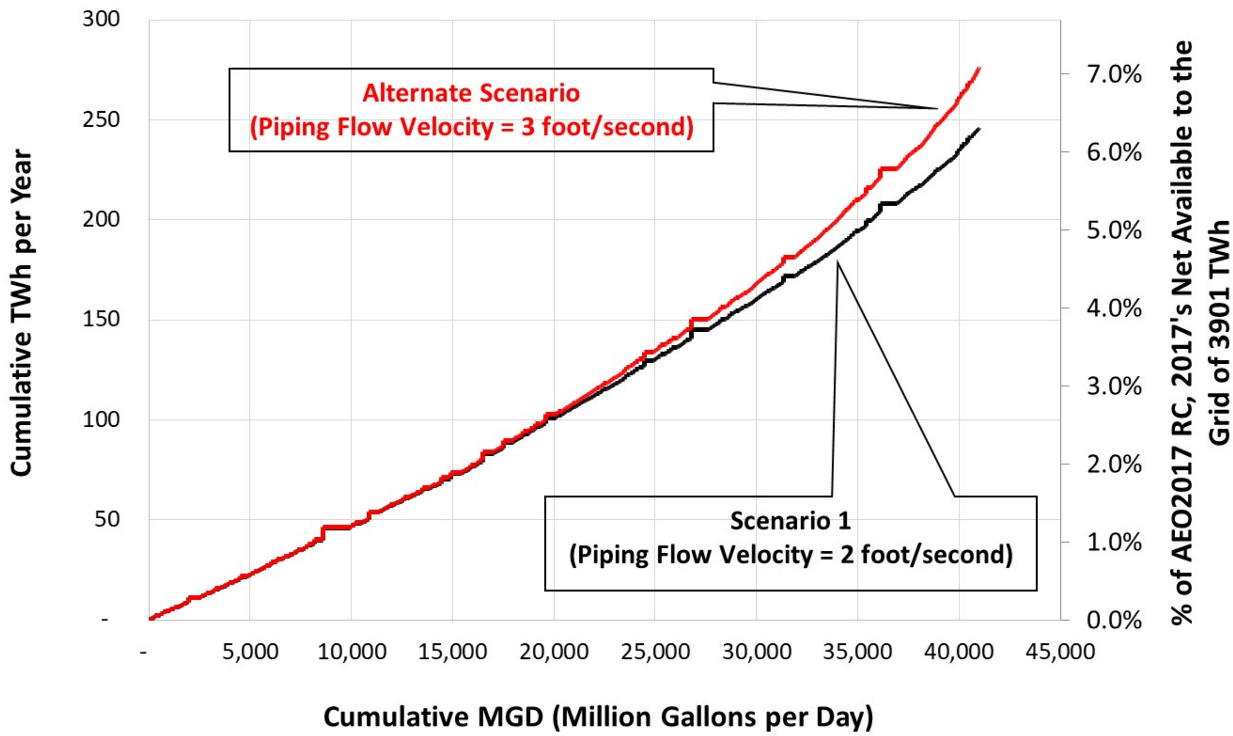


Figure A5-6. Parameter sensitivity scenario: Piping water flow velocity, 2 feet/second versus 3 feet/second
Source: LBNL

Increasing the piping water flow velocity from 2 to 3 feet per second increases the total energy requirement from 246 TWh to 276 TWh, as shown in Table A5-7.

Table A5-7. Piping Water Flow Velocity, 2 Feet/Second versus 3 Feet/Second Scenario Results

	Scenario 1 (Piping Flow Velocity = 2 feet/second)			Alternate Scenario (Piping Flow Velocity = 3 feet/second)		
Distance from Coastline (miles)	25	250	All	25	250	All
Desalination Energy Requirement (TWh)	34	105	171	34	105	171
Potable Water Pumping Energy Requirement (TWh)	4	27	75	4	31	105
Total (desalination + potable water pumping) Energy Requirement (TWh)	38	132	246	38	136	276
% of 2017 U.S. electricity consumption	1.0%	3.4%	6.3%	1.0%	3.5%	7.1%
Desalination % of Total	89%	80%	69%	89%	77%	62%

A5.6. Parameter Sensitivity Scenario: Cast Iron Piping Material versus Concrete Cast Iron Piping Material

Figure A5-7 shows the result of switching cast iron pipe to concrete pipe for each county's water supply piping. Note that the concrete pipe diameters are round (exactly like the cast iron pipe diameters) and an open channel concrete pipe could have a different pumping energy requirement and result.

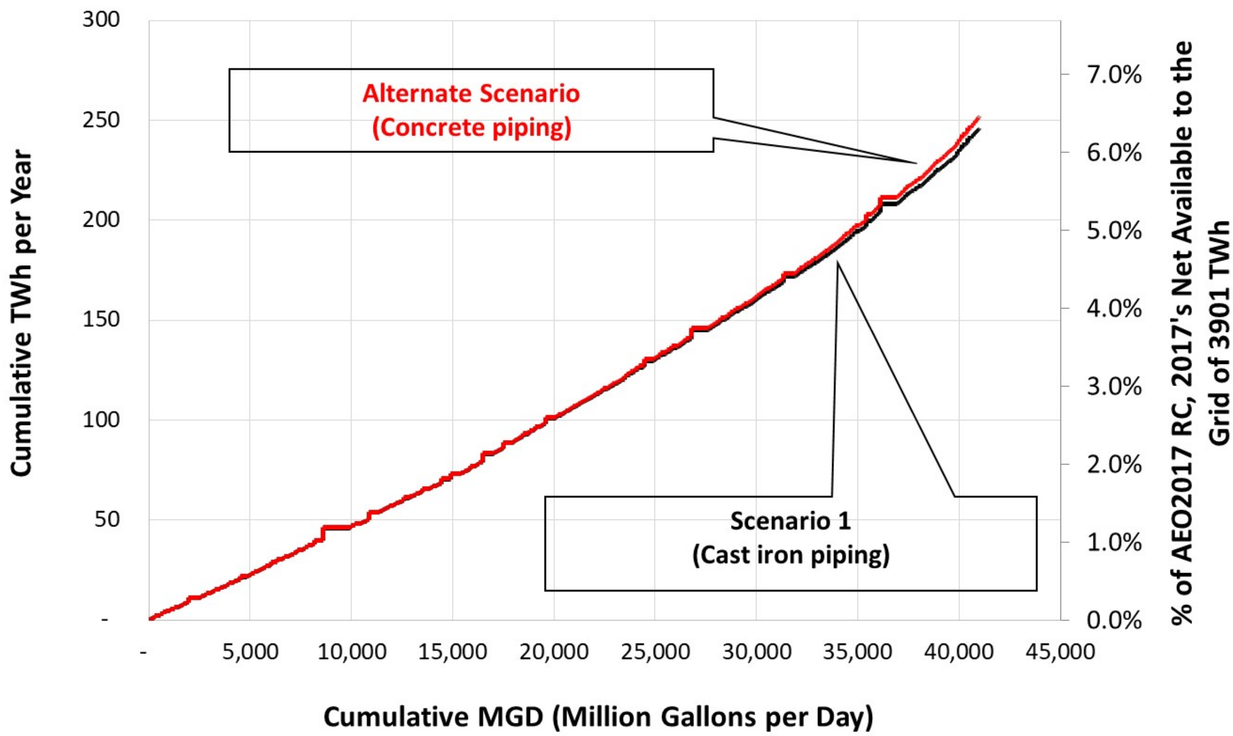


Figure A5-7. Parameter sensitivity scenario: Cast iron piping material versus concrete cast iron piping material
Source: LBNL

Switching cast iron pipe with concrete pipe increases the total energy requirement from 246 TWh to 252 TWh, as shown in Table A5-8.

Table A5-8. Cast Iron Piping Material versus Concrete Cast Iron Piping Material Scenario Results

	Scenario 1 (Cast iron piping)			Alternate Scenario (Concrete piping)		
Distance from Coastline (miles)	25	250	All	25	250	All
Desalination Energy Requirement (TWh)	34	105	171	34	105	171
Potable Water Pumping Energy Requirement (TWh)	4	27	75	4	27	81
Total (desalination + potable water pumping) Energy Requirement (TWh)	38	132	246	38	133	252
% of 2017 U.S. electricity consumption	1.0%	3.4%	6.3%	1.0%	3.4%	6.5%
Desalination % of Total	89%	80%	69%	89%	79%	68%

A5.7. Parameter Sensitivity Scenario: 90% Pump Efficiency versus 95% Pump Efficiency

Figure A5-8 shows the result of increasing the pumping efficiency from 90% (Scenario 1) to 95% in the alternative pumping efficiency scenario.

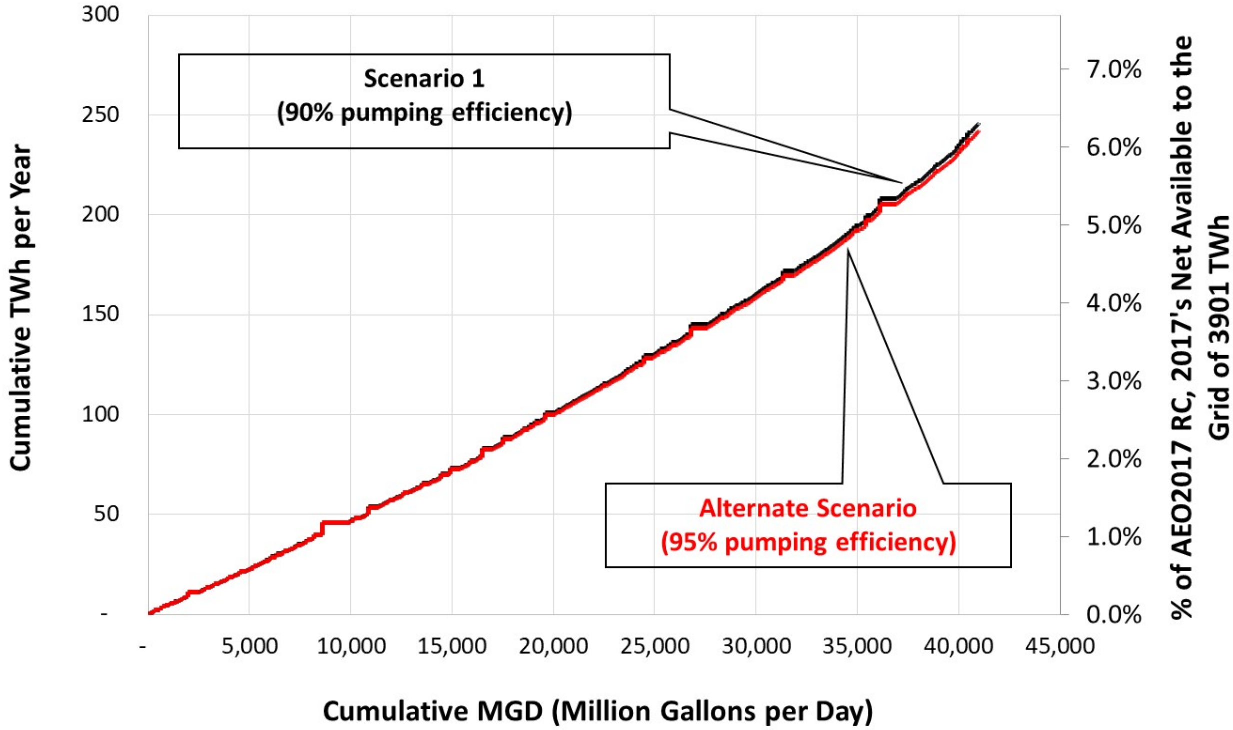


Figure A5-8. Parameter sensitivity scenario: 90% pump efficiency versus 95% pump efficiency
Source: LBNL

Increasing the pumping efficiency from 90% to 95% decreases the total energy requirement from 246 TWh to 242 TWh, as shown in Table A5-9.

Table A5-9. 90% Pump Efficiency versus 95% Pump Efficiency Scenario Results

	Scenario 1 (90% pumping efficiency)			Alternate Scenario (95% pumping efficiency)		
Distance from Coastline (miles)	25	250	All	25	250	All
Desalination Energy Requirement (TWh)	34	105	171	34	105	171
Potable Water Pumping Energy Requirement (TWh)	4	27	75	4	25	71
Total (desalination + potable water pumping) Energy Requirement (TWh)	38	132	246	37	130	242
% of 2017 U.S. electricity consumption	1.0%	3.4%	6.3%	1.0%	3.3%	6.2%
Desalination % of Total	89%	80%	69%	90%	81%	71%

A5.8. Parameter Sensitivity Conclusions

The dominant parameter affecting total cumulative energy for the scenarios is the water demand at each county. Minimizing water demand at each county has the greatest potential to lower total energy required—and greater water demand at each county increases total energy required. After water demand, decreasing desalination energy offers the next greatest opportunity to decrease total energy requirements. Although optimizing piping configurations to minimize distance and pumping elevation are important efforts, keeping flow velocities to a minimum (as well as increasing pumping efficiencies), has a similar effect on total pumping energy as optimizing distances and elevations might. Similarly, smoother pipe materials can also reduce pumping energy, but large water flows and pipe diameters limit this benefit because the ratio of circumference to area decreases as a function of diameter. Larger water flows through larger pipes has less pipe-wall surface area than smaller water flows through smaller pipes—therefore pumping energy for larger flows is less dependent on pipe materials than it is for smaller flows.

A scenario not presented here is to combine several water flows into one large pipe configuration supplying all water to a single state (for example) with distribution pipes off the main supply pipe. The large-scale infrastructure envisioned in these scenarios would likely be configured this way due to construction considerations. However, such a configuration has minimal effect on pumping energy estimated with the method presented in this report. With this method, aggregating county flow rates into a single pipe results in a larger pipe diameter for the aggregated supply pipe, which only reduces a minor amount of frictional loss. Therefore the method of estimating energy on a county-by-county basis results in nearly identical energy requirements as larger, combined water supply pipes and pumps do.

The scenarios presented here are only first-order estimates of the energy requirements of a hypothetical system. Designing and building the large-scale infrastructure envisioned in these scenarios will require significantly greater planning and detail than appropriate in this bandwidth report. As planning and detail progresses, these scenarios should by refined by adding additional considerations that can enhance the understanding and estimations of these scenarios and their energy requirements. The methods, assumptions, scenarios, and results presented in this bandwidth report provide a starting point to initiate additional analysis and planning.

Appendix A6. Brackish Water Desalination Current Typical Energy Intensity and Energy Consumption

Table A6-1 below provides the flow rate capacity values that were utilized in calculating energy consumption for brackish water desalination systems. Refer to Section 2.3. for information on the total number of brackish desalination facilities in the United States for municipal water production and the approach for determininig the values in Table A6-1.

Table A6-1. U.S. Brackish Water Desalination Capacity Values Applied for Each Unit Operation, 2016

Unit Operation	Total Installed Desalination Capacity (million m^3/year)	Total Installed Desalination Capacity (million gal/year)
System Type: Membrane		
Intake	2,760[a]	729,100
Pre-treatment	2,070[b]	546,800
Desalination	2,070	546,800
Post-treatment	2,070[b]	546,800
Concentrate Management	690[c]	182,300

[a] For intake, the energy intensity is based on the amount of water pumped. Recoveries of 75% for membrane systems are applied to calculate the amount of water needed to reach the product water capacity of 2,070 million m^3.
[b] This value is the same as desalination capacity because the energy intensity values are provided in units of energy per m^3 of product water
[c] The capacity for this unit operation was calculated based on the difference between the product water (2,070 million m^3) and the intake water (2,760 million m^3).
Source: (Global Water Intelligence 2017) and calculations as described above.

Table A6-2 and Table A6-3 present the energy intensities and estimated on-site and primary energy consumption for brackish water desalination system unit operations operating at CT conditions in 2016, in BBtu per year and GWh per year, respectively. For the brackish system considered here, only sub-surface intake was selected, as it best represented U.S. installations. The energy intensities are presented in terms of $kWh_{T,equiv}$ per m^3 of potable water produced for the pre-treatment, desalination, and post-treatment unit operations; and $kWh_{T,equiv}$ per m^3 of fluid pumped per meter of TDH for the intake and concentrate management unit operations. The CT energy consumption for these unit operations is estimated to account for 7,957–11,700 BBtu of on-site energy and 23,996–35,241 BBtu of primary energy in 2016 corresponding to a salinity range of 2,500–7,000 ppm TDS and 75% recovery.

Primary energy was calculated based on on-site CT energy adjusted to include off-site generation and transmission losses (U.S. Department of Energy 2014a).

Table A6-2. On-site Current Typical Energy Intensity and On-site and Primary Energy Consumption U.S. Brackish Water Desalination for Municipal Water Production in 2016 (BBtu/year)

Unit Operation	On-site CT Energy Intensity ($kWh_{T,equiv}/m^3$)	Capacity (million m^3/year)	On-site CT Energy Consumption, Calculated* (BBtu/year)	Off-site Losses, Calculated*,** (BBtu/year)	Primary CT Energy Consumption, Calculated*,** (BBtu/year)
System Type: Membrane					
Intake*** Sub-surface intake	0.0039	2,760	34	68	102
Pre-treatment					
Cartridge filtration	0.12	2,070	861	1,732	2,593
Desalination Reverse osmosis****	0.79–1.32	2,070	5,580–9,323	11,227–18,759	16,807–28,082
Post-treatment					
Remineralization	0.07	2,070	494	995	1,489
Disinfection	0.07	2,070	509	1,023	1,489
Boron removal*****	0.07	2,070	471	947	1,418
Fluoridation	**	**	**	**	**
Concentrate management***					
Surface water discharge	0.0039	690	8	17	25
Total System Type: Membrane			**7,957–11,700**	**16,009–23,541**	**23,996–35,241**

Current typical (CT)
* Totals may not sum due to independent rounding.
** Accounts for off-site electricity and steam generation and transmission losses. Off-site electrical losses are based on published grid efficiency. U.S. Energy Information Administration Monthly Energy Review, Table 2.4, lists electrical system losses relative to electrical retail sales. The energy value of electricity from off-site sources including generation and transmission losses is determined to be 10,553 Btu/$kWh_{T,equiv}$.
*** To account for pump and motor efficiencies, as well as total dynamic head (TDH) loss, intake and concentrate management energy intensities were normalized per unit head loss (kWh_e/m^3-m TDH). For the CT energy intensity, a combined system efficiency of 69.3% was applied (pump efficiency * motor efficiency = 72.9% * 95% = 69.3%) (DETR 1998, U.S. Department of Energy 2014b). There were limited reported values in the literature for concentrate management; therefore, energy intensities for intake and concentrate management were assumed to be the same (as pumping is the primary energy-intensive mechanism for open-ocean intake and surface water discharge). Intake water was assumed to be brackish water ranging from at 2,500–7,000 ppm.
**** Unit operation conditions: the low energy intensity value corresponds to a feedwater salinity of 2,500 ppm, and the high energy intensity value corresponds to a feedwater salinity of 7,000 ppm TDS; both systems operate with a recovery of 75% (Public Interest Energy Research 2011).
***** Boron removal also may be used in post-treatment for single-pass RO, but is not necessary for double-pass BWRO.

Table A6-3. On-site Current Typical Energy Intensity and On-site and Primary Energy Consumption U.S. Brackish Water Desalination for Municipal Water Production in 2016 (GWh/year)

Unit Operation	On-site CT Energy Intensity ($kWh_{T,equiv}/m^3$)	Capacity (million m^3/year)	On-site CT Energy Consumption, Calculated* (GWh/year)	Off-site Losses, Calculated*,** (GWh/year)	Primary CT Energy Consumption, Calculated*,** (GWh/year)
System Type: Membrane					
Intake*** Sub-surface intake	0.0039	2,760	10	20	30
Pre-treatment					
Cartridge filtration	0.12	2,070	252	508	760
Desalination Reverse osmosis****	0.79 - 1.32	2,070	1,635–2,732	3,290–5,498	4,926–8,230
Post-treatment					
Remineralization	0.07	2,070	138	278	416
Disinfection	0.07	2,070	145	292	436
Boron removal*****	0.07	2,070	149	300	449
Fluoridation	**	**	**	**	**
Concentrate management***					
Surface water discharge	0.0039	690	2	5	7
Total System Type: Membrane			**2,332–3,429**	**4,692–6,899**	**7,024–10,328**

Current typical (CT)
* Totals may not sum due to independent rounding.
** Accounts for off-site electricity and steam generation and transmission losses. Off-site electrical losses are based on published grid efficiency. U.S. Energy Information Administration Monthly Energy Review, Table 2.4, lists electrical system losses relative to electrical retail sales. The energy value of electricity from off-site sources including generation and transmission losses is determined to be 10,553 Btu/$kWh_{T,equiv}$.
*** To account for pump and motor efficiencies, as well as total dynamic head (TDH) loss, intake and concentrate management energy intensities were normalized per unit head loss (kWh_e/m^3-m TDH). For the CT energy intensity, a combined system efficiency of 69.3% was applied (pump efficiency * motor efficiency = 72.9% * 95% = 69.3%) (DETR 1998, U.S. Department of Energy 2014b). There were limited reported values in the literature for concentrate management; therefore, energy intensities for intake and concentrate management were assumed to be the same (as pumping is the primary energy-intensive mechanism for open-ocean intake and surface water discharge). Intake water was assumed to be brackish water ranging from at 2,500–7,000 ppm.
**** Unit operation conditions: the low energy intensity value corresponds to a feedwater salinity of 2,500 ppm, and the high energy intensity value corresponds to a feedwater salinity of 7,000 ppm TDS; both systems operate with a recovery of 75% (Public Interest Energy Research 2011).
***** Boron removal may also be used in post-treatment for single-pass RO, but is not necessary for double-pass BWRO.

A6.1. Current Typical Technology Selections by Unit Operation

A6.1.1. Intake and Concentrate Management

As discussed in Chapter 6 of Rao et al. (2016), the main energy requirement of intake and concentrate management is to pump water from the place of intake to the plant location and to pump the discharge and concentrate to the disposal area, respectively. For concentrate management, the lowest energy intensity option is surface water discharge.

References for energy intensity for both of these unit operations were found to be site specific, as they will depend upon the head loss associated with pumping. Due to this variability, the energy intensity for intake and concentrate management was instead calculated based upon the amount of energy required to pump water assuming negligible head loss (1 meter of TDH) using referenced pump and motor efficiencies in the following formula:

$$Energy\ intensity = \frac{\rho \cdot g}{\eta_{pump} \cdot \eta_{motor}}$$

For brackish water, a density of 1,002 kg/m^3 results in an energy intensity of 0.0039 kWh$_e$/m^3-m TDH for intake and concentrate management. For brackish water concentrate management, it is important to note that while surface water discharge is the lowest energy intensity and typically desired for plants, options may be limited due to location or environmental regulations. Information on other options (e.g., deep well injection, evaporation ponds, zero liquid discharge) can be found in *Volume 1: Survey of Available Information in Support of the Energy-Water Bandwidth Study of Desalination Systems* (Rao, et al. 2016). Many of these options are significantly more energy intensive, representing a barrier to brackish water uptake in the inland United States.

A6.1.2. Pre-treatment

For a brackish water desalination system using sub-surface intake, it was determined that cartridge filtration systems with an energy intensity of 0.12 kWh$_e$/m^3 were used (Duteau, Janin and Mallet 2015). Some brackish water pre-treatment methods can include chemical addition or media filtration, but cartridge filtration typically is the process for brackish water pre-treatment.

A6.1.3. Desalination

Reverse osmosis (RO) was chosen as the CT technology for the desalination unit operation for brackish water systems. It comprises 86% of U.S. brackish water installed production capacity for potable water production in the United States (Global Water Intelligence 2017). For a brackish water desalination unit operation (operating at 75% recovery), an energy intensity range of 0.79 kWh$_e$/m^3 to 1.32 kWh$_e$/m^3 for intake water salinities ranging from 2,500 ppm to 7,000 ppm TDS was selected (Public Interest Energy Research 2011).

A6.1.4. Post-treatment

Brackish water post-treatment methods include both remineralization and disinfection processes combined with boron removal with an additional energy intensity of 0.07 kWh$_e$/m^3, for a combined CT energy intensity of 0.21 kWh$_e$/m^3 for post-treatment (Glueckstern and Priel 2007). No estimate was found for the energy intensity of fluoridation, thus it is assumed to be negligible.

A6.2. Current Typical CO_2 Emissions for Brackish Water Desalination

Table A6-4 and Table A6-5 present the CO_2 intensities and annual emissions based on the estimated on-site CT energy consumption for each brackish desalination system unit operation. The CO_2 intensities are shown in terms of lb CO_2 per m^3 potable water produced for the pre-treatment, desalination, and post-treatment unit operations, and lb CO_2 per m^3 pumped water/concentrate per m of TDH for the intake and concentrate management unit operations in Table A6-4. Table A6-5 presents the same results, only in kg CO_2 per m^3, and emissions are presented in kilotonnes of CO_2. The CT CO_2 emissions for these unit operations operating at 2016 U.S. installed production capacity are estimated to be 1,378–2,025 thousand tons CO_2. This is equivalent to the annual CO_2 emissions from 264,116–387,996 passenger vehicles.

Table A6-4. Associated Current Typical CO_2 Emissions for U.S. Brackish Water Desalination for Municipal Water Production in 2016

Unit Operation	On-site CT Energy Intensity ($kWh_{T,equiv}/m^3$)	Capacity (million m^3/year)	CO_2 Emission Factor (lb $CO_2/kWh_{T,equiv}$)	CO_2 Emission Intensity (lb CO_2/m^3)	Total CO_2 Emissions (Mton CO_2/year)
System Type: Membrane (Reverse osmosis)					
Intake*	0.004	2,760	1.18	0.004	6
Pre-treatment	0.12	2,070	1.18	0.14	149
Desalination**	0.79–1.32	2,070	1.18	0.93–1.56	964–1,610
Post-treatment	0.21	2,070	1.18	0.25	259
Concentrate management*	0.004	690	1.18	0.004	1
Total for Unit Operations Studied* **					**1,378–2,025**

Current typical (CT)
* To account for pump and motor efficiencies, as well as total dynamic head (TDH) loss, intake and concentrate management energy intensities were normalized per unit head loss (kWh_e/m^3-m TDH). For the CT energy intensity, a combined system efficiency of 69.3% was applied (pump efficiency * motor efficiency = 72.9% * 95% = 69.3%) (DETR 1998, U.S. Department of Energy 2014b). There were limited reported values in the literature for concentrate management; therefore, energy intensities for intake and concentrate management were assumed to be the same (as pumping is the primary energy-intensive mechanism for sub-surface intake and surface water discharge).
** Unit operation conditions: the low energy intensity value corresponds to a feedwater salinity of 2,500 ppm, and the high energy intensity value corresponds to a feedwater salinity of 7,000 ppm TDS; both systems operate with a recovery of 75% (Public Interest Energy Research 2011).
*** Totals may not sum due to independent rounding.

Table A6-5. Associated Current Typical CO_2 Emissions for U.S. Brackish Water Desalination for Municipal Water Production in 2016 (kilotonne CO_2/year)

Unit Operation	On-site CT Energy Intensity ($kWh_{T,equiv}/m^3$)	Capacity (million m^3/year)	CO_2 Emission Factor (kg $CO_2/kWh_{T,equiv}$)	CO_2 Emission Intensity (kg CO_2/m^3)	Total CO_2 Emissions (kilotonne CO_2/year)
System Type: Membrane (Reverse osmosis)					
Intake*	0.004	2,760	0.53	0.002	5
Pre-treatment	0.12	2,070	0.53	0.07	135
Desalination**	0.79–1.32	2,070	0.53	0.42–0.71	874–1,461
Post-treatment	0.21	2,070	0.53	0.11	235
Concentrate management*	0.004	690	0.53	0.002	1
Total for Unit Operations Studied* **					**1,250–1,837**

Current typical (CT)
* To account for pump and motor efficiencies, as well as total dynamic head (TDH) loss, intake and concentrate management energy intensities were normalized per unit head loss (kWh_e/m^3-m TDH). For the CT energy intensity, a combined system efficiency of 69.3% was applied (pump efficiency * motor efficiency = 72.9%*95% = 69.3%) (DETR 1998, U.S. Department of Energy 2014b). There were limited reported values in the literature for concentrate management; therefore, energy intensities for intake and concentrate management were assumed to be the same (as pumping is the primary energy-intensive mechanism for open-ocean intake and surface water discharge).
** Unit operation conditions: the low energy intensity value corresponds to a feedwater salinity of 2,500 ppm, and the high energy intensity value corresponds to a feedwater salinity of 7,000 ppm TDS; both systems operate with a recovery of 75% (Public Interest Energy Research 2011).
*** Totals may not sum due to independent rounding.

A6.3. Sources for Brackish Water Desalination Current Typical Energy Intensity

Table A6-6 presents a summary of the main references consulted to identify CT energy intensity by unit operation for brackish water.

Table A6-6. Main Sources Referenced in Identifying Current Typical Intensity by Brackish Water Desalination System Unit Operation and Total

Unit Operation	Source Abbreviation	Description
Intake, Concentrate Management	(DETR 1998)	This report provided the CT pump efficiency. The CT pump degradation and efficiencies for brackish water were assumed to be the same as seawater. Therefore, the CT efficiency of brackish water pumps was determined to be 72.9%.
Intake, Concentrate Management	(U.S. Department of Energy 2014b)	This report provided the CT motor efficiency. Likewise for seawater, brackish water motor efficiencies were assumed to be the same. The CT motor efficiency was therefore determined to be 95%.
Pre-treatment	(Duteau, Janin and Mallet 2015)	The high value for cartridge filtration in brackish water pre-treatment was considered from this source. The report provides a pump power requirement for the sediment cartridge filter of 0.00022 kW, resulting in a calculated energy intensity of 0.12 kWh_e/m^3 of drinking water.
Desalination	(Public Interest Energy Research 2011)	A wide range of brackish water reverse osmosis energy intensity values were reported in the literature (0.5–3 kWh_e/m^3). The reported values for reverse osmosis specific energy consumption were determined from this source as 0.79–1.32 kWh_e/m^3 for 2,500–7,000 ppm TDS and were used as CT values.
Post-treatment	(Park and Bennett 2010)	This report provides a CT energy intensity value of 0.07 $kWh_e/m^3$for disinfection. Brackish water post-treatment is assumed to be similar to seawater post-treatment (remineralization, disinfection, and fluoridation). High energy intensity values for disinfection were used to make a conservative estimate). No energy intensity values were specifically reported for fluoridation.
Post-treatment	(Dundorf, et al. 2009)	This report provides CT energy intensity values for remineralization. Brackish water post-treatment is assumed to be similar to seawater post-treatment (remineralization, disinfection, and fluoridation). The high energy intensity value for remineralization (0.07 kWh_e/m^3) was considered the CT as a conservative estimate.
Post-treatment	(Glueckstern and Priel 2007)	This report provides a CT energy intensity value of 0.07 kWh_e/m^3 for boron removal. Boron removal is commonly used in single-pass brackish water desalination due to high concentrations of boron in permeate streams.

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