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Volume 1: Survey of Available Information in Support of the Energy-Water Bandwidth Study of Desalination Systems

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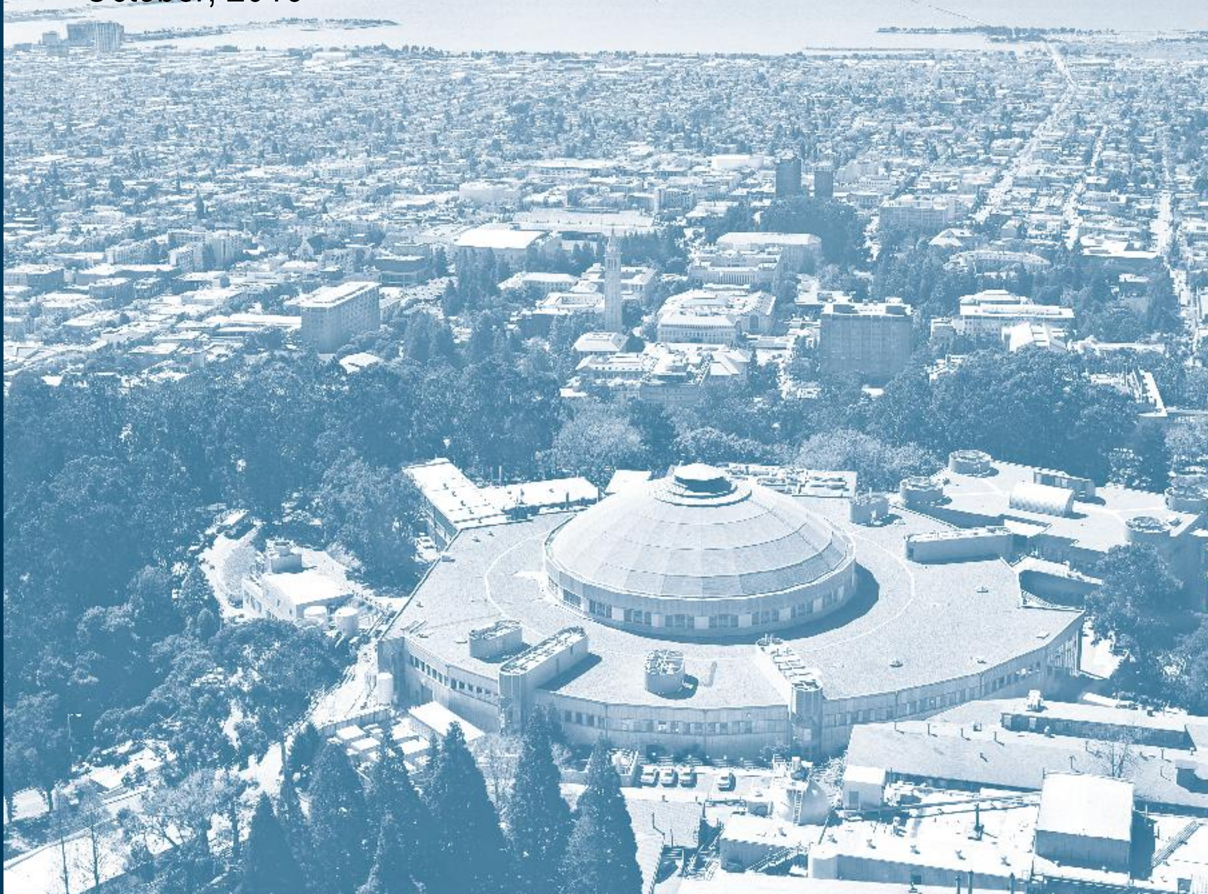

Preface

Reducing energy consumption through investment in advanced technologies and practices can enhance American manufacturing competitiveness. Energy bandwidth studies of U.S. manufacturing sectors serve as general data references to help stakeholders understand the range (or *bandwidth*) of potential energy savings opportunities. The U.S. Department of Energy's (DOE) Advanced Manufacturing Office (AMO) has commissioned a series of bandwidth studies to analyze energy-intensive processes and provide technology-based estimates of potential energy savings opportunities. Most recently, AMO has commissioned a bandwidth study to analyze the energy consumption characteristics of desalination systems for municipal water. The research will determine the energy consumption and carbon emissions implications of increasing the share of potable water in the United States provided by seawater desalination. The consistent methodology used in the previous bandwidth studies has provided a framework to evaluate and compare energy savings potentials within and across manufacturing sectors at the macroscale and will now be applied to the technology study area of desalination systems. The Energy-Water Bandwidth Study of Desalination Systems will expand the scope of previous bandwidth studies by also evaluating the carbon dioxide (CO_2) intensity and reduction opportunities and will inform a techno-economic analysis of desalination systems.

The complete information for this study will be provided in two volumes: *Volume 1: Survey of Available Information in Support of the Energy-Water Bandwidth Study of Desalination Systems* (this report) reviews the parameters that impact energy, emissions, and cost considerations, and provides background research and a framework for *Volume 2: Energy-Water Bandwidth Study of Desalination Systems.* Table P-1 shows the specific contents of the two volumes. With growing interest of desalination to meet domestic and global potable water demands, available results should be distributed as soon as they are developed; hence, Volume 1 is published in advance of Volume 2, and serves as an interim report for the Energy-Water Bandwidth Study of Desalination Systems.

Table P-1. Brief Summary of Content for the Two Desalination Study Volumes

Volume	Contents
Volume 1: Survey of Available Information in Support of the Energy-Water Bandwidth Study of Desalination Systems (this report)	• Boundary Analysis Framework • Energy Intensities for Five Unit Operations of Desalination • Framework for Establishing Desalination Uptake Scenarios
Volume 2: Energy-Water Bandwidth Study of Desalination Systems	• Energy Consumption and CO_2 Emissions for Several Sea and Brackish Water to Municipal Water Uptake Scenarios 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 • Current Energy and CO_2 Savings Opportunity • Energy and CO_2 Savings Opportunity from R&D Advancements

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List of Acronyms and Abbreviations

Π_S	the osmotic pressure of the saline water source
a_w	activity of water
BOD	biochemical oxygen demand
BWRO	brackish water reverse osmosis
CAPEX	capital expenses
CCPP	calcium carbonate precipitation potential
CDI	capacitive deionization
CF	concentration factor
COD	chemical oxygen demand
CSP	concentrating solar power
CT	current typical
DAF	dissolved air flotation
DOE	U.S. Department of Energy
EC	energy cost
ECU	electro-chlorination unit
ED	electrodialysis
EDR	electrodialysis reversal
EPA	U.S. Environmental Protection Agency
ERD	energy recovery device
FC	fixed cost
FO	forward osmosis
G	Gibbs free energy (available energy)
GOR	gained output ratio
HDH	humidification-dehumidification
kg	kilogram
kPa	kilopascal
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+$kWh_{e,equiv}$)
kJ	kilojoule
LCOE	levelized cost of electricity
LCOW	levelized cost of water
LSI	Langelier saturation index
$\dot{m}$	mass flow rate
m^3	cubic meter
MD	membrane distillation
MED	multi-effect distillation
MEH	multi-effect humidification
MF	microfiltration
MGD	million gallons per day

MJ	megajoules
MMBtu	million British thermal units
MSF	multi-stage flash
MVC	mechanical vapor compression
n_w	number of moles of water
NF	nanofiltration
NTU	nephelometric turbidity units
ppm	parts per million
psi	pounds per square inch
PV	photovoltaic
$\dot{Q}_{reversible}$	minimum rate of heat of separation for a reversible thermal process
R	ideal gas constant
RO	reverse osmosis
R_s	salt rejection
SDI	silt density index
SOA	state-of-the-art
SWRO	seawater reverse osmosis
T	Temperature
T_0	ambient temperature
T_H	temperature of high temperature reservoir
TBtu	trillion British thermal units
TDH	total dynamic head
TDS	total dissolved solids
TOC	total organic carbon
TSS	total suspended solids
TVC	thermal vapor compression
UF	ultra-filtration
UPC	unit production cost
UV	ultraviolet
$\overline{V}_w$	the molar volume of water
VC	variable cost, vapor compression
$\dot{W}_{reversible}$	minimum rate of work required for reversible separation
WHO	World Health Organization
Y	water recovery

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1.0. Executive Summary

The U.S. Department of Energy (DOE) has set a goal to reduce the cost of seawater desalination systems to $0.50/ cubic meter ($m^3$) through the development of technology pathways to reduce energy, capital, operating, soft, and system integration costs.[1] In support of this goal and to evaluate the technology pathways to lower the energy and carbon intensity of desalination while also reducing the total water cost, DOE is undertaking a comprehensive study of the energy consumption and carbon dioxide (CO_2) emissions for desalination technologies and systems.

This study is being undertaken in two phases. Phase 1, Survey of Available Information in Support of the Energy-Water Bandwidth Study of Desalination Systems, collected the background information that will underpin Phase 2, the Energy Water Bandwidth Study for Desalination Systems. This report (Volume 1) summarizes the results from Phase 1. The results from Phase 2 will be summarized in Volume 2: Energy Water Bandwidth Study for Desalination Systems (Volume 2). The analysis effort for Phase 2 will utilize similar methods as other industry-specific Energy Bandwidth Studies developed by DOE,[2] which has provided a framework to evaluate and compare energy savings potentials within and across manufacturing sectors at the macroscale. Volume 2 will assess the current state of desalination energy intensity and reduction potential through the use of advanced and emerging technologies. For the purpose of both phases of study, *energy intensity* is defined as the amount of energy required per unit of product water output (for example, kilowatt-hours per cubic meter of water produced). These studies will expand the scope of previous sectorial bandwidth studies by also evaluating CO_2 intensity and reduction opportunities and informing a techno-economic analysis of desalination systems. Volume 2 is expected to be completed in 2017.

The intent of this Volume 1 report is to report the results of the transparent survey of references to be used during Phase 2. It is not intended to provide final analysis results, but to provide the data and the analysis framework that will be used to evaluate the data in the survey that will be evaluated in Phase 2. Neither report will present primary (originally collected or produced) data.

The goals of this Volume 1 report are to:

1. Provide comprehensive, up-to-date, foundational data and information regarding the energy intensity of desalination technologies in a consistent and comparable framework.
2. Outline the framework to be used in Volume 2 -Energy Water Bandwidth Study of Desalination Systems for evaluating energy and CO_2 impact in the United States associated with greater uptake of sea and brackish water desalination.
3. Define the methodology to be used in the Energy Water Bandwidth Study of Desalination Systems for evaluating cost impacts from reducing the energy intensity of the desalination system.
4. Define the analytical boundary of a desalination system to be used for Phase 2 and the parameters affecting energy, CO_2, environmental, and cost considerations

Based on a survey of multiple sources published within the past five years, Table 1-1 provides a summary of the expected ranges of energy intensity and total water cost of desalination technologies. Table 1-1 is meant to be representative of globally reported desalination data and not definitive. Comparisons of energy intensity across desalination technologies, such as those shown in Table 1 1, should be accompanied by reference information that describes the system and operating conditions. This includes intake and product water flow rates, salinity, and temperature; system components; and temperature of heat sources and sinks. Where reported in the literature, reference information for the values reported in Table 1 1 can be found in Appendix A – Seawater Energy Intensity Findings Tables. Often, however, reported energy intensities are not accompanied by the appropriate reference information in the literature. Further, system boundaries are often not defined, and data can be regionally specific (particularly cost data).This makes comparing technologies/systems difficult as differences may be due to performance or system operating requirements. For example, the energy intensity of any system will depend on the amount of constituents to be removed from the intake water (i.e. the intake and product water salinities and flow rates). Without this information when comparing two systems, it is difficult to understand if differences in energy intensity are due to different operating salinities, system design (i.e. pump selection) or performance (i.e. inefficient operations). Thermal energy intensity values in this report are electrical equivalents. Methodologies for converting thermal energy into equivalent electrical energy and summing to find an overall energy intensity are discussed in Section 4.1.3.2. Further analysis, such as rejecting values with insufficient reference information, will be performed to refine these energy-intensity and cost estimates before they are used in Phase 2.

This report summarizes the energy intensity of each unit operation of the desalination processes—as well as the parameters impacting energy, cost, and environmental impact. The data for Phase 1 are the energy intensity and consumption of current typical and state-of-the-art technologies and systems, or those that are commercially available and in use today, both domestically and globally. The report data are based on a survey of available references as of the date this report was published. Focus is given to seawater desalination to produce potable water. In addition, desalination of brackish water (water with less salinity than seawater but greater than freshwater) is also discussed. Variations in energy intensity and total water costs can be attributed to factors such as feedwater salinity, water production rate (e.g, plant size), temperature, feedwater constituents, unit cost of energy, output water quality, energy/heat recovery, gained output ratio (for thermal processes), and environmental factors. The unit cost of energy and financing arrangements or mechanisms for desalination plants are significant factors as well, but fall outside of the scope of this report.

This report provides background information for the Phase 2 study. As such, the information provided is specific to the scope of that work; which is desalination of sea and brackish water sources for municipal water supply. Other applications for desalination, which would require separate research, analysis, and discussion, include production of water of lower (e.g., recycled water) and higher (e.g., ultrapure) quality than municipal water; treatment of wastewater streams (e.g., industrial, municipal) for reuse; and treatment of produced waters from oil and gas extraction. Many of the technologies reviewed here are applicable to these other desalination applications. However, there will be differences in the background information collected for analysis of these other applications, and therefore collection of information specific to these applications is required.

Table 1-1. Summary of Globally Reported Current Typical Seawater and Brackish Water Desalination Energy Intensity and Water Costs

System	Reported Low Energy Intensity*			Reported High Energy Intensity*			Reported Total Water Cost[3]** ($/m^3)
	Electrical (kWh_e/m^3)	Thermal ($kWh_{e,equiv}/m^3$)	Total ($kWh_{T,equiv}/m^3$)	Electrical (kWh_e/m^3)	Thermal ($kWh_{e,equiv}/m^3$)	Total ($kWh_{T,equiv}/m^3$)	
Reverse Osmosis (seawater)	1.58	–	1.58[4]	7.5	–	7.5[5]	0.45***–1.72
Reverse Osmosis (brackish water)	0.3	–	0.3[6]	3	–	3[7]	0.2–1.33
Multi-stage flash	7.5	2.5	10[8]	30.3	5	35.3[9]	0.56–1.75
Multi-effect distillation	4	1.5	5.5[10]	20.2	2.5	22.7[11]	0.52–1.5
Electrodialysis (brackish water)	0.5	–	0.5[12]	1.8	–	1.8[13]	0.6–1.05
Thermal Vapor Compression	–	16.3	16.3	–	16.3	16.3	0.27–2.6
Mechanical Vapor Compression	7	–	7	12	–	12	

Note: kWh = kilowatt-hours
* A challenge identified in the literature is the lack of consistent reporting on reference conditions, such as salinity, flow rates, recovery, and input thermal energy temperature.
** Cost is for energy (electricity, thermal, or both sources), capital expenses, and operations and maintenance
*** The value of $0.45/m^3 is from a first-year operation; $0.52 is a more realistic minimum.

2.0. Introduction to the Desalination Analysis

Population growth, urbanization, and agriculture stress the existing U.S. fresh water supply and changing weather conditions could increase water stresses in the future. Over one-third of the global population live in countries with water supply scarcity, and this share is expected to increase.[14] In 2008, almost one billion people (about 15% of the world's population) in developing countries did not have access to potable water.[15] The United Nations estimates that 1.8 billion people will live in areas of physical water scarcity by 2025.

While water efficiency can provide a significant amount of relief, new sources of water will be needed to meet projected water demands. Saline water (which encompasses seawater and brackish water for the purposes of this report) is a far less utilized water source for potable water compared to fresh ground or surface water partly because of the energy intensity necessary to remove its salt content. *Energy intensity* is defined as the amount of energy required per unit output (for example, kilowatt-hours per cubic meters of water produced). The current typical energy intensity of installed sea and brackish water desalination facilities in the United States is approximately 3.2 $kWh_{T,equiv}/m^3$ (ranging between 1.6 and 4.8 $kWh_{T,equiv}/ m^3$); whereas the energy intensity of conventional extraction, conveyance, and treatment of surface and groundwater for public use ranges from 0.12 $kWh_{T,equiv}/m^3$ in New York state to nearly 2.6 $kWh_{T,equiv}/m^3$ in Southern California.[16] The large range of energy intensities for conventional water extraction and conveyance is due to differences in distance and elevation over which the water needs to be conveyed. To put these water supply energy intensities in perspective, 2.5 $kWh_{T,equiv}$ is required to operate a small room air conditioner for 1.4 hours.[17]

Figure 2-1 visualizes the energy intensity of different freshwater options in California. Seawater and brackish water energy intensity estimates are from plants in operation throughout California. Water source salinity, plant size, temperatures (of incoming thermal energy sources and feedwater), and flow rates are not reported by the source and will be further investigated in Phase 2 of this work. Desalination systems include all of the steps of a conventional water treatment plant. Seawater desalination technologies are uncommon in the United States for providing municipal water for a number of reasons, including: (1) high capital cost, (2) high cost of potable water produced through desalination of seawater (due in large part to high capital costs, but also energy costs), (3) difficulty in acquiring the coastal land for development, (4) high energy intensity, (5) the resulting energy source-dependent CO_2 emissions, and (6) environmental impacts of saline water intake and concentrate discharge.

These challenges are limiting the development of desalinated water supply in the United States. However, desalination offers several benefits, including: (1) abundant (and usually no-cost) feedwater (e.g., ocean water), (2) resiliency against droughts and water scarcity, (3) less and more predictable variation in total water cost over time in regions where rights to freshwater sources are contentious, and (4) potential to serve as energy storage for integrating renewable energy sources into our electric grid. Due in part to these reasons, seawater desalination uptake is much greater as a fraction of total supply in several regions throughout the world compared to the United States, particularly those where the driving energy source is very low cost (e.g., the Middle East) and/or fresh water resources are insufficient to support the regional population.

Further, brackish water treatment with membranes is practiced by over 300 facilities in the United States, producing one million gallons per day (MGD).

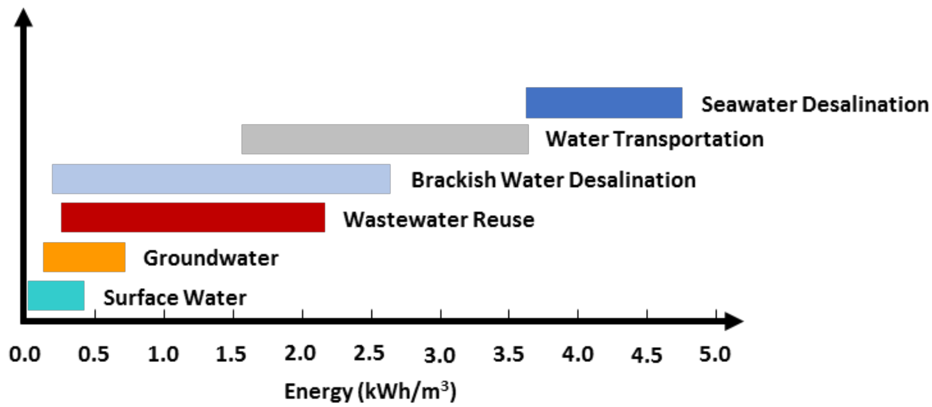


Figure 2-1. Energy Intensity of Different Freshwater Options in California[18]

While the energy intensity of reverse osmosis (RO) has reduced since the 1970s, further research and analysis of the entire desalination system is needed to highlight the energy and environmental impacts and understand the opportunities for advancement relative to conventional fresh water supply. One such example is the Affordable Desalination Collaboration's demonstration-scale RO treatment system utilizing energy recovery via pressure exchangers.[19]

To research and compare desalination systems, it is necessary to develop a framework that describes the boundary and the operation of each unit operation. Important evaluation parameters of the desalination system must be uniformly applied to each unit operation. Researching and reporting findings within this framework creates a comprehensive and comparable understanding of the energy, CO_2 emissions, and cost implications of various desalination systems. The framework will allow for transparent analytical results and robust findings. Different technologies can be compared for various levels of the feedwater quality, output water quality, water recovery (% of intake water converted to product water), desalination technology used, energy sources (and temperatures), or any other system characteristic.

2.1. Bandwidth Analysis: A Framework

This report, *Volume 1: Survey of Available Information for the Energy-Water Bandwidth Study of Desalination Systems* (hereafter referred to as "Volume 1"), reviews data and information for sea and brackish water desalination technologies for municipal (i.e., potable) water production, and outlines a framework for evaluating desalination systems. The follow-up report, *Volume 2: Energy-Water Bandwidth Study of Desalination Systems* (hereafter referred to "Volume 2") will report on the Phase 2 research that builds upon the work reported in Volume 1 and explore several scenarios to better understand the challenges and opportunities to expand the share of U.S. public municipal water supplied through desalination of sea and brackish water. The Bandwidth Study methodology rigorously evaluates candidate technology pathways to reduce the current typical total cost of water produced through desalination by assessing state-of-the-art technologies, as well as technologies under research and development that have the potential to reduce future energy and CO_2 emissions in the United States. Additional research and analysis will explore cost and environmental considerations (e.g., concentrate production, intake considerations). The framework for the Phase 2 work will include five unit operations: intake, pretreatment, the desalination process, post-treatment, and concentrate management. A simplified process flow diagram for the bandwidth study displaying these five unit operations is shown in Figure 2-2. Within each of these unit operations, energy consumption will be analyzed, including energy consumed for pumping (for feedwater conveyance and/or pressurization) as well as energy/pressure recovery for the desalination process. While the primary focus of these studies is on seawater desalination, brackish water desalination also will be considered.

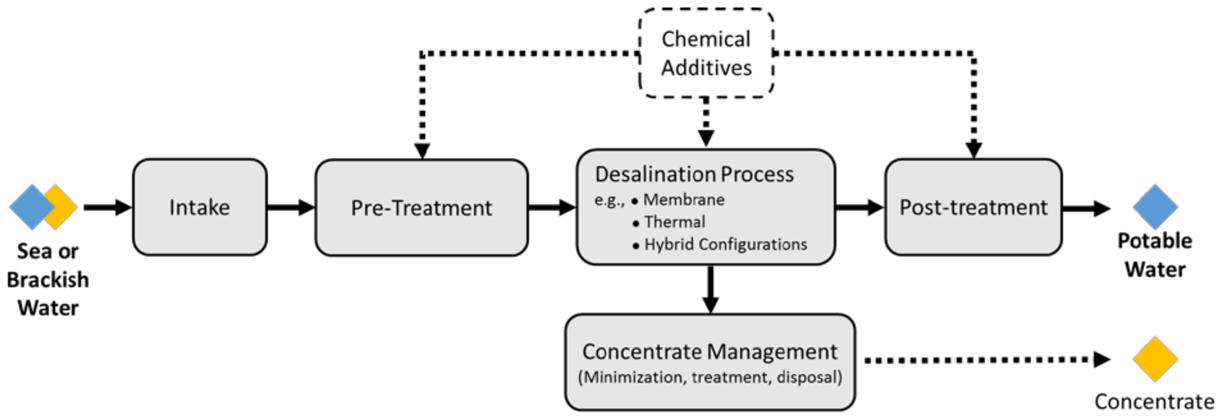


Figure 2-2. Simplified Five-Unit Operation Desalination System Process Flow Diagram

2.2. Purpose of this Report

The purpose of this report is to establish the approach for the Phase 2 work and to compile the background information necessary to evaluate the energy and CO_2 implications of increasing the share of U.S. municipal water supplied through saline water desalination. The objectives of the current report are as follows:

1. Provide comprehensive, up-to-date, foundational data and information regarding the energy intensity of desalination technologies in a consistent and comparable framework.
2. Outline the framework to be used in Phase 2 for evaluating the energy and CO_2 impact in the United States associated with greater uptake of sea and brackish water desalination.
3. Define the methodology to be used in Phase 2 for evaluating cost impacts from reducing the energy intensity of the desalination system.
4. Define the analytical boundary of a desalination system to be used in Phase 2 and the parameters affecting energy, CO_2, environmental, and cost considerations.

The report also outlines the framework for determining CO_2 emissions and the levelized cost of water from a desalination plant. The report intends to provide transparency into the research and analysis conducted in Phase 2. While there are several applications for desalination, the information compiled in this report is specific to desalination as a means to treat saline water for use as municipal (i.e., potable) water use.

Volume 2 will include the results from this report and evaluate the current typical, state-of-the-art, and practical minimum energy intensities for three to five uptake scenarios (see Section 13.2). An uptake scenario is the total amount of potable water that would need to be produced from desalination to meet selected criteria. For example, one uptake scenario may be to provide potable water from desalination to serve the needs of the entire U.S. population living within 10 miles of an ocean. The resulting potable water produced, energy consumption, and CO_2 emissions impacts will be evaluated. Further, the study will also evaluate concentrate production and capital and operating costs.

Due to the growing interest nationally and globally in desalination to meet existing and potential water demands, it is important for results to be made available as they are developed. With that purpose in mind, this report has been developed as an interim report to precede *Volume 2: Energy-Water Bandwidth Study of Desalination Systems.*

2.3. Feedwater and Output Water Characterization Overview

"Standard seawater" contains about 35,000 milligrams per liter (mg/L) parts per million (ppm) total dissolved solids (TDS), or about 3.5% TDS. The actual TDS content may vary within wide limits from the Baltic Sea, with 7,000 ppm, to the Red Sea and Persian Gulf, with up to 45,000 ppm.[20] Table 2-1 provides information collected on the typical seawater composition in the Pacific Ocean.

Table 2-1. Typical Pacific Ocean Seawater Composition[21]

Parameter	Requirement
pH	8.1
TDS	35,000 ppm
Chloride	19,700 ppm
Sodium	10,900 ppm
Sulfate	2,740 ppm
Magnesium	1,310 ppm
Calcium	410 ppm
Potassium	390 ppm
Bicarbonate	142 ppm
Bromide	65 ppm
Fluoride	13 ppm
Boron	4-5 ppm
Manganese	0.0004 ppm
Other Solids	34 ppm

References differ on the characterization of brackish water, depending on the water source location;[22] it is difficult to establish a general type of "brackish" water. Table 2-2 provides the characterization of different brackish water sources around the United States. The lower limit for brackish water is 1,000 ppm TDS, with water below this considered to be freshwater.

Table 2-2. Characteristics of Different Brackish Water Sources[23]

Parameter	Cape Hatteras, North Carolina	Coalinga, California	Wellton-Mohawk, Arizona	Fort Morgan, Colorado
pH	7.4	7.7	7.95	7.4
TDS (ppm)	8,076	2,478	3,628	1,880
Sodium (ppm)	4,861	1,123	1,944	519
Chloride (ppm)	6,696	369	1,537	123
Magnesium (ppm)	1,398	362	376	148
Calcium (ppm)	545	323	510	748
Sulfate (ppm)	173	1,310	938	998
Bicarbonate (ppm)	223	132	355	274

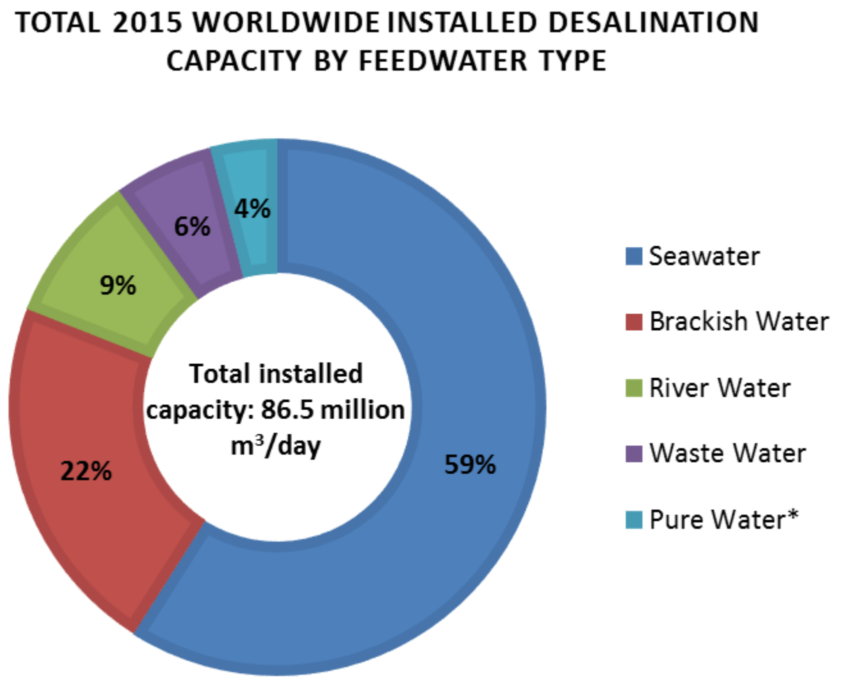
The World Health Organization (WHO) and the U.S. Environmental Protection Agency (EPA) recommend that drinking water TDS be no more than 500 ppm TDS.[24] Table 2-3 describes the EPA guidelines that by desalination plants must meet for product drinking water.

Table 2-3. EPA Drinking Water Guidelines[25]

Parameter	Requirement
Color	15 Pt/Co Scale
Turbidity	<0.3 NTU
pH	6.5–8.5
TDS	500 ppm
Chloride	250 ppm
Chlorine	4 ppm
Aluminum	0.05–0.2 ppm
Iron	0.3 ppm
Copper	1 ppm
Zinc	5 ppm
Manganese	0.05 ppm
Sulfates	250 ppm

2.4. Current Desalination Uptake Numbers (Globally and U.S., as available)

In 2013, Voutchkov estimated that desalination provides 1.5% of global water supply.[26] The installed global desalination capacity in 2015 was 86.5 million m^3 per day, with 59% being from a seawater feed, as shown in Figure 2-3. As shown in Figure 2-4, the majority of global desalination plants (65%) operate using RO technology, while 21% and 7% of the worldwide installed capacity are using multi-stage flash (MSF) distillation and multi-effect distillation (MED), respectively. In recent years, the use of RO technology has been steadily growing.[27] Figure 2-5 displays the annual installed capacity by technology globally as of 2014.



* Pure water sources are desalinated to achieve ultrapure water recovered for certain processes

Figure 2-3. Total Worldwide Installed Desalination Capacity by Feedwater[28]

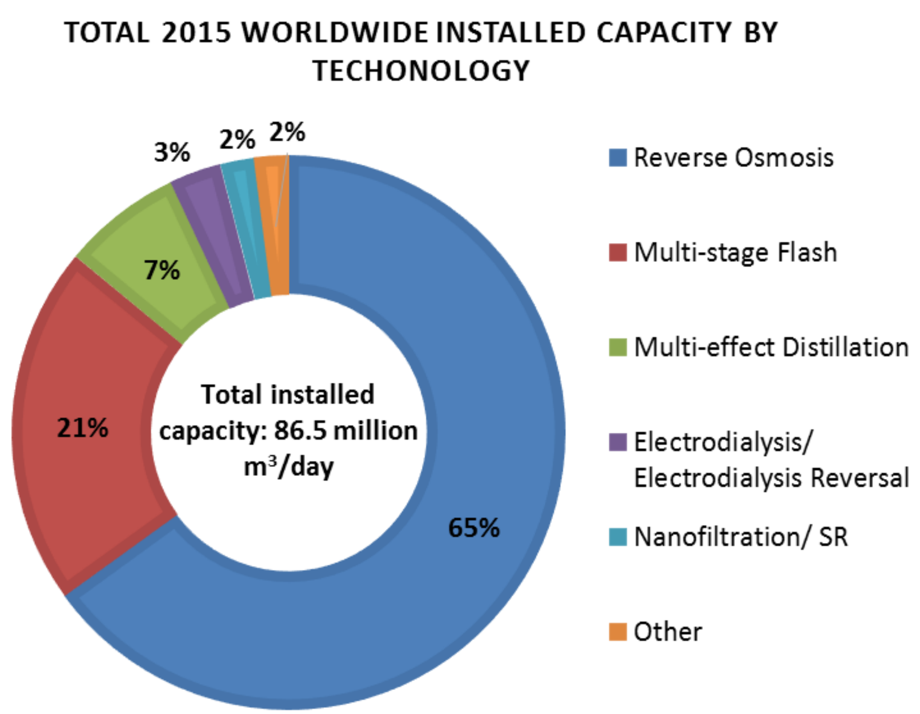


Figure 2-4. Total Worldwide Installed Desalination Capacity by Technology[29]

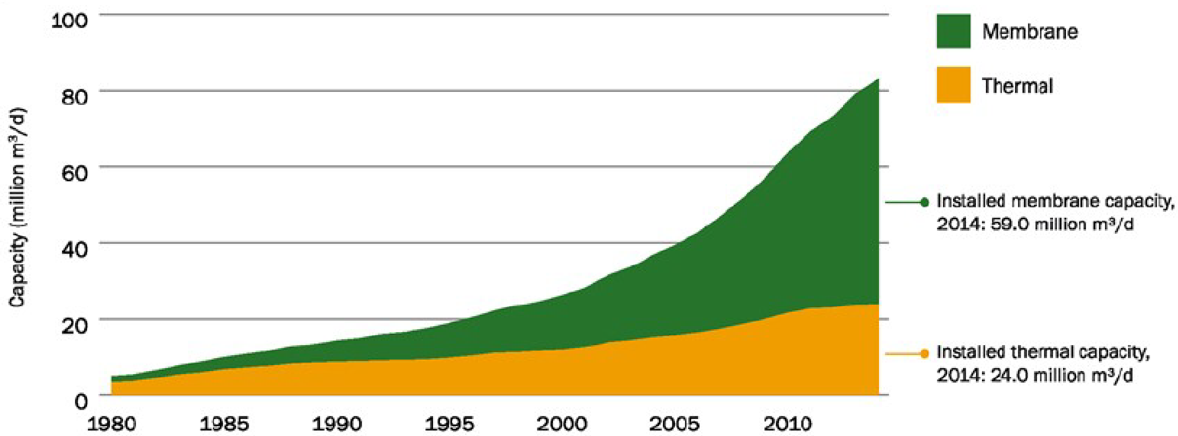


Figure 2-5. Global Cumulative Installed Membrane and Thermal Capacity 1980 to 2014[30]

In 2012, the global production of about 65.2 million m^3 per day of desalinated water required the use of at least 75.2 terawatt-hours (TWh) of electrical energy per year, which equaled about 0.4% of global electricity consumption.[31]

3.0. Thermodynamic Minimum

The thermodynamic minimum energy requirement for desalinating pure water from saline water is considered here to have three sequential components: (1) the minimum energy required for negligible recovery (i.e., 0% recovery for a reversible process), (2) the minimum energy required when considering a reversible process at a recovery greater than 0%, and (3) the minimum energy required when considering the irreversible process used for desalination.

The first is independent of the separation technology/process employed. Conceptually, this is the work required by a compressor to overcome the difference in vapor pressure between seawater and fresh water[32] or the difference in chemical potential between the intake water and the products (concentrate and pure water).[33] This value is not achievable, but provides the theoretical minimum energy requirement for separation of pure water from sea and brackish water by a reversible process. The second will be the minimum energy required when considering separation of pure water from saline water for a practical amount of product water recovery. It is also not process specific. The third is the minimum energy required for recovery of non-negligible amounts of pure water from saline water when considering a specific process and losses due to irreversibilities (losses arising from friction and heat transfer to the environment). The three components of the minimum energy requirements build off of each other with the minimum energy requirement for one component greater than that of the previous. The various minimum energy requirements for desalination provide a benchmark for measuring the potential for and advances in reducing desalination energy requirements. This benchmark can be used to establish more realistic projections (and bounds) for the future energy savings resulting from research and development (R&D).

The calculated minimum energy required to extract pure water from seawater (at 35,000 ppm TDS, 25˚C, for negligible recovery and a reversible process) varies slightly in the literature, but is approximately 0.7–0.79 kWh/m^3 of water produced.[34] The derivation for this theoretical minimum energy requirement has been well developed.[35] One such formulation is shown in Equation 1. Here, the governing equation is the opposite of the energy required for mixing pure water and the sea/brackish water constituents at isothermal and reversible conditions:[36]

$$-d(\Delta G_{mix}) = -RTln a_w dn_w$$

Equation 1: Minimum energy requirement for recovery of an infinitesimal volume of pure water from saline water under a reversible process and isothermal conditions

Where

G = Gibbs free energy (available energy)

R = ideal gas constant

T = absolute temperature

a_w = activity of water

n_w = number of moles of water

The activity of water is defined as the ratio of the water vapor pressure above the saline solution (p) to the water vapor pressure above the pure product water (p_o). This is shown in Equation 2.

$$a_w = {}^{p}/_{p_o}$$

Equation 2: Activity of water

An activity of water of 1 indicates pure water; whereas 0 indicates the water is completely saturated with salts.

Equation 1 can also be written to show the dependence of the minimum energy requirement for negligible recovery of pure water using a reversible process under isothermal conditions on osmotic pressure as:

$$-d(\Delta G_{mix}) = \Pi_S \overline{V_w} dn_w$$

Equation 3: Minimum energy requirement for recovery of an infinitesimal volume of pure water from saline water under a reversible process and isothermal conditions expressed as a function of osmotic pressure

Where,

Π_S = the osmotic pressure of the saline water source

$\bar{V}_w$ = the molar volume of water

To find the reversible work ($W_{reversible}$) required to separate salt from water, either side of Equation 1 can be integrated over the number of moles of water in the solution at the initial and final states.[37]

$$W_{reversible} = \int RT ln a_w dn_w$$

Equation 4: Minimum work requirement for recovery of an infinitesimal volume of pure water from saline water under a reversible process and isothermal conditions

While the above formulations (including Equation 4) are found throughout the literature, it is not easily applied to situations where the minimum energy requirement for practical recovery is desired (i.e., greater than negligible water recovery). A more useful formulation for practical pure water recoveries uses a control volume approach and considers the Gibbs free energy entering (via the saline water source) and exiting (via the product water and concentrate). The approach has been developed by Mistry et al. (2011); the resulting equation for minimum work of separation for a reversible process is given in Equation 5.[38]

$$\dot{W}_{reversible} = \dot{m}_p G_p + \dot{m}_c G_c - \dot{m}_{sw} G_{sw}$$

Equation 5: Alternate formulation for the minimum work requirement for removal of salt from saline water under a reversible process, from Mistry et al. 2011[39]

Where,

$\dot{W}_{reversible}$ = minimum rate of work required for reversible separation

$\dot{m}$ = mass flow rate of product (p), concentrate (c), or seawater (sw)

G = Gibbs free energy for the product (p), concentrate (c), or seawater (sw)

As noted by the authors, when evaluating thermal processes for separation, the heat of separation is a more accurate representation of the minimum energy requirement. This will take into account the efficiency of converting heat into work. For a reversible process, the efficiency of a Carnot Engine (the maximum efficiency for converting heat into work based on physical laws) can be used to calculate the required heat to produce a given amount of work. Equation 6 from Mistry et al. (2011) shows the minimum heat of separation using a reversible thermal process:[40]

$$\dot{Q}_{reversible} = \frac{\dot{m}_p G_p + \dot{m}_c G_c - \dot{m}_{sw} G_{sw}}{1 - {}^{T_0}/_{T_H}}$$

Equation 6: Minimum heat of separation for removal of salt from saline water under a reversible process using a thermal process

Where,

$\dot{Q}_{reversible}$ = minimum rate of heat of separation for a reversible thermal process

T_0 = ambient temperature

T_H = temperature of high temperature reservoir

The minimum energy requirement is a function of key feedwater characteristics, including:

- **Temperature:** For thermal processes, the temperature of the incoming heat source will in-part govern the required energy for desalination. Also, temperature of the feedwater will impact the solubility of the intake solution. Higher-temperature feedwaters will have a higher solubility for most compounds, as well as a higher vapor pressure than lower temperature feedwaters. Some compounds are exceptions, such as calcium sulfate, and will have a lower solubility with increasing temperature.
- **Salinity:** Salinity will affect the vapor pressure above the feedwater. Lower salinities will have a vapor pressure closer to the vapor pressure above pure water. This will make the water activity closer to 1.
- **Water constituents:** The above analysis and references are for seawater and brackish water of similar constituents to seawater. The properties of each are described in Section 2.0. For feedwater with different constituents than standard seawater (e.g., industrial wastewater, produced water from oil and gas extraction), the above relations should be adjusted for the makeup—specifically the ionic strength—of the feedwater.
- **Recovery:** This will affect the volume of water over which work must be applied for separation.

The theoretical minimum energy requirement will also be a function of the amount of constituents removed, i.e., the output water quality. However, the discussion here focuses on production of pure water (0 ppm TDS).

To help understand the minimum energy requirement of a reversible process for producing pure water from saline water at non-zero recoveries, Figure 3-1 shows the relationship between percent recovery, salinity, and minimum energy requirement for a reversible process on the left[41] and the relationship between feedwater temperature, percent recovery, and the minimum energy requirement for a reversible process on the right.[42] The chart on the left also indicates typical operating conditions for percent recovery when using seawater RO, which is 45%–55%. It is developed through integration of Equation 1. The minimum power requirement for 50%

recovery of seawater, as shown in the chart on the left, is 1.06 kWh/m^3. The minimum power requirement decreases when any of the following are lowered: feedwater temperature, feedwater salinity, recovery, recovered water quality (higher TDS).

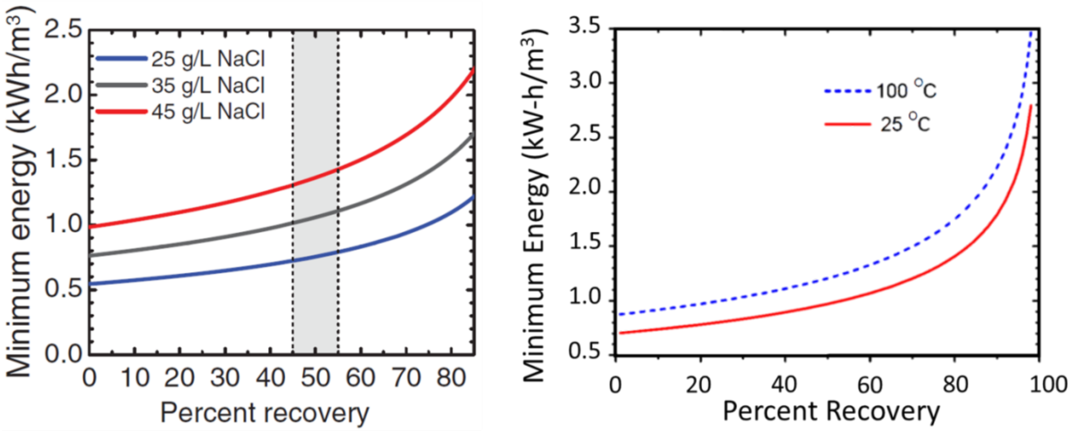


Figure 3-1. (Left) The Minimum Energy Requirement for a Reversible Separation of Pure Water from Saline Water of Various Feedwater Salinities as a Function of Percent Recovery at Constant Temperature.[43] (Right) Minimum Energy Requirements for 25°C and 100°C feedwater as a Function of Percent Recovery at Constant Salinity.[44]

The graphs in Figure 3-1 are provided to illustrate trends. Table 3-1 and Table 3-2 provide specific values for the minimum energy requirements for desalination. The minimum energy requirements for 0% fresh water recovery at 25°C for various feedwater salinities using a reversible process are summarized in Table 3-1. The reported energy requirements are Gibbs free energy of mixing for different volumetric ratios of seawater (at 35,000 ppm TDS) mixing with fresh river water (at 88 ppm TDS). As mentioned earlier, Gibbs free energy of salts mixing in fresh water (0 ppm TDS) is synonymous to the minimum energy requirements for saline water separation at 0% recovery.

Table 3-1. Minimum energy requirement (kWh/m^3) for various feedwater salinities at 25°C and 0% recovery[45]

TDS (ppm)	Minimum Energy Requirement (kWh/m^3)
35,000	0.77
31,500	0.72
28,000	0.68
24,500	0.63
21,000	0.58
17,500	0.52
14,000	0.46
10,500	0.38
7,000	0.30
3,500	0.19

Stoughton and Lietzke (1965) developed the variation in minimum energy requirement for desalination via a reversible separation process with feedwater temperature and percent recovery, and it is reproduced in Table 3-2.[46] As shown, increases in feedwater temperature and percent recovery will result in higher minimum energy requirements. Since Stoughton and Lietzke published their findings in 1965, more accurate correlations for seawater properties have been developed by Nayar et al. 2016.[47] The impact of these updated correlations on the determination of the minimum energy requirement for reversible desalination will be investigated during Phase 2 of this work.

Table 3-2. Minimum energy requirement (kWh/m^3) for seawater (34,500 ppm TDS) for various temperatures and % recovery[48]

	% Recovery				
T (°C)	0	25	50	75	100
25	0.706	0.814	0.987	1.342	2.91
50	0.765	0.884	1.073	1.463	3.19
75	0.820	0.948	1.151	1.571	3.45
100	0.871	1.006	1.222	1.667	3.69

The minimum energy requirement cannot be achieved due to: minimum energy requirements for the enabling desalination process (e.g., high-pressure pumping, heating), and losses from irreversibilities from the desalination process.

Irreversibilities are unavoidable losses and are specific to the separation processes. These include energy losses due to friction or heat losses to the environment. The development of these losses (including expansion into topics such as entropy generation and exergy destruction) are discussed in the literature[49] and will not be reproduced here (or in Volume 2). Some relevant results from the literature will be discussed here.

The magnitude of the energy losses associated with irreversibilities is process specific. Mistry et al. (2011) calculated an efficiency of several desalination processes by considering the ratio in Equation 7.[50] The authors refer to this efficiency as the “Second-Law Efficiency” in reference to the Second Law of Thermodynamics, from which it is derived.

$$\eta = \frac{Minimum\ work\ required\ for\ separation\ using\ a\ reversible\ process\ for\ zero\ recovery}{Actual\ amount\ of\ work\ required\ for\ an\ irreversible\ desalination\ process\ at\ recovery > 0}$$

Equation 7: Second-Law Efficiency as developed by Mistry et al. (2011)

Using this definition of efficiency, the authors have compared several desalination operations to each other. The value from such a comparison is that it allows for an understanding of how close a desalination technology can operate to the minimum energy requirement for producing pure water from saline water. Desalination operations with a high Second Law Efficiency will have lower minimum losses than those with lower Second Law Efficiencies. The Second Law Efficiency for several desalination systems as calculated in Mistry et al. (2011) is shown in Table 3-3.[51]

Table 3-3. Second Law Efficiency as Calculated by Mistry et al. Conditions at which efficiencies were calculated are shown below the table.[52]

Process	Second Law Efficiency	Attribution of greatest loss (% of Second Law loss)
Multi-effect distillation (MED)	5.9%	Effects (56.5%)
Multistage flash (MSF)	2.9%	Feed heaters (73.9%)
Direct contact membrane distillation (DCMD)	1.0%	MD Module (34.5%)
Mechanical vapor compression (MVC)	8.5%	Evaporator-condenser (57.2%
Reverse osmosis (RO)	31.9%	RO module (54.8%)
Humidification-dehumidification (HD)	2.4%	Dehumidifier (53.6%)

MED: 25°C seawater temperature, 4.2% feedwater salinity, 7% maximum salinity, 70°C steam temperature, 40°C temperature in last (6th) effect, 1 kilogram per second (kg/s) pure product water flow rate.
MSF: 25°C seawater temperature, 4.2% seawater salinity, 3,384 kg/s seawater flow rate, 116°C steam temperature, 40ºC brine reject temperature, 378.8 kg/s pure product water flow rate.
DCMD: 27°C seawater temperature, 3.5% seawater salinity, 1 kg/s seawater flow rate, 4.4% recovery of pure water, 90°C heat source.
MVC: 25°C seawater temperature, 3.5% seawater salinity, 60°C top brine temperature, 40% recovery of pure water, 29.7°C product water temperature, 27.2°C discharged brine temperature.
RO: 25°C seawater temperature, 1 bar seawater pressure, 3.5% seawater salinity, 1 kg/s seawater flow rate, 40% recovery of pure water.
HD: 30°C seawater temperature, 3.5% seawater salinity, seawater to dry air mass flow rate ratio of 3, 90% effectiveness of humidifier and dehumidifier, 70°C top brine temperature, 4.5% recovery of pure water.

The analysis conducted by Mistry et al. (2011)[53] includes losses in high-pressure pumping (e.g., pump system efficiency), heat transfer, compressing, flashing, expansion (without phase change), bringing the product water back to ambient temperatures, and the chemical disequilibrium between the concentrate and discharge source. The results of the authors' analysis are specific to the prescribed input conditions and process arrangement. The operating conditions under which the systems in Table 3-3 are evaluated are shown below the table.

Tow et al. (2015) built upon Mistry et al. (2011) and applied Equation 7 to operational data from thermal, seawater RO, brackish water RO, and electrodialysis (ED) desalination plants, as well as modeled and pilot forward osmosis (FO) and thermal plants.[54] Desalination systems were chosen to represent a wide range of salinities and recoveries. By applying real-world conditions, the analysis conducted by Tow et al. (2015) provides a more practical understanding of the Second Law Efficiency of a desalination operation.[55] Their comparison allows for the selection of a technology that can operate closest to the minimum energy requirement for a given inlet and product water salinity. Their findings are reproduced in Figure 3-2. Arrows indicate the initial feedwater salinity (left end point) to final salinity of the concentrate (right arrow head).The source for each technology scenario in the figure is provided in Table 3-4. It is important to note that as technologies mature, operators/designers gain more experience with the various desalination technologies (e.g., autonomous improvement), and with additional R&D into energy optimized desalination, the relative positions of the technologies in Figure 3-2 may change in the future.

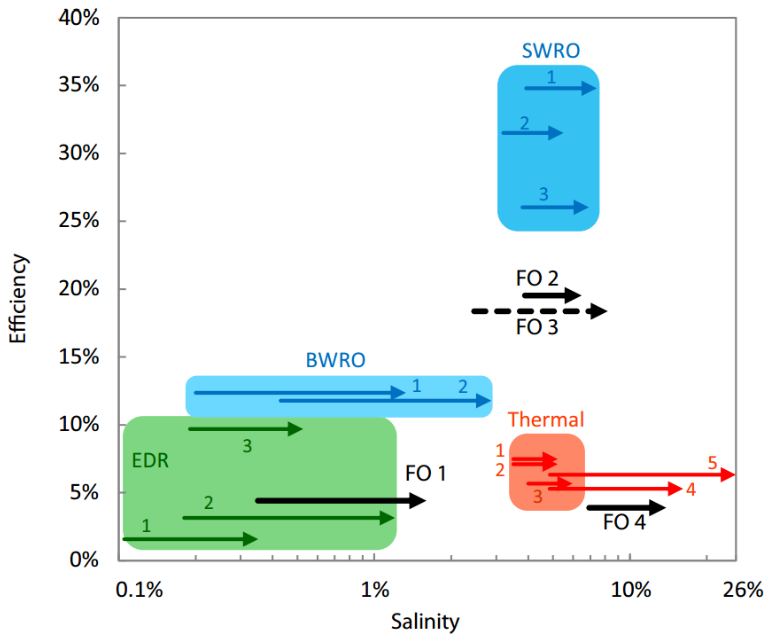


Figure 3-2. Second Law Efficiency for various desalination technologies. The beginning point of each arrow indicates the feedwater salinity. The endpoint of each arrow indicates final concentrate salinity. See Table 3-4 for the technology scenario.[56]

Table 3-4. Technology scenario selected for Figure 3-2.[57]

SWRO 1	Skikda, Algeria
SWRO 2	Tampa Bay, USA
SWRO 3	Hadera, Israel
Thermal 1	MVC (typical seawater)
Thermal 2	TVC-MED (typical seawater)
Thermal 3	MSF, Shuweihat, Saudi Arabia
Thermal 4	MVC, Barnett Shale, USA
Thermal 5	MVC, model
EDR 1	Melville, Canada
EDR 2	Yuma, USA
EDR 3	Foss Reservoir, USA
BWRO 1	Wadi Ma’in, Jordan
BWRO 2	El Paso, USA
FO 1	FO – RO pilot
FO 2	FO – RO model
FO 3	Dilution pilot (non-regenerating)
FO 4	Thermal draw regeneration pilot

The achievement of the minimum energy requirement for an irreversible process at non-negligible recovery will be limited by several operational and design requirements and characteristics. These factors will be examined in further detail in Volume 2, particularly in the selection of the "Practical Minimum" energy intensity. The Practical Minimum energy intensity is the energy intensity for desalination when using advanced desalination processes and technologies described in the literature, but with limited or no commercial availability. A brief discussion of these requirements and characteristics is included here. One operational requirement is the minimum operating set point for an RO system to ensure desired recovery volumes. For example, as saline feedwater flows through RO membranes in series it becomes more concentrated. The minimum operating pressure must be greater than the osmotic pressure difference between the concentrate and permeate at the exit of the module.[58] Zhu et al. (2009) refers to this as the "thermodynamic restriction."[59] While a system cannot operate below the thermodynamic restriction, this restriction can be reduced through system design, such as introducing a staged RO process. Additional operational characteristics—such as operational set points (operators will typically operate an RO plant well above the thermodynamic restriction to ensure adequate product water output), desalination module cleaning protocols, pretreatment processes used, pump system efficiency (conveyance and pressurization), efficiency of energy recovery devices, and desalination system load profile (i.e., variations in product water flow rate)—will all impact the energy consumption of the desalination system. Site-specific conditions, including distance from intake, distance from concentrate disposal site, and feedwater constituents, will also impact energy requirements.

Additionally, some parameters that lead to a higher theoretical minimum, may in fact improve the efficiency of the separation process. For example, while increased temperature raises the theoretical minimum energy requirement, it will lower feedwater viscosity and enhance the flow rate through the membranes. However, this will also lead to increased salt passage (lower rejection). For thermal processes, higher feedwater temperatures will result in less energy required to heat the water for desalination.

Ultimately, however, operators and designers of desalination facilities will operate the plant to minimize the cost for producing water. The system configuration and operational characteristics for minimizing water costs may not align with those that minimize energy consumption. Amortization, operation, and maintenance costs drive water costs as well, and will influence desalination system design and operation. These considerations, along with operational requirements and characteristics, are discussed in Chapter 4.0 Boundary Analysis Framework.

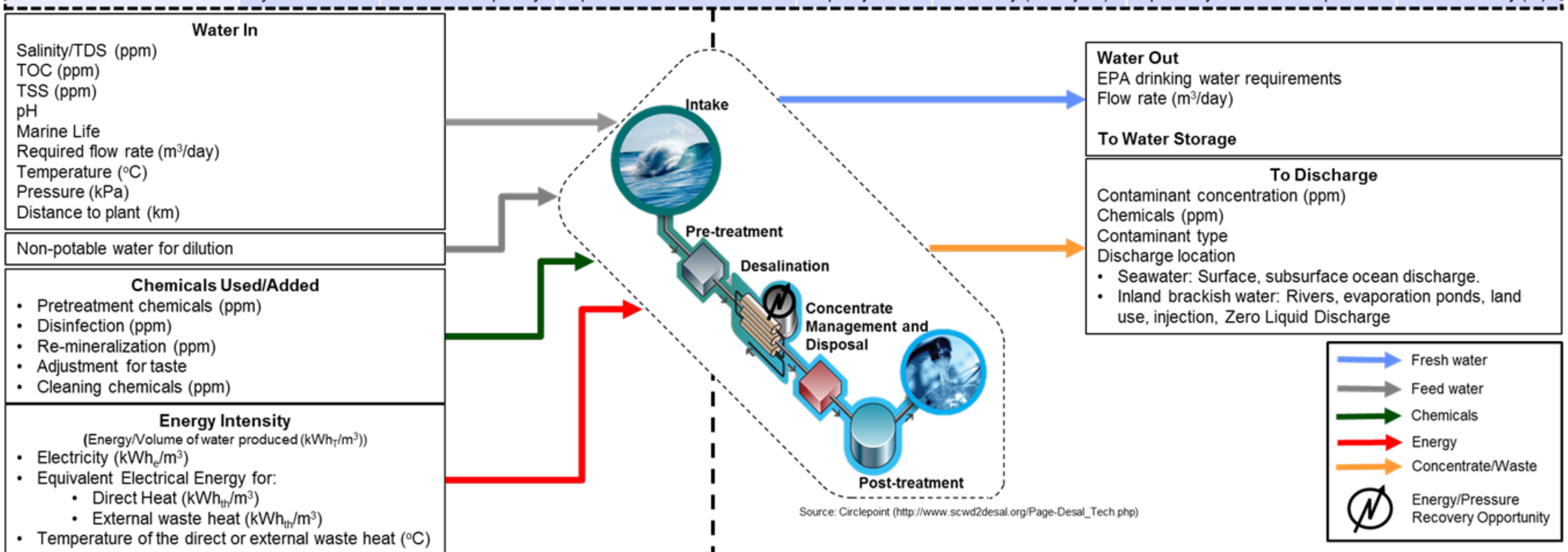
4.0. Boundary Analysis Framework

This section introduces the boundary analysis framework that is applied to each individual unit operation (unit operation) within a desalination system. This analysis framework enables an assessment of energy and CO_2 emission intensities, cost and environmental considerations, and other factors for each unit operation. The consistency within the analysis framework makes it applicable to each individual unit operation as well as the whole integrated desalination system. A whole system boundary analysis 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. A consistent boundary analysis framework will allow for tracking of the quality of water in and out, chemicals added, and constituents removed. Most important, the use of a consistent analysis framework across all desalination system options enables equitable comparisons and more robust conclusions regarding energy consumption and CO_2 reduction potential.

4.1. Analysis Framework Introduction

Figure 4-1 shows a general boundary analysis framework applied to the whole desalination system. This diagram highlights all the important metrics that need to be considered when studying a desalination system. The same analysis framework is applied to each individual unit operation within a desalination system.

Whole System Economic and Operational Characteristics							
Fixed Cost ($)	Construction	Siting	Permitting	Land Use	Equipment	Construction time	
Variable Cost ($)	Labor	Chemicals	Maintenance	Parts	Disposal		
Energy Cost ($)	Electricity	Natural Gas	Steam				
Operational characteristics	Water quality	Flow rates (m^3/day)	Temperature (°C)	Pressure (PSI)	Energy (kWh, MMBtu)	Chemicals	Brine (m^3/day)
	System Lifetime	Modulation capability	Operation when under loaded	Capacity Factor	Availability (hours/year)	Operability with other components	Water recovery (%)



Whole System Environmental Considerations	
Emission Intensity (tCO_2/G)	• CO_2 emissions (tCO_2/m^3 of freshwater produced)
Other	• Marine life • Concentrate disposal • Consumables disposal and chemical use/disposal • Electric grid impact • Water system integration • Co-location with power generators

Figure 4-1. General Boundary Analysis Framework Overview

The white boxes in the boundary analysis framework highlight materials flow, important parameters, and appropriate metrics for each unit operation. The blue boxes on the top and bottom provide economic, operational, and environmental considerations for each unit operation. The first column indicates the category of economic, operational, and environmental consideration, and the columns to the right provide the specific considerations. Components of the general diagram shown in Figure 4-1 are described in more detail below.

4.1.1. Water In

Ultimately, the purpose of the desalination system is to produce water of a desired quality (e.g., potable water) from the feedwater. Tracking the feedwater quality allows for an assessment of the progress made at each unit operation toward generating potable water. Further, factors such as energy intensity, water recovery, and membrane lifetime are strong functions of feedwater salinity. The feedwater composition may significantly change from intake to the desalination unit operation due to filtration and the addition of chemicals to remove biomaterials and other solids in order to optimize the performance of the desalination unit operation.

In addition to the water entering the desalination system, plants might also take advantage of available water sources (power plant cooling water, tertiary treated wastewater, etc.) to dilute their concentrate stream prior to discharge. For example, the Claude “Bud” Lewis desalination plant in Carlsbad, California, mixes its concentrate stream with the cooling water leaving the nearby power plant for dilution prior to discharge into the ocean.

4.1.2. Chemicals Used/Added

Several chemicals are continuously or periodically added to the feedwater, mainly during the pretreatment unit operation. These chemicals include biocides, coagulants, antiscalants/flocculants, anti-foaming, anti-corrosion, acids or bases for pH control, and cleaning agents, some of which are used during cleanings. Understanding the required dosage of these chemicals, their impact downstream (i.e., membrane degradation because of excess chlorination, reduction of energy requirements of the membrane/thermal process), and the ways to neutralize or dispose of them enables identification of energy- and cost-saving opportunities.

4.1.3. Energy Input

The two main energy sources for desalination are electricity and heat (thermal energy). These energy sources are:

- purchased (electricity or natural gas),
- imported to the facility as waste heat (e.g., low-grade heat from power plants, jacket water from generators, compressor stations, or diesel engines),
- generated on-site using renewable resources (e.g., solar, geothermal), or
- provided through a combination of those options.

By one estimate, energy costs make up 28%–50% of the overall cost of water production by seawater RO desalination.[60] Figure 4-2 shows the share of energy consumption for each unit operation of an RO desalination system.

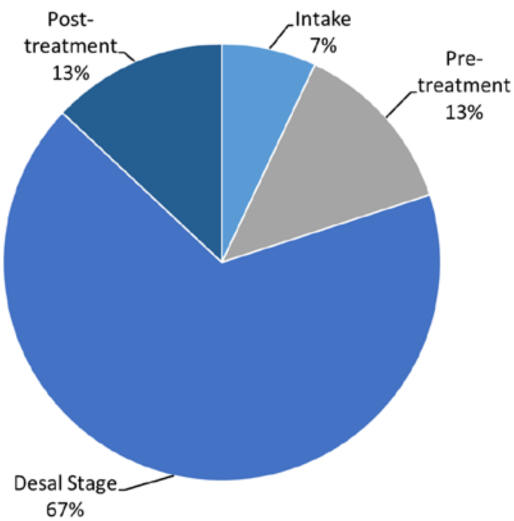


Figure 4-2. Energy Use for Various Elements of the Seawater Reverse Osmosis Desalination Process[61]

As a general principle, energy accounting in Phase 2 will track and account for any energy consumed by the desalination system. This will require tracking and accounting for both the quantity of a particular type of energy that is consumed within the facility boundaries (site energy) and the energy required to produce and distribute the energy consumed on-site. The sum of site energy and the energy required to produce and distribute the energy is referred to as *primary energy.* This document only reports site energy. Volume 2 will seek to report both site and primary energy consumption, with the latter being relevant to determining CO_2 emissions.

A site-to-primary conversion factor is applied to the site energy to determine the corresponding primary energy consumption. Figure 4-3 summarizes this energy accounting methodology. Site-to-primary conversion factors are only applied to the energy sources imported into the desalination plant boundary (crossing the dotted line). The method for determining the appropriate site-to-primary as recommended for use during the Phase 2 research is described in more detail below. Section 4.1.7.1 further discusses how this energy accounting approach will be used to determine CO_2 emissions under the uptake scenarios evaluated during the Phase 2.

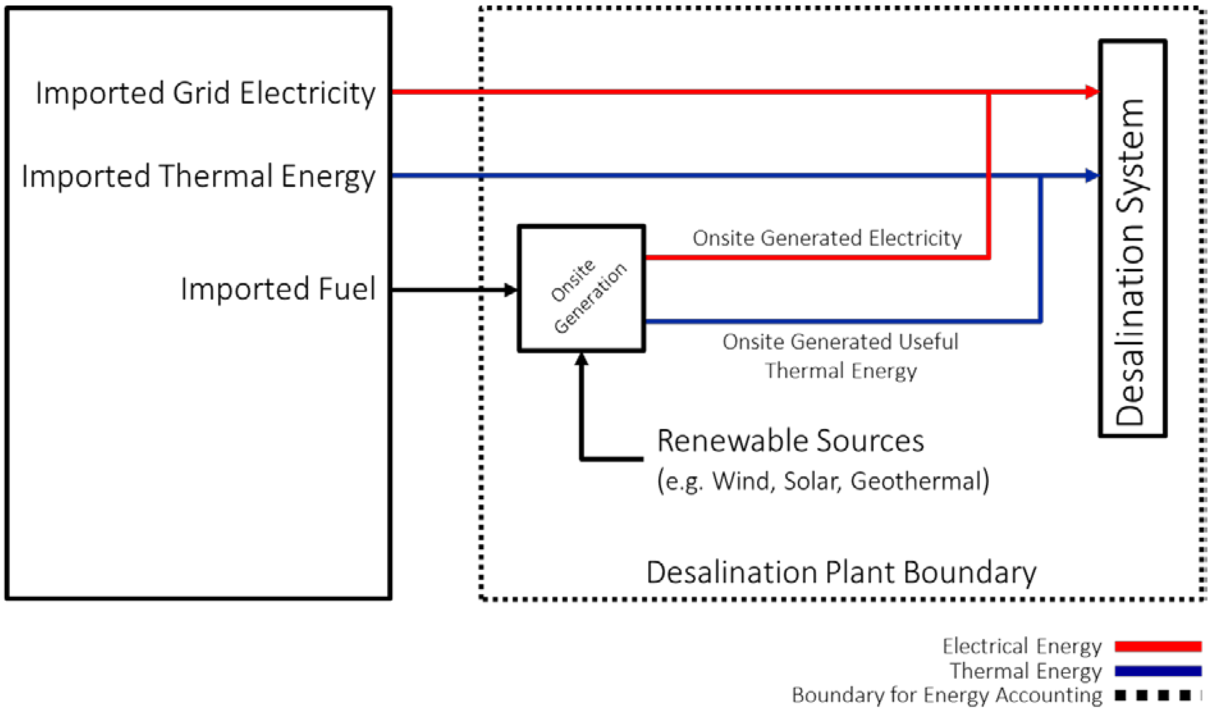


Figure 4-3. Imported grid electricity and thermal energy is converted to primary energy using site-to-primary conversion factors

4.1.3.1. Electrical Energy

Electricity can be either purchased from the grid or generated on-site. If purchased from the grid, a site-to-primary conversion factor accounting for distribution, transmission, and generation losses will be used and obtained from EPA's eGrid (available at https://www.epa.gov/energy/egrid). For generalized analyses or those that span multiple electric territories, a site-to-primary conversion factor of three (3) may be applied instead of site-specific conversion factors. This assumes that the U.S. electric grid has an average generation, transmission, and distribution efficiency of 33% and is consistent with findings from the DOE Energy Information Administration.[62]

If electricity is generated on-site from renewable resources (e.g., solar and wind) it will be accounted for without any additional site-to-primary conversion factors. In other words, the site and primary energy consumption are assumed to be the same. If electricity is generated on-site using a fossil-fuel powered generator, the input thermal energy to the generator will be accounted for, rather than the resulting electricity generated. See the next section for thermal energy accounting.

4.1.3.2. Thermal Energy

Thermal energy generated on-site (e.g., on-site boiler or hot water) will be accounted for based on the input fuel used to generate the thermal energy. In general, transmission and distribution losses for fossil-fuel sources will be assumed to be small and a site-to-primary conversion factor will not be applied to the input fuel. For purchased thermal energy (e.g., purchased steam), a site-to-primary conversion factor accounting for generation efficiency will be applied. If the plant is importing waste heat from a neighboring facility (e.g., power plant cooling water), a site-to-primary conversion factor will not be applied.

Thermal desalination technologies (e.g., MSF, MED, vapor compression [VC]) commonly use a combination of thermal (Megajoules [MJ]/m^3) and electrical (kW/m^3) energies. To report total energy intensity for each thermal technology, thermal and electrical energy intensities will be combined. The value of the thermal energy needs to be converted to an equivalent electrical energy (i.e., the exergetic value of the heat being utilized to drive the desalination process). For that reason, the temperature of the thermal energy input should be considered, since the exergetic value of heat is dependent upon the source (and sink) temperatures (i.e., similar to the work that can be extracted from a heat engine or a Carnot cycle). However, many sources in the open literature do not report the temperature of the thermal energy along with the thermal energy consumption value. Where provided, electrical equivalent thermal energy values as stated in the original reference are used. In instances where this information is not reported, equivalent electrical energy for thermal energies can be calculated by multiplying the reported thermal energy consumption by 33%, which is equivalent to the United States' electricity generation, transmission, and distribution efficiency. This is the methodology adopted for this report when equivalent electrical energy is not provided. The equivalent electrical energy calculated using this method is the amount of electricity that would be generated in a typical U.S. thermal power plant using the same thermal energy source.

In this report, electrical energy consumption is denoted with a subscript "e" (i.e., kWh_e/m^3). Thermal energy consumption is denoted with a subscript "th" (i.e., $kWh_{e,equiv}/m^3$), and represents the electrical equivalent of the thermal energy consumed. The subscript "T" (i.e., $kWh_{T,equiv}/m^3$) denotes the total electrical and thermal energies (reported in electrical equivalent energy).

4.1.4. Water Out

To identify the energy, chemicals, and other operational and cost factors for the next unit operation, the quality of the processed water leaving each unit operation is tracked in the analysis framework. Further, a comparison of inlet to outlet water quality may help to identify improvement opportunities.

4.1.5. Concentrate Stream to Concentrate Management

Almost all unit operations of a desalination system (with the exception of intake) have some sort of a reject or concentrate stream that requires treatment before being safely discharged. Water recovery for the desalination unit operation in seawater RO ranges from 45%–55%, meaning 45%–55% of the feedwater entering a desalination system is converted to concentrate with 1.5 to 2 times greater solute concentrations than the feedwater.[63] For thermal systems, recoveries are generally less, and the concentrate is subsequently less saline. In addition, the concentrate stream contains all the chemicals added in different unit operations of the process and could contain excess amounts of heat as well. Characterizing the reject or concentrate stream leaving each unit operation will help to better understand environmental impacts of desalination, which is a significant barrier to the uptake of desalination systems. It will also allow the identification of the sources of problematic constituents in the concentrate.

4.1.6. Economic and Operational Characteristics

4.1.6.1. Fixed Cost

Fixed or capital costs can be categorized as costs required for construction, equipment purchases, and permitting.[64] Figure 4-4 provides a breakdown of average capital expenses (CAPEX) for seawater RO facilities.[65] "Power System" in Figure 4-4 refers to the cost of installing substations and transmission lines in order to power the desalination plant. It also includes the costs associated with locating a facility closer to the point of use and a suitable power source.[66] For more information regarding the economics of desalination systems, refer to the techno-economic analysis in Section 11.0.

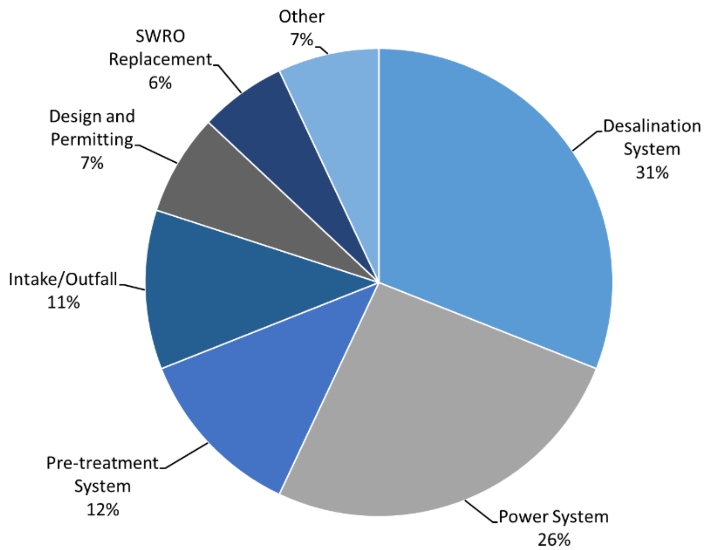


Figure 4-4. Proportional CAPEX Costs of a Typical Seawater RO Facility[67]

4.1.6.2. Variable Cost

Major variable costs for desalination plants include the cost of labor, chemicals, and maintenance.[68] The variable costs breakdown for a typical seawater reverse osmosis (SWRO) and large seawater thermal desalination plant are provided in Figure 4-5. Note the inclusion of membrane replacement here and in Figure 4-4 (as "SWRO Replacement") indicates that the classification of fixed and variable costs may vary from source to source. In addition Figure 4-5 summarizes ranges of different variable costs for SWRO. Ranges for seawater thermal desalination were not found in the literature.

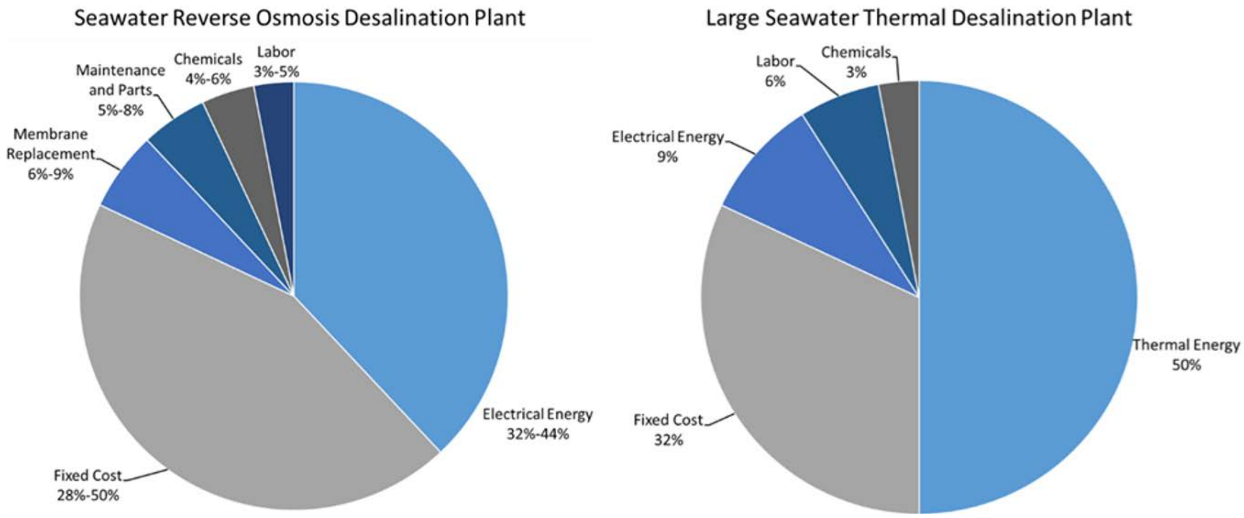


Figure 4-5. Operation and Maintenance Parameters for a Typical RO Seawater Desalination Plant (left)[69] and Typical Large Seawater Thermal Desalination Plant (right)[70]

4.1.6.3. Energy Cost

This describes the cost of purchased energy imported to the plant. This cost is primarily driven by energy consumption at the facility. In addition to advancements in materials, processes, treatment methods, and sensors, several factors such as co-location with existing power plants or on-site generation of renewable energy can reduce this cost. Additionally, factors such as energy purchasing contracts and the ability to provide ancillary and demand response services to the electric grid can also affect energy costs.

4.1.6.4. Operational Characteristics

Operational characteristics include a wide range of parameters that will help to better understand the limitations and operating conditions of a desalination plant (or a unit operation in the plant). To that end, water quality, required flow rate, dispatchability, availability, capacity factor, water production flexibility, and water storage capacity are some of the operational characteristics of interest. Operational characteristics enable an evaluation of how well the desalination system can integrate into the existing electric grid (or other energy transmission system) and water network, and how the system can best serve water demands.

Some Middle Eastern desalination plants highlight the importance of operational characteristics. Some of these are located to serve as combination plants, producing both electricity and water (high-pressure steam produces the electricity and low-pressure steam produces the water). The co-production of water and electricity requires coordination of each process. To provide some flexibility in production, membrane plants that can convert some of the electricity to water production are introduced. Documenting operational characteristics can increase understanding of such interactions between energy and water sectors.

Desalination plants are large consumers of energy, especially electrical energy. The high electricity demand of desalination plants creates a grid integration challenge, but also presents an opportunity. The challenge lies in the fact that desalination facilities need to be located close to a suitable power source and in an area where the electricity transmission and distribution system is not congested. However, desalination plants can provide resources to the grid as well. Depending on the plant's operational flexibility and presence of on-site water storage, a plant's production can ramp up or down, to either shed load or take excess load from the grid. Providing such ancillary services are valuable to the electric grid and can also unlock revenue streams for the desalination plant through demand response (DR) incentive or capacity payments. However, to better assess grid integration and DR potential of desalination plants, operational characteristics such as process flexibility, dispatchability, capacity factors, presence of water storage, and presence of centralized process control require further investigation.

4.1.7. Environmental Considerations

Environmental impacts of desalination processes include emissions associated with the source(s) of energy consumed, marine life impacts of coastal wildlife, and the consequences of improper concentrate disposal. Many environmental considerations and impacts are difficult to quantify. Nevertheless, they are significant to track in order to reduce negative environmental impacts and costs associated with disposal, siting, and permitting. Awareness of environmental considerations and corresponding actions can also mitigate local community concerns regarding the impact of a desalination system.

4.1.7.1. Carbon Dioxide Emissions

The CO_2 emissions of a desalination plant are directly related to the source of energy imported to the plant or consumed at the plant. For the purposes of Volume 2, all energy types delivered into the facility boundaries will be accounted for on a primary (source) energy basis. Conversion from site to primary energy accounts for the losses in generation, transmission, and distribution of various energy types. Energy accounting and conversion of site energy to a primary basis is discussed in detail in Section 4.1.3. Electric or thermal energy generated on-site using renewable sources (e.g., solar, geothermal, and wind) have an emission factor of zero. However, there is an emission factor associated with all non-renewable sources (e.g., fossil fuels). Once the primary energy consumption is determined, greenhouse gas emissions can be calculated using EPA's "Emission Factors for Greenhouse Gas Inventories" or DOE's Energy Information Administration's "Voluntary Reporting of Greenhouse Gases Program" technical guidelines.

4.1.7.2. Other Considerations

Each unit operation of the desalination process has its own unique environmental considerations. Coastal and inland desalination plants pose different environmental concerns due to their geographical location. Marine life impact associated with water intake is an important environmental consideration for coastal plants. On the other hand, surface and groundwater pollution, as well as soil damage, are the environmental considerations relevant to inland desalination plants.

The following Sections (4.2–4.6) will qualitatively apply the boundary analysis framework presented here to each unit operation of the desalination process (as shown in Figure 2-2), highlighting the parameters and metrics for each materials flow, operational characteristic, and environmental impact that may affect energy consumption, CO_2 emissions (as it relates to the relevant energy source for each unit operation), and costs.

4.2. Intake

Intake design and placement can affect the efficiency and performance of the entire desalination system.[71] The location of the desalination plant dictates the feedwater quality, which affects the energy and chemical requirements and the amount of energy required to convey the feedwater from source to the facility. Figure 4-6 shows the boundary analysis framework applied to the intake unit operation. The intake unit operation, along with the concentrate management unit operation, is the primary sources of environmental impact for a desalination facility.

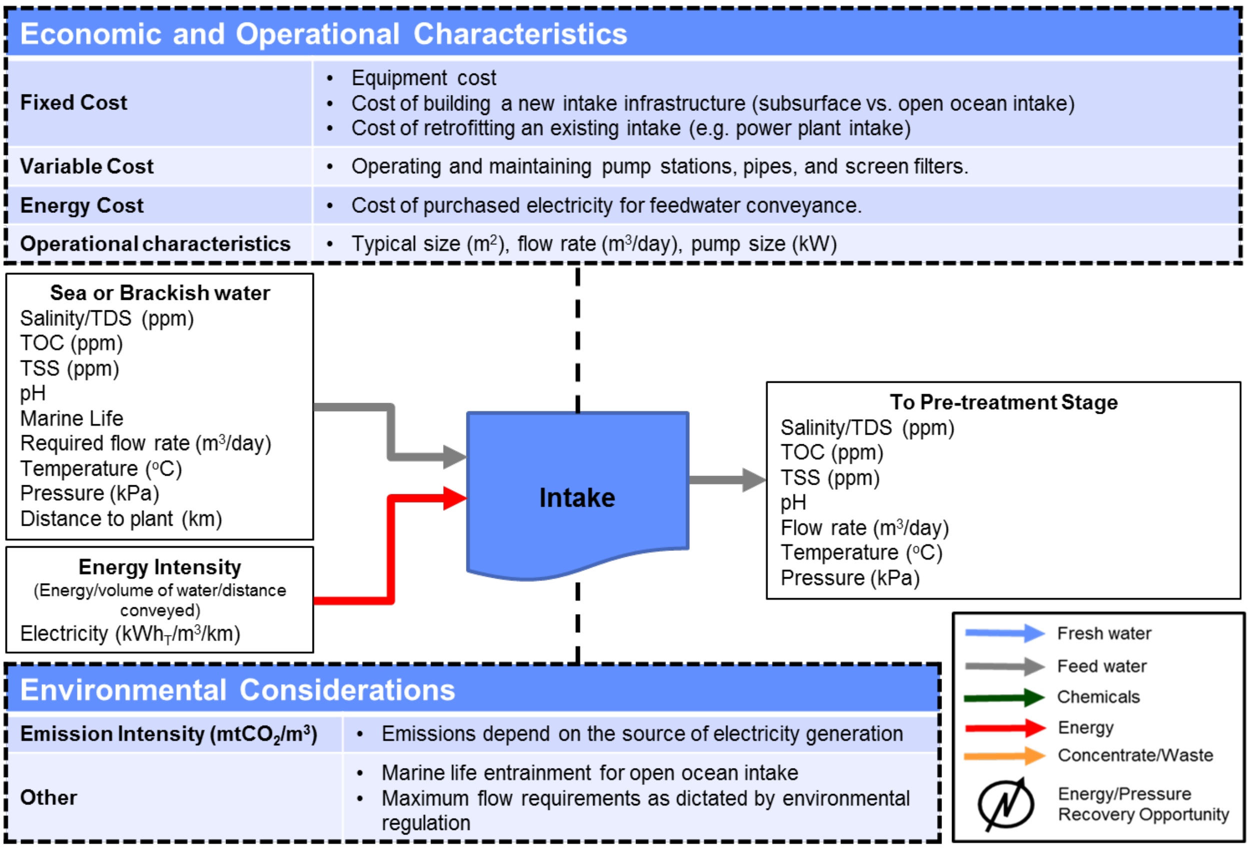


Figure 4-6. Intake Unit Operation Boundary Analysis Framework

4.2.1. Water In

The two sources of feedwater analyzed in this study are seawater and brackish water. For a breakdown and more detailed characterization of different feedwater compositions, refer to Section 2.2.

Parameters that will affect system performance (and by extension, energy consumption and CO_2 emissions) are highlighted in the boundary analysis framework, and are further described below. Not all of these parameters impact the energy consumption of the intake operation, but they will impact the performance later on, therefore they are tracked here.

- **Salinity/TDS:** Higher concentrations of salt may increase the desalination process energy intensity (particularly for membrane-based systems) and dictate the type and dosage of chemicals used in the pretreatment unit operation. Both the salts and the chemicals will have to be removed/recovered in the concentrate management unit operation, which increases energy consumption, adds to operational cost, and impacts the environment.

- **TOC:** Total Organic Carbon (TOC) is an indirect measure of organic molecules present in water. TOC is often used as a non-specific indicator of water quality and is the primary indicator used to define organics present in the feedwater of desalination systems.
- **TSS:** Total Suspended Solids (TSS) are solids in water that can be trapped by a filter. TSS can include a wide variety of materials, such as silt, decaying plant and animal matter, industrial wastes, and sewage.
- **pH:** The pH values are typically constant for each type of source water, but they can be affected by natural or anthropogenic sources. pH control is another supplementary method for enhanced coagulation and filtration. pH values are more essential during post-treatment unit operation and before water system integration. A pH value below seven can corrode system components such as pipes, instrumentation, and racks.[72] Polyamide RO membranes are designed for a pH range of 2–11. Cellulose acetate membranes are more sensitive to corrosion due to lower pH, but they are seldom used.
- **Marine Life:** In addition to the TSS, presence of marine life may affect intake design and screening. Presence of marine life in the intake water dictates the magnitude and robustness of the downstream pretreatment unit.
- **Required flow:** In addition to determining if a certain system can be physically designed, permitted, and constructed at a given location, there needs to be sufficient confidence that the desired flowrate can be obtained over the installation lifespan. This includes consideration of both demand and expected conditions (e.g., recharge, tidal influences, fouling, etc.).[73] The required flowrate may be restricted by marine life impacts. Ultimately, potable water production may be limited by the available feed flow.
- **Temperature:** The viscosity of water is affected by its temperature; a higher temperature of water fed to the desalination unit operation will require less pumping energy than a lower feed temperature due to lower viscous effects through the membrane barrier layer.[74] The flux through an RO membrane is reduced about 3% per degree Celsius temperature drop due to the increase in viscosity. For thermal-base desalination technologies, higher feedwater temperatures reduce the amount of additional/imported energy that needs to be applied to the desalination system. As an example, if the feedwater is obtained from a power plant cooling process, the elevated temperatures could reduce energy requirements for a thermal desalination technology, but will often lower permeate water quality for an RO process, possibly requiring a higher level of treatment.[75] Theoretically the solubility of salts in the water is a function of temperature, with solubility generally being lower at lower temperatures. As a result, the theoretical minimum energy requirement of the system will decrease with a reduction in feedwater temperature. This has a minor impact for the range of temperatures generally considered for saline water desalination. For more discussion on temperature effects on the thermodynamic minimum energy intensity, see the discussion in Section 3.
- **Pressure and distance to plant:** Pressure requirements to overcome pipe losses and elevation changes can also be referred to as the Total Dynamic Head (TDH), measured

in feet of water. These parameters are used to calculate the amount of energy consumed in the intake unit operation as the feedwater is conveyed from source to the plant. Pumping energy requirements are driven by flow rate, pressure, and elevation change. If the concentrate is disposed at the water source, the distance from the plant will also affect the energy requirements for concentrate disposal.

4.2.2. Chemicals

Addition of chemicals during the intake unit operation is not common, with the exception of hypochlorite, which is added at the intake in a seawater desalination plant. Sodium hypochlorite is introduced into the seawater intake to prevent fouling of the mechanical equipment, such as the seawater circulating pumps and bar screens.[76] Sodium hypochlorite is typically generated using an electro-chlorination unit (ECU).

4.2.3. Energy

The intake unit operation primarily consumes electricity for pumps to convey feedwater from its source to the plant. The metric used throughout the literature to quantify intake energy intensity is *energy per volume of feedwater.* However, this metric does not take into account total dynamic head, which will impact the intake's energy intensity. A metric scaled to distance conveyed (e.g., $kWh_{T,equiv}/m^3/km$)[77] may be more representative. Factors such as site location, site conditions, and technology options (i.e., open-ocean intakes, subsurface intakes, co-location with an existing intake) can significantly affect the energy intensity of the desalination system.

4.2.4. Water Out

Water leaving the intake and entering the pretreatment unit operation should have the same characteristics as the feedwater source. Some intake technologies can act as pre-filters, reducing suspended solids and organic matter in the feedwater. Subsurface intakes have shown significant reduction in algae, bacteria, and total organic carbon.[78] For more information regarding the impact of different intake technologies on the quality of the feedwater please refer to Section 6.2.

4.2.5. Reject Stream

The only reject stream leaving this unit operation would be the backwash water used to clean the intake screens.[79]

4.2.6. Economic and Operational Characteristics

4.2.6.1. Fixed Cost

Generally, factors contributing to the fixed costs for the intake unit operation are construction of the intake itself (e.g., open-ocean intake, wells), piping, pumping stations, and intake screens.[80] The fixed cost varies for plants depending on the feedwater quality. Seawater intakes require (more expensive) corrosion-resistant materials due to the high salinity of the source water. The length, and hence the cost, of the conveyance piping can vary greatly, from a near-shore location (e.g., in a slough setting) to an intake point several hundred to several thousand feet offshore.[81]

4.2.6.2. Variable Cost

Variable cost associated with the intake unit operation is due to labor cost for periodic intake system cleaning and pipe and pump station maintenance.[82]

4.2.6.3. Energy Cost

Pump stations in the intake unit operation are the consumers of electricity. Another energy-consuming unit within the desalination system is the ECU, which is often attributed to the intake system at a seawater desalination plant for generating sodium hypochlorite. The energy cost associated with the intake unit operation is due to purchased electricity for these electricity-consuming processes.

4.2.6.4. Operational Characteristics

Economic and operational considerations while evaluating different intake technologies include required capacity (in terms of volume of water per day), geology, and feedwater quality. The applicability of different intake types depends upon the project-specific siting options, site geology, local ecology, cost, regulations, and stakeholder considerations. Environmental impacts (and associated permitting), especially impingement and entrainment concerns, are typically the most challenging (and costly) influence on how the intake design is selected and the manner in which it is constructed and operated.[83]

For SWRO systems, the intake design and placement can play an important role in the effectiveness and performance of the next unit operation (pretreatment).[84] Subsurface intakes have shown significant reductions in algae, bacteria, and total organic carbon (TOC),[85] as the water is naturally filtered through sand during the intake process. Subsurface intakes eliminate biopolymers and polysaccharides, which are key components of biological and organic fouling in the SWRO system.[86]

4.2.7. Environmental Considerations

A major concern associated with seawater intake is the impingement and entrainment of marine organisms.[87] Impingement and entrainment may restrict intake type location and selection. Carbon dioxide emissions related to electricity consumption are another environmental impact.

4.3. Pre-treatment

The purpose of pretreatment is to remove source water constituents such as sediments, organic materials, and microbes. Two factors that strongly influence the pretreatment unit operation are the feedwater source and the choice of desalination unit operation technology. Feedwater source is important because if the feedwater is collected through an open-ocean intake and the desalination technology is reverse osmosis, then rigorous pretreatment is needed. The following unit operations typically occur during pretreatment:[88]

- Screening
- Chemical dosing for biological control
- Coagulation/flocculation and associated chemical addition
- Dissolved air flotation

- Coarse filtration
- Fine filtration, comprised of membrane or media filtration (often using a range of effective pore sizes)
- Chemical addition for scale inhibition and/or chlorine reduction (these can also be done at the desalination unit operation)

The pretreatment unit operation is a complex process, where various chemicals may be added to the feedwater, and constituents removed. Figure 4-7 shows the boundary analysis framework as it applies to the pretreatment unit operation. The boundary analysis framework shows the dependence of the pretreatment unit operation on upstream (source water from the intake unit operation) and downstream (choice of desalination technology) processes.

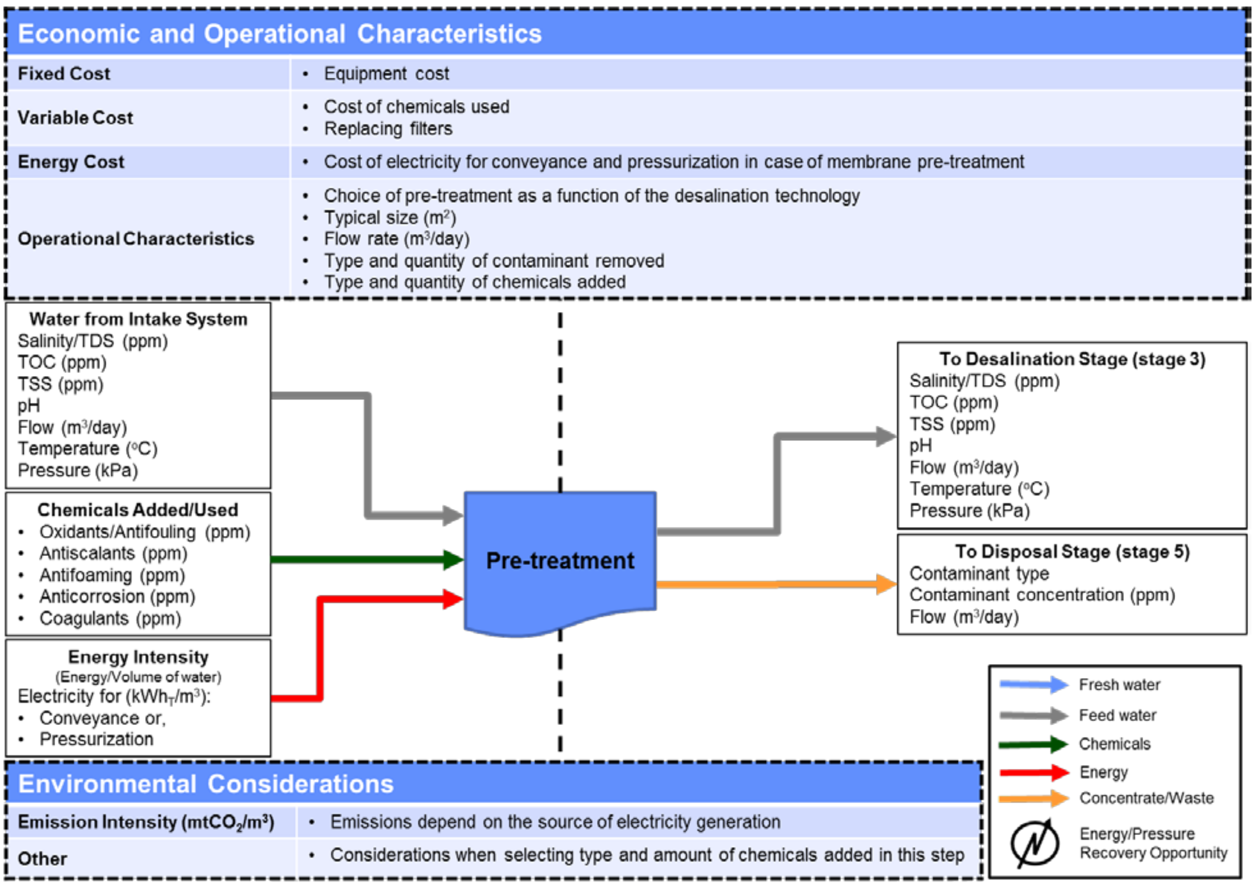


Figure 4-7. Pre-treatment Unit Operation Boundary Analysis Framework

4.3.1. Water from Intake

Since minimal or no treatment occurs during the intake unit operation, it can be assumed that the water entering pretreatment has the same composition as the feedwater. The same parameters and metrics introduced in the previous section are also used to characterize the water entering the pretreatment unit operation.

4.3.2. Chemicals

Pre-treatment processes also remove constituents that cause fouling and biofouling. Suspended solids (the primary source of TSS and turbidity), microbes, microorganisms, and organic and inorganics compounds are the main causes of fouling and biofouling.[89] The feedwater quality from natural sources is influenced by anthropogenic and weather-related events. This changes the quality and quantity of potential foulants. Constant monitoring of the parameters that identify the presence of foulants (introduced in the previous section) will allow the pretreatment unit operation to run more efficiently by dynamically adjusting the treatment level and chemical dosage required.[90]

Selecting the chemicals to add in the pretreatment unit operation depends on the core desalination technology. Chemicals are added for reasons such as biofouling control, particulate coagulation, scaling, dechlorination, and corrosion control. For a list of chemicals commonly used for pretreatment please refer to Table 7-2 in Section 7.2.

Chemicals added in the pretreatment unit operation may need to be removed and disposed of in later unit operations. Excessive dosage of pretreatment chemicals translates to higher energy consumption and costs in the desalination, post-treatment, and concentrate management unit operations. Many of the chemicals used in this unit operation, with the exception of chlorine, are non-toxic and used in levels lower than those in EPA regulations.[91] However, they can accumulate in multi-pass systems and reach levels which require treatment before discharge. Moreover, some of the pretreatment chemicals can react with feedwater constituents (i.e., bromide) and create by-products and precipitates that can pass through RO membranes and complicate the post-treatment process. Strong acids, such as sulfuric or hydrochloric acids, prevent calcium and magnesium bicarbonate precipitation but also alter the pH of the water, an important property that affects subsequent unit operations in the desalination processes.[92]

4.3.3. Energy

The main source of energy for this unit operation is electricity (purchased or generated on-site). Pre-treatment technologies such as coagulation, sedimentation, passive screening, cartridge filtration, ozonation, dissolved air flotation (DAF), ultraviolet (UV), ultrafiltration and micro filtration (UF/MF) are all electricity-consuming processes.

4.3.4. Water to Desalination

The quality of the water leaving the pretreatment unit operation is strongly dependent on the desalination technology. Monitoring the pH, TOC, and TSS are important for membrane technologies, as those parameters will help minimize membrane damage and fouling.

4.3.5. Reject Stream

Materials separated during passive screening, solids removed through processes such as DAF, strainer washwater, and membrane backwash are constituents of the reject stream leaving the pretreatment unit operation.[93]

Backwash water is generated during the periodic cleaning of pretreatment filters and contains particulates and other compounds removed from source water prior to desalination. Backwash water usually needs treatment prior to disposal since it has high levels of TSS and may have significant environmental consequences if not treated or discharged properly.[94]

4.3.6. Economic and Operational Characteristics

4.3.6.1. Fixed Cost

Fixed costs include construction of a pretreatment unit, equipment, and media or membrane purchases. The relative cost of a pretreatment system is directly dependent on the source water quality and the number of pretreatment unit processes required for providing suitable water quality to the desalination system and targeted capacity of the desalination system.[95]

4.3.6.2. Variable Cost

Cost of chemicals is the largest contributor to the variable cost in the pretreatment unit operation. Membrane/media and filter replacement is another important contributor to the variable cost of this unit operation.

A well designed pretreatment unit operation can reduce the overall cost of a desalination process. The significant benefit of advanced pretreatment options (e.g., UF/MF-based pretreatment) is realized through reduced operating costs. The annual costs for a seawater RO system with UF/MF pretreatment are projected to be approximately 5% lower than one with a conventional pretreatment system.[96] Also, proper pretreatment ensures that the capacity of the desalination plant can be sustained. Poor pretreatment may force operation at lower recovery and thus lower productivity.

4.3.6.3. Energy Cost

Electricity cost is the primary energy cost associated with this unit operation.

4.3.6.4. Operational Characteristics

The main function of the pretreatment unit operation is removal of foulants and possible mineral scale precursors from the feedwater to protect the desalination system components used downstream. Thus, the operational characteristics of the pretreatment unit operation are strongly tied to the desalination technology used in the next unit operation. Improper pretreatment can have operational impacts downstream such as increased RO feed pressure, higher energy consumption, increased concentration polarization, lower plant availability, and higher membrane replacement rates.[97] On the other hand, impacts on thermal systems, while similar, have some specific differences such as scale formation and the subsequent poor heat transfer, and corrosion which can introduce heavy metals into the water.

The designed capacity of the pretreatment unit operation is an important operational characteristic. The capacity of the pretreatment unit operation needs to be designed with sufficient margin. For RO plants, decline in membrane permeability is common, which results in lower permeate production. Excess pretreatment capacity will avoid the decline in permeate production by increasing the feedwater flow into the desalination unit operation if necessary.[98]

4.3.7. Environmental Considerations

Chemicals used in the pretreatment unit operation are the main cause of environmental concern. However, the environmental concerns of using chemicals in this unit operation do not manifest until the concentrate management and concentrate disposal unit operation. Therefore, they will be addressed when describing that unit operation.

4.4. Desalination

Desalination processes treat water of an undesirable quality (saline water for the purposes of both phases of this study) to produce a usable freshwater stream (i.e., the desired product) and a separate concentrate stream. As the water leaves the pretreatment unit operation, it enters the desalination unit operation where it is converted to fresh water (product water). Figure 4-8 shows the boundary analysis framework applied to the desalination unit operation.

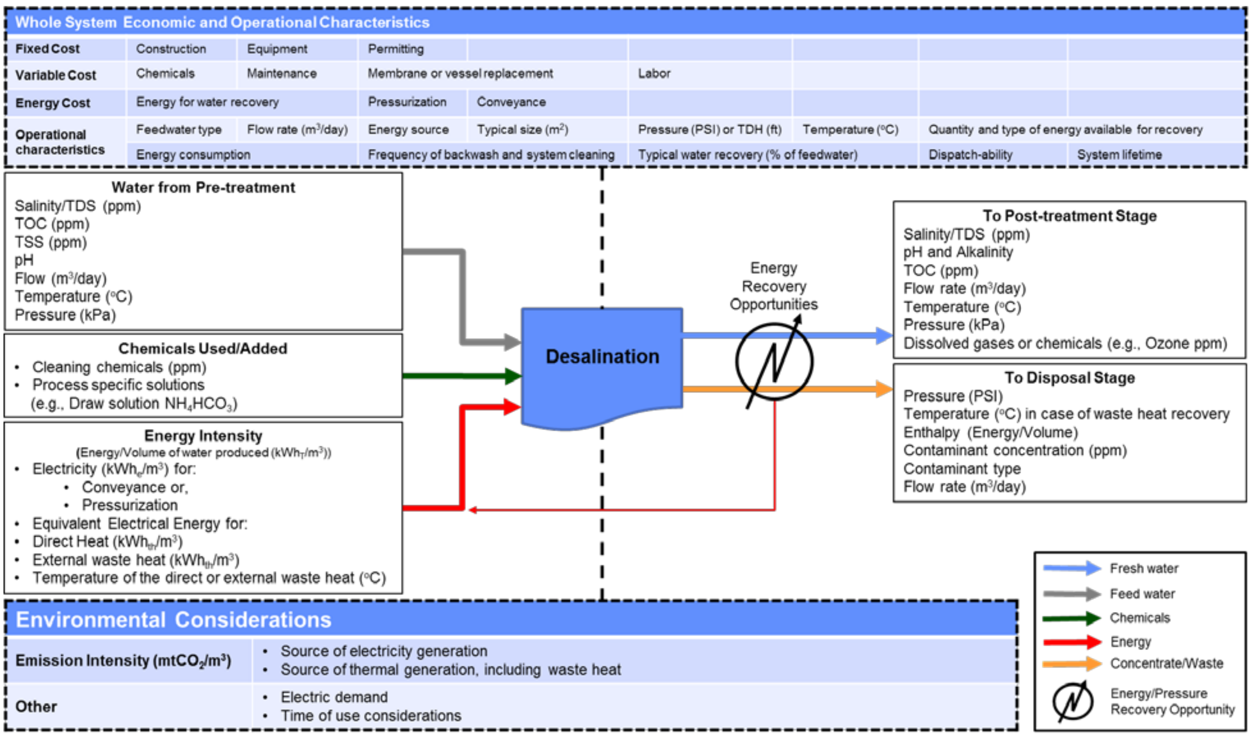


Figure 4-8. Desalination Unit Operation Boundary Analysis Framework

4.4.1. Water from Pre-Treatment

All the parameters introduced in the earlier sections including TDS, TOC, TSS, pH, and flow are still important to monitor and control in order to optimize the energy, emissions, and cost factors of the desalination unit operation. Silt density index (SDI) and modified fouling index (MFI) are two metrics that are specifically monitored in RO systems to measure the fouling capacity of the water entering the desalination unit. However, since these are specific to a desalination technology, they have not been added to the boundary analysis framework for the desalination unit operation. In addition to the original constituents of the feedwater, the water entering the desalination unit operation contains the chemicals added in the intake and pretreatment unit operations. The pH is carefully monitored to ensure the entering water meets the optimal pH range for the desalination technology being used.

4.4.2. Chemicals

Antiscalants and chemicals to control pH may be added directly at the desalination unit in RO systems. Cleaning chemicals are used periodically to clean the system. Cleaning intervals have to be established for each desalination plant individually and are typically every three to six months, depending on the plant's feedwater quality.[99] The cleaning intervals are often based on experience, and at the present time accurate monitoring of the onset of fouling and mineral scaling episodes is unavailable. For this reason, plants rely on operator experience to determine cleaning frequency.

In RO plants, alkaline cleaning solutions (pH 11–13) are used for removal of silt deposits and biofilms, whereas acidified solutions (pH 1–3) remove metal oxides and scaling. Further chemicals are often added to improve the cleaning process of RO membranes, such as detergents, oxidants, complexing agents, or biocides for membrane disinfection.[100] The frequency of system cleaning is plant- or process-specific, and depends on the production rate and salt rejection.

In distillation plants (e.g., MSF, MED) cleaning is typically simple. Copper-nickel heat exchanger surfaces are washed with acidified warm seawater to remove alkaline scaling. The acidic solution often contains a chemical inhibitor which is added to protect the plant from corrosion. Many named cleaning and disinfection chemicals may be hazardous to aquatic life, so that disposal to the ocean is regulated. Neutralization of the alkaline or acidic solutions and treatment of additional cleaning agents before discharge to the ocean removes any potential toxicity.[101]

4.4.3. Energy

Membrane-based desalination technologies (e.g., RO, nanofiltration [NF]) require water pressurization. Electricity is the sole source of energy for water pressurization. Electrodialysis is a membrane-based technology that does not require pressurization and uses electricity as its sole source of energy to create a potential difference in order to push ions through charged membranes. The energy consumption of such technologies is reported as kWh_e/m^3 of product water produced. The electricity can either be purchased from outside of the plant boundaries or generated on-site using available renewable (solar, wind, geothermal) or non-renewable (natural gas, diesel) sources.

Thermal and hybrid desalination technologies (e.g., MED, MSF, VC, MD, RO-MSF, RO-MED) use a combination of electricity and direct heat as their energy sources. Electricity is primarily used for the purposes of water conveyance and creation of a partial vacuum inside the distillation vessels.

Energy needed for thermal desalination is often satisfied by direct heat (thermal energy) utilization. The thermal energy could either be imported into the facility in terms of steam or waste heat (many waste heat sources are in the range of 40ºC–90ºC[102]) or generated on-site using fossil fuels or renewable resources, such as solar thermal or geothermal. Even though thermal energy consumption is typically reported in the units of million British thermal units [MMBtu]/m^3 or MJ/m^3, for the purposes of this study, equivalent electrical energies in the units of $kWh_{e,equiv}/m^3$ are reported when only thermal energy is consumed. This choice is made for thermodynamic accuracy, consistency, and ease of comparison between different technology options with different energy sources. Ideally, the temperature of the thermal input and sink would be provided in the literature, allowing for a calculation of the system efficiency. However, this information is often omitted in the available literature. Please refer to Section 4.1.3.2 for more details on the calculation of electrical equivalency based on the values reported in the available literature.

As mentioned in the previous section, the pretreatment unit operation can affect all the downstream processes. The impact of inadequate pretreatment on the desalination unit operation would increase RO feed pressure and thus result in higher energy consumption due to factors such as high feed-to-concentrate pressure drop, reduced membrane permeability, and higher osmotic pressure caused by increased concentration polarization.[103]

In membrane plants, a large fraction of the energy leaving the desalination unit operation in the pressurized concentrate stream of seawater or highly brackish RO desalination systems can be recovered using an energy recovery device. Energy recovery technologies and devices are discussed in further detail in Section 8.2.7.

4.4.4. Water to Post-Treatment

The TDS of the product water from the desalination unit operation is typically less than 500 ppm, which makes it suitable for potable use. However, desalinated water is limited in minerals such as calcium and magnesium, and a certain degree of remineralization may be needed to make the water palatable and non-corrosive as well as to meet health requirements.[104] Monitoring the pH and alkalinity of the freshwater leaving the desalination unit operation assists plant operators in selecting an appropriate remineralization process. In some cities, product water is simply blended with other potable sources instead of remineralization.

4.4.5. Reject Stream

The constituents of the reject stream and their concentrations are vital in the selection of appropriate concentrate management and concentrate disposal technologies. Table 4-1 summarizes the constituents and concentrations of the concentrate stream. Composition of the concentrate stream can vary significantly based on the conditions of the feedwater. Where “NR” is indicated, a concentration range was not found and/or reported in the literature. Different concentrate management and concentrate disposal strategies are discussed in further detail in Section 10.2.

Table 4-1. Characterization of Seawater Concentrate (Reject) Stream[105]

Parameters (Units)	Membrane (RO)	Thermal (MSF)
pH	4–8	8.9
TDS* (ppm)	~50,000	NR
Temperature (ºC)	Ambient	10–15 above ambient
Antiscalants (ppm)	2	2
Coagulants (ppm)	1–30	Not commonly used in thermal technologies
Antifoaming (ppm)	Not commonly used in membrane technologies	0.1
Cleaning Solutions	NR	NR
Alkalinity ($CaCO_3$ ppm)	142–470	NR
Chlorine (ppm)	NR	2
SiO_2 (ppm)	15.6–116	NR
Na^+ (ppm)	991–15,500	26,142
Mg^{2+} (ppm)	245–2,020	3.625
K^+ (ppm)	79–134	870
Ca^{2+} (ppm)	540–1,537	1,850
Fe^{2+} (ppm)	0.4	NR
Mn^{2+} (ppm)	0.2	NR
Cl^- (ppm)	4,068–28,800	38,821
$SO^{2-}{}_4$ (ppm)	1,553–5,920	4,560
$NO^-{}_3$ (ppm)	14.6	NR
$NO^-{}_2$ (ppm)	NA	NR
$PO^{3-}{}_4$ (ppm)	0.04–2	NR
$HCO^-{}_3$ (ppm)	199–576	190
*The salinity of the reject stream of a SWRO with feedwater salinity of 35,000 ppm TDS, 30% recovery, and assuming 100% salt rejection, would be concentrated by a factor of 1.43, leading to a reject stream salinity of ~50,000 ppm. Concentration Factor (CF) is calculated using the following equation: CF= $[1-Y(1-R_s)]/(1-Y)$, where Y is the water recovery (30%) and R_s is the salt rejection (100%).		

4.4.6. Economic and Operational Characteristics

4.4.6.1. Fixed Cost

Capital expenditures for permitting, plant construction, and equipment purchases are the main fixed costs associated with building the desalination unit operation. For a similar plant capacity, thermal processes require larger footprints and use more costly materials and equipment than membrane-based technologies.[106]

4.4.6.2. Variable Cost

Equipment replacement and labor are major variable costs for the desalination unit operation. Further, thermal processes use more chemicals compared to membrane processes, in order to control scaling, corrosion, and foam formation which can add to their variable cost.[107]

4.4.6.3. Energy Cost

The energy cost depends on the technology option selected for this unit operation. Please refer to Section 4.4.3 for information regarding energy sources for each type of desalination technology. Energy costs typically account for 41% of an SWRO desalination plant's operating cost[108] and 67% of the entire plant's energy consumption is due to the desalination unit operation alone.[109]

4.4.6.4. Operational Characteristics

Operational characteristics vary, depending on the type of technology and the source of feedwater. An important operational characteristic for membrane technologies is transmembrane pressure, a function of the feedwater salinity, which for seawater typically ranges from 800 to 1,200 pounds per square inch (psi) for SWRO.[110] In addition to permeability and salt rejection characteristics, the potential for membrane fouling affects treatment costs.

Membrane manufacturers typically guarantee their membranes for a period of 5 years. However, with proper pretreatment and maintenance, that number can be extended to 10 years, resulting in significant cost savings.[111] On the other hand, irreversible fouling can lead to much shorter membrane life. Membrane lifetime can be improved by sufficient pretreatment, developing fouling-resistant membranes, or better monitoring and maintenance of membranes to mitigate fouling before it becomes irreversible.

Other operational characteristics such as required throughput, operating hours, and operational flexibility could affect the integration of large desalination plants with the energy grid.

4.4.7. Environmental Considerations

In addition to energy source emissions (i.e., emissions from the power plant for grid-purchased electricity) in the desalination unit operation, the management of the concentrate stream from this unit operation represent a major environmental challenge. Concentrate management and concentrate disposal are further discussed in Section 4.6.

4.5. Post-treatment

Desalinated water is often considered corrosive because at high salt rejection operation the product water mineral content is low and may not be suitable for consumption without adequate post-treatment.[112] Remineralization and disinfection are required to meeting drinking water standards. Additionally, removal of elements such as boron may be required.[113] The U.S. drinking water standard for boron is 2.6 mg/L), but it is often required to be below 1.0 mg/L for horticultural reasons, particularly in regions with high levels of water reuse.

The boundary analysis framework for the post-treatment unit operation is shown below in Figure 4-9.

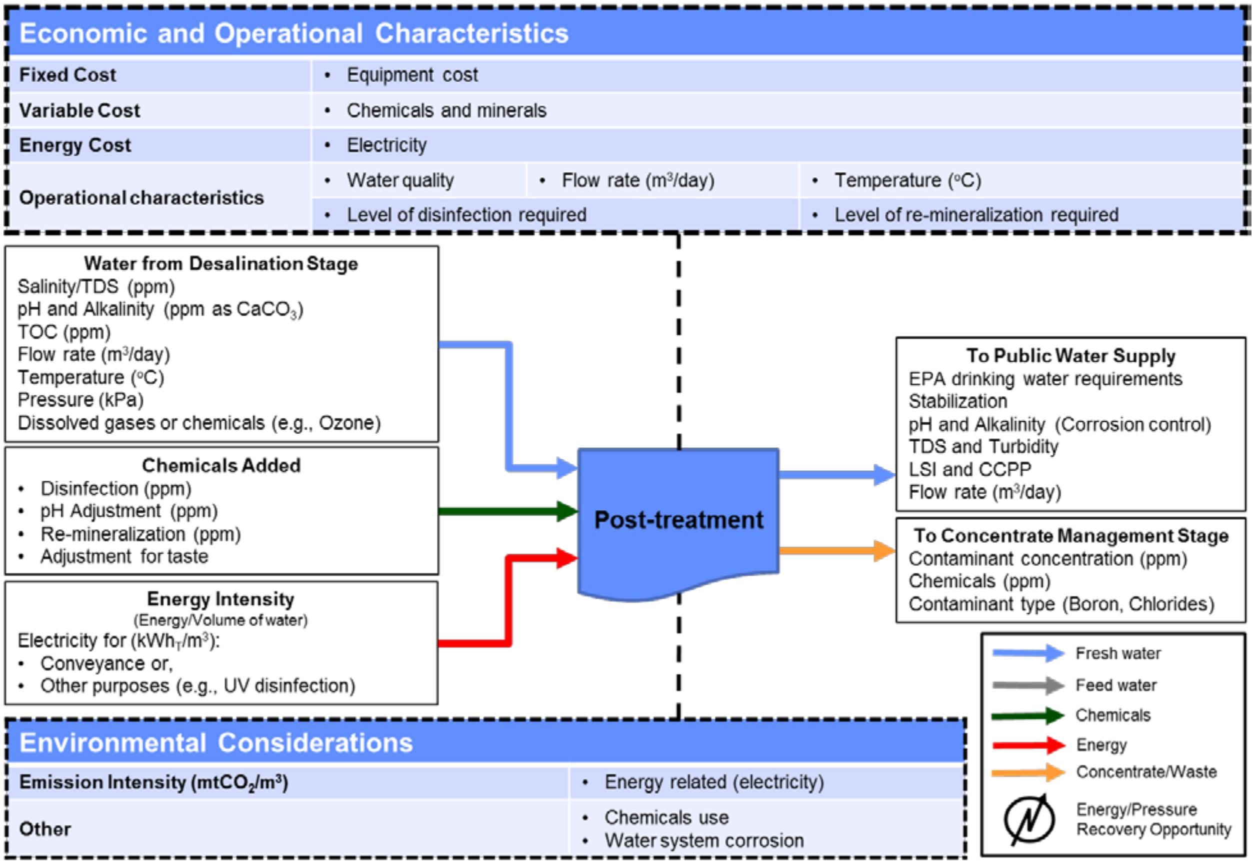


Figure 4-9. Post-treatment Unit Operation Boundary Analysis Framework

4.5.1. Water from Desalination

Product water quality entering the post-treatment unit operation depends on the type of desalination technology employed in the previous unit operation. Product water from thermal technologies typically has a lower TDS than the membrane technologies.[114] While disinfection requirements for potable water generally do not vary across the desalination unit operation used, remineralization requirements will vary. Thermal desalination processes will require higher levels of remineralization compared to membrane-based processes.

4.5.2. Chemicals

Desalinated water typically tends to be more corrosive than surface and groundwater sources.[115] Before integration with the water system, it needs to be stabilized by the addition of chemicals or blending with other potable sources. Table 4-2 provides a list of chemicals that can be added during post-treatment. Calcium (in the form of calcium carbonate) and magnesium are two main chemicals added to desalinated water in the post-treatment unit operation.[116]

Table 4-2. Chemicals Added for Seawater Desalination Post-treatment[117]

Chemical Added	Purpose
Calcium carbonate (calcite)	Increase the hardness and alkalinity (adjust pH to stabilize) of desalinated water
Calcium hydroxide (hydrated or slaked lime)	
Calcium magnesium carbonate (dolomite)	
Calcium oxide (quicklime)	
Carbon dioxide	
Sodium bicarbonate	
Sodium carbonate (soda ash)	
Sodium hydroxide (caustic soda)	
Sulfuric acid	
Chlorine/hypochlorite	Disinfection
Fluorosilicic acid	Product water fluoridation
Magnesium sulfate	Meet drinking water requirements
Magnesium chloride	Meet drinking water requirements
Corrosion inhibitors (e.g., poly-phosphates, monophosphates, zinc orthophosphate and silicates)	Conditioning of soft and low buffering capacity waters to prevent corrosion

Desalination post-treatment processes require higher quality standards compared to other unit operations. After post-treatment, water from the plant will enter the distribution system and there are no remaining downstream processes to remove contaminants. For this reason, the chemical additives' quality and dose rates must be strictly controlled as chemical additives that introduce new contaminants or are dosed in excess quantities cannot be further removed.[118] Water quality criteria following post-treatment is measured by several categories. For drinking water, key criteria include alkalinity, pH, and TDS concentration.

Typical desired pH values are in the range of 6.5 to 8.5, though higher values have been associated with lower corrosion and improved disinfection efficiency.[119]

4.5.3. Energy

The post-treatment unit operation uses about 13% of the entire seawater RO system's energy, mainly in the form of electricity for pumping to provide potable water pressure, water conveyance within the plant, and disinfection processes.[120]

4.5.4. Water to Public Supply/Storage

Water leaving the post-treatment unit operation should comply with the EPA regulations. Attainment of this requirement is site specific and dependent on the water source, desalination process, and existing water system where the product water will be integrated.

4.5.5. Reject Stream

Having a reject stream leaving the post-treatment unit operation is not common. The only reject water from this unit operation is due to regular system cleaning conducted to flush out the precipitated calcium carbonate during pH adjustment or removal of boron from ion exchange resins.

4.5.6. Economic and Operational Characteristics

4.5.6.1. Fixed Cost

Fixed cost for the post-treatment unit operation includes the cost of construction and equipment purchased. Product water is typically stored in a water storage tank or pumped to a water treatment facility prior to water system integration. The cost of building storage reservoirs, pumping stations, and pipes to convey water to a water treatment facility can also be included in the fixed cost of the post-treatment unit operation.

4.5.6.2. Variable Cost

Cost of labor, maintenance, parts, chemicals, and minerals added to the product water make up the variable cost of this unit operation.

4.5.6.3. Energy Cost

The primary source of energy used in post-treatment is electricity, and the energy cost depends on electricity consumption and unit cost.

4.5.6.4. Operational Characteristics

Product water quality (pH, alkalinity, hardness, etc.) and flow rate dictate the level of post-treatment required. In addition, the water system that the product water is being integrated with will further refine the operational characteristics of the post-treatment unit operation.

4.5.7. Environmental Considerations

If the post-treatment is not done properly, the desalinated water can corrode pipes, causing lead and other metals to enter the water system. Physical damage to the pipes leads to leaks and failures. If a facility utilizes a calcite (limestone) dissolution process to adjust pH of the product water during post-treatment and uses sulfuric acid in the limestone reactor (which are often open to the atmosphere), there is the possibility that there may be unintentional CO_2 emissions to the atmosphere.[121]

4.6. Concentrate Management and Disposal

There is concern that saline water desalination can lead to adverse environmental impacts on coastal water and marine life. To mitigate this concern, environmental impact analyses on both the concentrate management/disposal and intake are performed before siting and permitting. This is a consideration when planning and permitting a desalination plant. The concern over concentrate management and disposal is mostly due to the high salinity concentrate that is emitted into the sea or other receiving bodies/wells of water. In addition to the removed sea/brackish water constituents (relative to the receiving body of water) the concentrate stream may be at increased temperature and/or higher density, and contain residual chemicals from the pretreatment process, heavy metals from corrosion, or intermittently used cleaning agents. The effluent from desalination plants is a multi-component residual stream, with multiple potential effects on water, sediment, and marine organisms.[122]

The use of a consistent boundary analysis framework shown in Figure 4-10 is highlighted in this unit operation, as it allows tracking of the type of chemical and minerals present in the concentrate stream, as well as their concentrations.

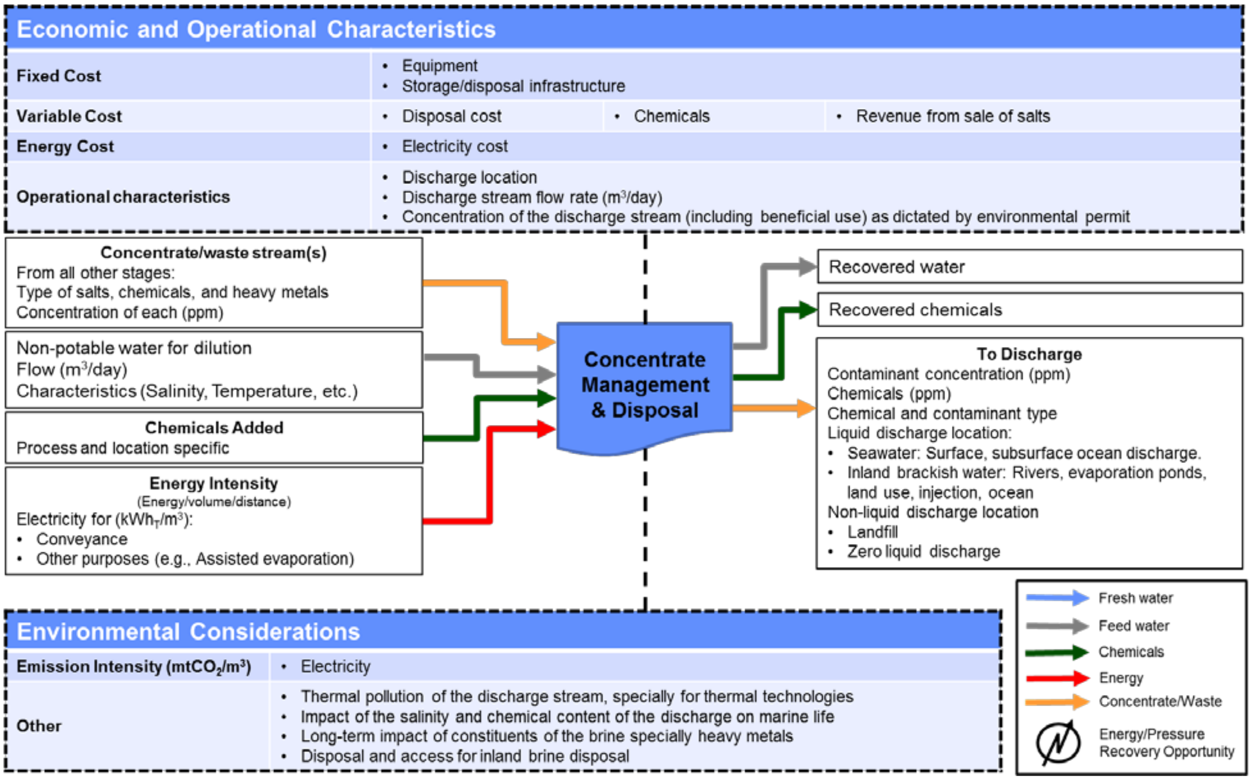


Figure 4-10. Concentrate Management and Disposal Unit Operation Boundary Analysis Framework

The choice of concentrate management strategy and the disposal method depends on the location of the desalination plant. Management and disposal methods are discussed in more detail in Section 10.2.

4.6.1. Concentrate and Waste Streams

The process water entering the concentrate management unit operation is the combination of reject streams from all other previous unit operations. However, treatment of the concentrate stream leaving the desalination unit operation is the main concern. The concentrate stream from the desalination unit operation has been previously characterized in Table 4-1. Most of the chemicals and elements listed in that table either entered the system with the feedwater or were added during pretreatment. Other metals such as copper, nickel, iron, chromium, and zinc enter the system from corrosion processes, which commonly occur in thermal technologies.[123] Some methods of concentrate management include blending with other sources of water such as power plant cooling water, natural seawater, or municipal wastewater into this unit operation in order to reduce salinity prior to discharge.[124]

Concentrate typically has low levels of turbidity (usually less than two nephelometric turbidity units, or NTU), TSS, and TOC (less than 5 mg/L). If the plant pretreatment side streams are discharged along with the concentrate, the blending can elevate turbidity, TSS, and TOC.

Concentrate also contains the chemicals used for acid and scale inhibition rejected by the RO membranes, which affects the overall mineral content and quality. Scale inhibitor levels in concentrate are usually less than 20 ppm.[125] Table 4-3 describes some limitations and regulations specific to desalination plants in the United States for concentrate management and disposal. It is meant to be representative, and not comprehensive.

Table 4-3. Limitations and Regulations of Discharge from Seawater Desalination Plants[126]

Desalination Plant	Total Flow (MGD)	Maximum TDS (ppm)	Chronic Toxicity* (TUc)	Flow Ratio**
Claude "Bud" Lewis Carlsbad Desalination Plant (feedwater TDS of 33,500 ppm)	54–60.3	44,000	16.5	Mixing Zone*** 15.1:1
Tampa Bay Seawater Desalination Facility (feedwater TDS of 25,000 ppm)	56.59	35,800	none	Dilution = 28:1

* Chronic toxicity is the development of adverse effects as the result of long-term exposure to a toxicant or other stressor.
** Flow ratio (also referred to as *mixing ratio* or *dilution ratio*), is the ratio of the parts of solute to the parts of solvent.
*** As defined by the California Ocean Plan, the mixing zone for the acute toxicity objective shall be 10% of the distance from the edge of the outfall structure to the edge of the chronic mixing zone (zone of initial dilution). Initial dilution is the process which results in the rapid and irreversible turbulent mixing of wastewater with ocean water around the point of discharge.

4.6.2. Chemicals

Use of treatment chemicals is not common in the concentrate management and disposal unit operation, and was not identified in the literature reviewed.

4.6.3. Energy

The electrical energy in the concentrate management and disposal unit operation is used to convey concentrate to the disposal location. Inland concentrate disposal typically requires higher energy because of unavailability of a convenient disposal location (i.e., open ocean discharge). The energy demand can vary depending on the choice of technology used in this unit operation. More information on energy consumption in concentrate disposal can be found in Section 10.0.

4.6.4. Recovered Water and Chemicals

Most seawater desalination plants take advantage of their proximity to the coast to discharge their treated concentrate stream directly into the ocean. However, using some technologies such as electrodialysis or zero liquid discharge (ZLD) in the concentrate management unit operation will allow more water to be separated from the concentrate, which in turn increases the recovery of the overall desalination system. Alternatively, a technology like wind-aided evaporation (WAE) can reduce the volume of the concentrate.

4.6.5. Reject Stream

Liquid discharge and ZLD are two main approaches for managing the disposal of the reject stream. Liquid discharge includes techniques such as dispersion, mixing, and dilution of the concentrate stream, which are critical to reducing environmental impact. If not handled properly, liquid discharge may damage the disposal environment (i.e., aquatic life in the case of ocean discharge or the groundwater in the case in inland disposal). Zero-liquid discharge is a more recent concentrate management method to recover more distilled water from the concentrate and lower the amount of liquid waste that can cause damage to aquatic environments. There are several emerging technologies for ZLD, such as WAE and VC crystallizers. However, ZLD is not practiced and is currently not economically feasible for seawater desalination. The ZLD approach at present is not economical for inland water desalination unless the environmental and disposal cost is high enough to justify it.

4.6.6. Economic and Operational Characteristics

4.6.6.1. Fixed Cost

Construction cost and equipment purchase are the fixed costs identified in this unit operation. The construction cost depends on the physical location (coastal vs. inland) of the plant and the type of concentrate management and disposal technology used. Most of the desalination plants yielding the lowest water production costs have concentrate discharges either located in coastal areas with intensive natural mixing, or are combined with power plant outfall structures which use the buoyancy of the warm power plant cooling water to provide accelerated initial mixing and salinity plume dissipation at lower cost.[127]

4.6.6.2. Variable Cost

Labor and maintenance make up the variable cost of this unit operation. Seawater desalination plants have more low-cost options when it comes to discharging their reject stream, where inland brackish water desalination plants have limited options. As an example, deep well injection and ZLD increases the total costs of brackish water desalination by 50%–200% above the desalination process costs alone.[128] Regardless of the location or feedwater quality, factors such as salinity of concentrate, disposal method, and concentrate volume influence the variable cost of this unit operation and ultimately the entire desalination plant.[129]

Desalination plants can also tap into their concentrate stream as a source of revenue. Concentrate can be purified, and the salts can be sold for beneficial use (i.e., road salt as well as providing feedstock for the chemical industry).[130] Even though many studies have been done on beneficial use of concentrate salts, no examples of this practice in industry were found. A potential application may be selective precipitation of concentrate salts for mixing with construction materials.

4.6.6.3. Energy Cost

The energy cost of the concentrate management and disposal unit operation is mainly due to the cost of electricity required to convey the concentrate to the disposal location. Higher pumping requirements for inland desalination plants will result in higher overall energy costs.

4.6.6.4. Operational Characteristics

Important operational characteristics of the concentrate management and disposal unit operation are the concentrate flow rate, disposal location, and salinity tolerance of the disposal location.

4.6.7. Environmental Considerations

In general, direct concentrate discharge can have the following results on receiving waters:[131]

- Eutrophication[132]
- pH variation
- Accumulation of heavy metals
- Sterilizing properties of the disinfectants
- Ion imbalance toxicity[133]

Marine pollution (thermal and chemical pollution) is the main environmental consideration for coastal desalination plants. All the chemicals, metals, and concentrated salts present in the concentrate can impact phytoplankton, invertebrates, and vertebrates in the marine environment. Chlorine, heavy metals, and halogenated compounds are examples of chemicals present in the concentrate stream that can damage the marine environment. Halogenated compounds, which could be carcinogenic to animals, are a by-product of chemical reactions that might occur between constituents of the feedwater and the added chemicals.[134]

Inland concentrate disposal has the potential to pollute fresh surface water and groundwater. It might also irreversibly damage soils and ecological systems. Different coastal and marine ecosystems vary in their sensitivity to concentrate and chemical waste discharge. The least sensitive are high-energy oceanic coasts that have strong waves and exposed rocky shores; whereas the most sensitive are coral reefs, salt marshes, and mangroves.[135]

5.0. Overview of Energy Utilization in Seawater Desalination Systems

Table 5-1 outlines operational and system information of selected U.S. desalination plants that currently provide drinking water. For the purposes of this report and ensuing Volume 2, *seawater* will be defined as having a salinity of (or near) 35,000 ppm TDS. With this definition, the Carlsbad, California, desalination facility would be categorized as a "seawater" desalination facility, whereas the others would be categorized as "brackish" water facilities. Note that the Tampa Bay, Florida, facility denotes itself as a "seawater" facility, although the intake salinity is 25,000 ppm. Four of the five facilities are located on the west coast in California, while the other is located in Florida. The table provides information on the specific processes in use in these facilities; all five utilize RO as the main desalination process.

Table 5-2 and Table 5-3 below provide a summary of the energy intensity ranges found in the literature for best available and most representative options for the five seawater desalination unit operations (intake, pretreatment, desalination, post-treatment, and concentrate management) for a membrane system (Table 5-2) and a thermal system (Table 5-3). Thermal energy intensity values in this report are electrical equivalents. Energy requirements are reported as found in the literature with the accompanying reference information (i.e. feedwater and product water salinity, flow rates, and temperatures; system components; and temperatures of the heat sources and sinks) provided below the table. Often, the appropriate reference information is not provided in the literature. This information is critical in better understanding the drivers behind the energy intensity ranges and when comparing across desalination technologies. Table 5-2 and Table 5-3 are provided as a summary of the energy intensities reported in the literature. Further analysis on these values will be conducted in the second phase of this research and reported in Volume 2 to describe the variance in energy intensities. For more information on the energy intensity values researched please see the following sections, as well as Appendix A.

Table 5-1. Details on Significant U.S. Seawater Desalination Plants[136]

Plant Name	Claude "Bud" Lewis Carlsbad Desalination Plant	Tampa Bay Seawater Desalination Facility	Santa Catalina Island	Sand City Coastal Desalination Facility*	San Nicolas Island
Location	Carlsbad, CA	Tampa, FL	Santa Catalina, CA	Sand City, CA	Oxnard, CA
Capacity	50 million gallons per day	25 million gallons per day	325,000 gallons per day	300,000 gallons per day	42,000 gallons per day
Desalination Process	Reverse Osmosis	Reverse Osmosis	Reverse Osmosis	Reverse Osmosis	Reverse Osmosis
Recovery	50%	57%	30%–35%	Data not available	42%
Water Salinity	33,500 ppm	25,000 ppm	Data not available**	"Brackish" seawater, 17,000–28,000 ppm	Data not available
Completion	2015	2007	1991; 2nd unit added in 2015	2010	2015 (new RO units installed)
Product Application	• Serves 400,000 people in San Diego County • 7% of San Diego's water supply	• Supplies to more than 2.5 million residents of Tampa Bay • 10% of Tampa Bay's water supply	• 25%–30% of the island's water supply	• Serves 200 businesses, 4,000 people, and as many as 40,000 visitors in Monterey Peninsula	• Meets the island's daily water demand (15,000 gallons per day for about 200 military and civilian personnel)
Intake Process	Open-Ocean Intake (72-inch seawater feed pipe)	Open-Ocean Intake	Subsurface Intake (Beach Wells)	Subsurface Intake (Beach Wells) – 18 m deep, 61 m from surface, 760 m from plant	Subsurface Intake (Beach Wells)
Pre-treatment	• Media filtration • Cartridge filtration	• Coagulation • Flocculation • Sand Filtration • Diatomaceous earth filters • Cartridge Filters	• Media Filtration	• Cartridge Filters • Antiscalant Addition	• Microfiltration
Energy Recovery	• Pressure Exchangers	• Turbine System	• Data not available	• Pressure Exchangers	• Data not available
Post-treatment	• Re-mineralization • Disinfection • Fluoridation	• Re-mineralization • Stabilization • Blending	• Chlorination • Re-mineralization	• UV Disinfection • Chlorination	• Data not available
Concentrate Management	Surface water discharge	Surface water discharge	Surface water discharge	Deep disposal well	Data not available

*Based on the lower salinity of the feedwater and the system design, the Sand City facility is actually now commonly classified as a brackish water desalination facility, but it was previously widely considered to be a seawater desalination facility.
**Water salinity information for these two plants will be pursued further during Phase 2

Table 5-2. Membrane Seawater Desalination System Energy Summary

Unit Operation	Technology	Reported Range[a]	
		Low Energy Intensity	High Energy Intensity
		Total ($kWh_{T,equiv}/m^3$)	Total ($kWh_{T,equiv}/m^3$)
Intake	Subsurface Intake[137]	0.14	0.16
Pre-treatment	Coagulation	*	*
	Flocculation[138]	0.0024	0.0026
	Media Filtration[139]	0.02	0.26
	Dissolved Air Flotation[140]	0.09	0.11
Desalination	Reverse Osmosis[141]	2	7.5
Post-treatment	Re-mineralization (Blending)[142]	0.04	0.07
	Disinfection[143]	0.04	0.07
Concentrate Management	Surface Water Discharge[144]	0.035	0.105

[a] Energy consumption for processes in the membrane seawater desalination system are electric only; there is no thermal energy consumption.
* No values were determined specifically for coagulation, but an energy intensity value ranges from 0.011 $kWh_{T,equiv}/m^3$ to 0.12 $kWh_{T,equiv}/m^3$ for flocculation, coagulation, and filtration[145]

Open Ocean Intake: Low-intensity value – To pump water 120 feet (40 feet above sea level, 50 feet of suction lift, 30 feet of head loss) through a two-mile pipeline from offshore radial collector wells. High-intensity value – assuming five beach wells all 20 m deep, with 94% pump efficiency and 82% motor efficiency.
Pre-Treatment: Flocculation intensity values – based on a surface water treatment plant, 1–100 MGD. Media filtration low-intensity value – cartridge filter in a beach well intake scenario. Media filtration high-intensity value – pressure sand filter pretreatment.
Desalination: Low intensity value – 40%–60% recovery. High-intensity value – for a double-pass RO facility.
Post-Treatment: Re-mineralization: Lime and carbon dioxide post-treatment for a demonstration plant in California. Disinfection: from a study in California's Northern and Central Coast.

Table 5-3. Thermal Seawater Desalination System Energy Summary

Unit Operation	Technology	Reported Range					
		Low Energy Intensity			High Energy Intensity		
		Electric (kWh_e/ m^3)	Thermal ($kWh_{e,equiv}$/ m^3)	Total ($kWh_{T,equiv}$/ m^3)	Electric (kWh_e/ m^3)	Thermal ($kWh_{e,equiv}$/ m^3)	Total ($kWh_{T,equiv}$/ m^3)
Intake	Open Ocean Intake[146]	0.05	0	0.05	0.58	0	0.58
Pre-Treatment	Dissolved Air Flotation[147]	0.09	0	0.09	0.11	0	0.11
	Media Filtration[148]	0.05	0	0.05	0.26	0	0.26
	Chlorination[149]	0.00053	0	0.00053	0.0021	0	0.0021
Desalination	Multi-Effect Distillation[150]	1.5	4	5.5	2.5	20.1	22.6
Post-Treatment	Re-mineralization (Blending)[151]	0.04	0	0.04	0.07	0	0.07
	Disinfection[152]	0.04	0	0.04	0.07	0	0.07
Concentrate Management	Surface Water Discharge[153]	0.035	0	0.035	0.105	0	0.105

Open Ocean Intake: Low intensity value – assuming a 500 m distance to the plant, 3 m/km head loss, 94% pump efficiency, and 82% motor efficiency. High-intensity value – actual testing value from a facility in California in 2008 with 70% pump efficiency and 95% motor efficiency

Pre-Treatment: Media filtration low-intensity value – single-stage gravity granular media filtration process. Media filtration high intensity value – pressure sand filter pretreatment. Chlorination intensity values – based on a surface water treatment plant, 1–100 MGD.

Desalination: Low intensity value – includes integration of waste heat. Thermal energy intensities are converted to equivalent electricity, assuming a 33% generation, transmission, and distribution efficiency. Temperature of the steam, low-grade heat or waste heat is not reported by the references.

Post-Treatment: Re-mineralization: Lime and CO_2 post-treatment for a demonstration plant in California. Disinfection: From a study in California's Northern and Central Coast.

6.0. Seawater Intake Energy Intensity

Seawater intake is the first unit operation of the seawater desalination process. The main energy requirement is to pump water from the place of intake to the plant location. Energy consumption of the intake unit operation will depend upon the feedwater conveyance distance. Vince et al. (2008) notes that the intake pumping electricity consumption is actually proportional to the total manometric height between the feed source and the plant (taking elevation and distance into account).[154]

The intake system energy consumption is affected by the pump efficiency, frictional losses (caused by screens or other mechanical filters and pipe walls), and the relative location of the water source to the plant in terms of distance and elevation.[155] Plant size also has an impact on energy costs, as plants with less water throughput typically have smaller pumps with lower efficiencies. At scales, larger pumps are more energy efficient, which reduces energy costs and consumption.[156] Typically, water intake accounts for about 15%–20% of the total energy of the desalination plant.[157] Water intake systems for seawater desalination can be divided into two main categories: open-ocean and subsurface intake systems.

6.1. Seawater Intake Energy Intensity Summary

Table 6-1 provides a summary of the findings on energy intensity for the intake unit operation. Energy requirements are reported as found in the literature; further analysis on these values will be conducted in Phase 2. The two options for seawater desalination plants—open ocean and subsurface intake—are discussed in more detail in Section 6.2 below. Both options require electricity for pumping, and the energy intensity will be specific to the distance and elevation that the source water must travel to reach the plant, as well as the type of pumps used. See Table A-1 in Appendix A for full details on the referenced values and full findings from referenced sources on intake energy intensity.

Table 6-1. Seawater Desalination Intake Energy Intensity Summary

Process	Reported Range	
	Low Energy Intensity	High Energy Intensity
	Total[a] ($kWh_{T,equiv}/m^3$)	Total[a] ($kWh_{T,equiv}/m^3$)
Open Ocean Intake[158]	0.05	0.58
Subsurface Intake[159]	0.14	0.16

[a] Energy consumption for intake processes is electric only; there is no thermal energy consumption.

Open Ocean Intake: Low-intensity value – assuming a 500 m distance to the plant, 3 m/km head loss, 94% pump efficiency, and 82% motor efficiency. High-intensity value – 3 millimeter (mm) screen, with 200 feet of total dynamic head (TDH), actual testing value from a facility in California in 2008 with 70% pump efficiency and 95% motor efficiency.
Subsurface Intake: Low-intensity value – to pump water 120 feet (40 feet above sea level, 50 feet of suction lift, 30 feet of head loss) through a two-mile pipeline from offshore radial collector wells. High-intensity value – assuming five beach wells all 20 m deep, with 94% pump efficiency and 82% motor efficiency.

6.2. Description of Technology or Process Energy Use

6.2.1. Open-Ocean Intake

Open-ocean intake systems collect seawater directly through an onshore or offshore inlet. Offshore inlets are the most common configuration.[160] Water passes through a screen or physical barrier to prevent additional debris or organisms from entering the intake, and pumps move water to the desalination plant. Open-ocean systems typically require full pretreatment systems, adding to the energy consumption of the plant.

Economies of scale also play a factor in the energy consumption of open-ocean intake systems. Figure 6-1 presents different system scales based on projections derived from a seawater RO demonstration-scale plant; the energy intensity reduction for larger plant sizes demonstrates the per-unit energy savings at larger scales. Larger plants will typically have larger pumps and pipe diameters, which are both typically more energy efficient than their smaller counterparts.

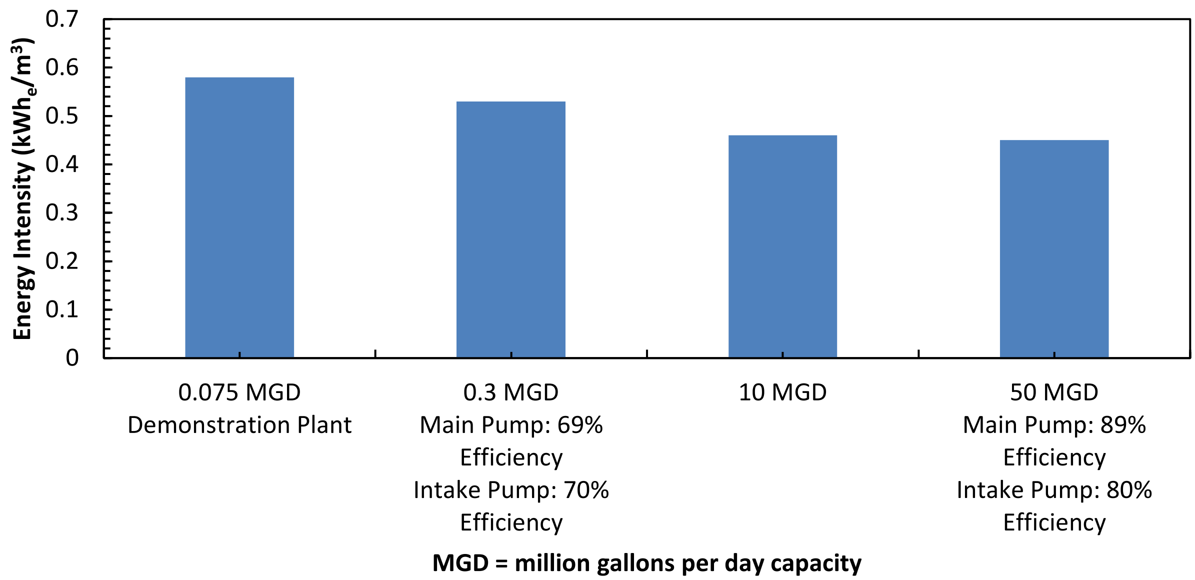


Figure 6-1. Intake Energy Intensity for an Open-ocean Intake at a SWRO Demonstration Plant, and Projected Values for Larger Scales[161]

In general, environmental concerns typically have more influence on intake system selection than energy costs. Two key environmental concerns are impingement (when aquatic organisms are pulled irreversibly against intake screens) and entrainment (when organisms are pulled into intake systems). Subsurface systems can reduce these ecological harms by separating the water intake from direct sea life contact, but this is not always a possibility, and the installation of open-ocean intakes is usually more cost-effective.[162]

6.2.2. Subsurface Intake

Subsurface intakes collect water from under the sea floor. They typically involve a well at the surface and a series of inlets underground, configured based on the geology to capture embedded groundwater. In subsurface intake systems, water passes through the (typically sandy) ground instead of a screen, and suspended contaminants and organisms that can be a problem for open-ocean systems are filtered out. The reduction of suspended solids at the subsurface intakes reduces the need for their filtration at the desalination facility, possibly permitting a lower level of pretreatment before desalination; however, depending on geography there may still be the need for solids (i.e., iron and manganese) removal through sand filtration.[163]

7.0. Seawater Pretreatment Energy Intensity

For U.S. seawater desalination plants, the pretreatment unit operation involves the addition of chemicals as well as different types of filtering processes. At the seawater desalination facility in Carlsbad, California, the seawater received from the intake (open ocean with 33,500 ppm TDS) is sent through a multimedia filter, followed by microfiltration; during these two steps algae, organic particles, sand particles, smaller impurities, and other particles are removed.[164] At the desalination facility in Tampa, Florida (open saline water with 25,000 ppm TDS), pretreatment steps include coagulation, flocculation, sand filtration, diatomaceous earth filters, and cartridge filters before the water is fed to the desalination unit operation.[165]

The pretreatment step or steps used in a desalination plant depend on whether a membrane or thermal desalination process is being utilized. The water fed to a thermal desalination process requires less extensive pretreatment compared to a membrane desalination process.[166] Pre-treatment is especially important for membrane desalination plants, as seawater that is not properly treated can reduce the ability of water to pass through the membranes, thereby increasing the required osmotic pressure (and by extension the energy requirements) to achieve the desired recovery, and reducing the lifetime of the membranes.

7.1. Energy Requirements for Pre-treatment of Seawater

Table 7-1 provides a summary of the findings on high and low energy intensity for the pretreatment unit operation. Energy requirements are reported as found in the literature; further analysis on these values will be conducted in Phase 2. If a subsurface system is used, pretreatment needs can be decreased significantly, as the sandy floor acts as a natural filter for suspended solids.[167] Using beach sand as a natural filter can eliminate the need for pretreatment. Beach well intake can deliver feedwater with an SDI value of 0.3–1 with no need for further pretreatment.[168] An open-ocean intake will require more pretreatment systems, to remove solids and unwanted compounds in the water. Pretreatment often involves the combination of multiple different steps, which will vary depending upon the intake process and desalination technology used. It can involve chlorination, DAF, flocculation, coagulation, sedimentation, media filtration, and/or membrane filtration. For pretreatment, often times the energy intensity for numerous steps is reported together (e.g., flocculation, coagulation, and filtration as one energy intensity number). Backwashing (not listed in Table 7-1 since it is a periodic process) will also contribute to energy needs for pretreatment. Backwashing is used to remove particles trapped in the system that can reduce feedwater throughput, and is therefore a necessary operational practice. Therefore, backwash frequency can assist in optimizing the system energy efficiency if the proper membranes and pretreatment practices are carefully selected.[169] See Table A-2 in Appendix A for full details on the referenced values and full findings from referenced sources on pretreatment energy intensity.

Table 7-1. Seawater Desalination Pre-treatment Energy Intensity Summary

Technology	Reported Range	
	Low Energy Intensity Total[a] ($kWh_{T,equiv}/m^3$)	High Energy Intensity Total[a] ($kWh_{T,equiv}/m^3$)
Chlorination[170]	0.00053	0.0021
Flocculation[171]	0.0024	0.0026
Sedimentation	0.0023	0.0037
Dissolved air flotation[172]	0.09	0.11
Membrane filtration[173]	0.11	0.40
Media filtration[174]	0.02	0.26

[a] Energy consumption for pretreatment processes is electric only; there is no thermal energy consumption.

Chlorination: Intensity values based on a surface water treatment plant, 1–100 MGD.
Flocculation: Intensity values based on a surface water treatment plant, 1–100 MGD.
Sedimentation: Intensity values based on a surface water treatment plant, 1–100 MGD.
Dissolved air floatation: No additional notes.
Membrane filtration: Low-intensity value – no additional notes. High-intensity value – actual testing value from a facility in California in 2008 using an ultrafiltration system (0.01 micron, and a water flux of 0.815 m^3/m^2/day, 20 gallons per square feet per day [gfd]).
Media filtration: Low-intensity value – cartridge filter in a beach well intake scenario. High-intensity value – pressure sand filter pretreatment for iron and manganese removal

7.2. Description of Technology or Process Energy Use

Pre-treatment technologies used for desalination include chlorination, dissolved air flotation, coagulation, flocculation, sedimentation, media filtration, and membrane filtration (microfiltration/ultrafiltration).

7.2.1. Chlorination

Chlorination involves adding chlorine or hypochlorite to kill microorganisms in the water feed. The process helps deter growth in the transport piping and potential biological fouling on the desalination membranes caused by these microorganisms.[175] The on-site energy requirement of using chlorine for disinfection is negligible compared to membrane filtration, which requires separate powered equipment.[176] Many large-scale facilities practice on-site generation of hypochlorite. For these facilities, the energy requirements associated with chlorination will increase. Onsite generation of hypochlorite will be further explored during Phase 2. Although chlorination is currently one of the most common forms of disinfection processes, desalination plants often consider alternatives due to the produced by-products and posed hazards of handling the material.[177]

7.2.2. Dissolved Air Flotation

Dissolved air flotation is used to remove oils, organics, and other light solids from the intake water stream. It involves dissolving air into the intake water while it is under pressure. The air forms bubbles, which attach to the suspended matter and cause it to float to the surface, where it is removed using a surface skimmer. Open-ocean intakes require this process more than subsurface intake systems, as a means of removing oil and algae, including high algal loads that result from intermittent and unpredictable algal blooms and red tide events.[178] The energy consumption for DAF ranges from 0.09 $kWh_{T,equiv}/m^3$ to 0.11 $kWh_{T,equiv}/m^3$.[179]

7.2.3. Flocculation and Coagulation

Flocculation and coagulation refer to the separation and removal of unwanted colloids and particles from the water fed into the desalination system. Coagulation involves adding chemicals that destabilize colloids which are suspended in the water, causing them to agglomerate for easy removal.[180] Energy intensities for pretreatment using coagulation, flocculation, and filtration in California were reported to range from 0.011 to 0.12 $kWh_{T,equiv}/m^3$.[181]

During flocculation, high molecular weight compounds are added to the water and attach to the unwanted particles. This step helps eliminate approximately 85% of the suspended matter by agglomerating particles for easier removal.[182] A plant that produces 100 MGD would require 0.0024 $kWh_{T,equiv}/m^3$ of energy for flocculation and a plant that produces 1 MGD would require 0.0026 $kWh_{T,equiv}/m^3$.[183]

7.2.4. Media, Cartridge, Disc, and Diatomaceous Filtration

The energy intensity of a filter process is determined by the resistance of water passing through the filter media, and the specifications of any backwash processes used for the filter system. Proper pump sizing can also be a source of energy savings.

Media filtration is used to remove suspended solids from the intake water stream and often follows flocculation or coagulation. It typically refers to granular filtration. Granular media filters work by allowing the intake water to flow through a bed of media which filters out larger solids. Some of the large RO desalination facilities rely on a single-stage gravity granular filtration process. The media types can either be gravity-fed or pressure-driven. Pressure-driven filters are more common in small and medium plants (< 20,000 m^3/day). They typically require more energy than gravity systems, but are cost-competitive, space-efficient, and relatively easy to install. Pressure filters are common when plants have an open-ocean intake system or the seawater contains a higher contaminant concentration.

Cartridge filters are typically made of plastic. The filters use a backwash system to keep the filter clean and reduce the need for replacement; however, the filters need to be regularly replaced due to wearing. Cartridge filtration is sometimes used as a redundant pretreatment system. Additionally, they may be paired with micro/ultrafiltration.

Disc filters are composed of a series of compressed plastic discs. They filter out particles of a specific size. Disc filters also use a backwash system but do not require as much water as other filters. They often require high horsepower pumps to run their backwash cycles, resulting in slightly higher energy requirements for the trade-off of less water consumption.

Diatomaceous filters work as a fine media filter in which a layer of diatomaceous earth is accumulated on the outside of a filter candle, and the very fine particles are removed as they build up a filter cake. Backwashing of the diatomaceous earth filters is required when the flows are reduced and a new layer of diatomaceous earth is deposited on the filter candles. The accumulated solids and the diatomaceous earth must be disposed of in an acceptable manner, which may include dewatering to reduce the volume.

7.2.5. Membrane Filtration

The two common categories of membrane filtration are microfiltration (MF) and ultrafiltration (UF). The primary distinction between these is pore size, where microfiltration covers pore size ranges of around 0.05–10 nanometers (µm) and ultrafiltration covers ranges of around 0.005–0.02 µm, though these numbers may vary.[184] Microfiltration energy requirements range from 0.058 $kWh_{T,equiv}/m^3$ to 0.188 $kWh_{T,equiv}/m^3$.[185]

Energy needs for membrane filtration systems depend on the system's operating pressure, with higher pressure systems requiring more energy to maintain the necessary flow rate.[186] Membrane filtration can have pressure pump systems or vacuum pump systems. Pressure pump systems push water through the filter in an enclosed vessel, while vacuum pump systems pull water through the filters in an open tank. Vacuum systems operate at lower pressures and typically use 10%–30% less energy than pressure systems for medium/high turbidity water at temperatures of 18°C –35°C.[187] Pressure systems become more cost-competitive at lower temperatures (< 15°C) with less contaminants, or when the system operates at a higher pressures—such as with offshore open-ocean intake systems.

7.3. Other Relevant Considerations from the Framework

7.3.1. Chemical Addition

Chemical addition during pretreatment adjusts the properties of the feed seawater and prepares it for the desalination unit operation. Appropriate chemical additions can increase the lifetime of the system and also reduce its energy intensity. For example, scaling affects the pretreatment and desalination unit operations by restricting flow in pipes and reducing the effectiveness of membranes for pretreatment and desalination.[188] Table 7-2 below outlines chemicals used for specific pretreatment systems, as well as chemicals added that protect downstream processes like the desalination unit operation. Where "NR" is indicated, a concentration range was not reported and/or found in the literature.

Table 7-2. Seawater Pre-Treatment Chemicals[189]

Type	Purpose and Other Considerations	Composition	Dosage (ppm)	
			Membrane (RO)	Thermal (MSF, MED)
Oxidants	Oxidation of organic materials to prevent biofouling. Excessive use of oxidants will result in membrane damage. Some membranes prefer no oxidants, and require the use of sodium bisulfate before the membranes to remove chlorine. In addition, the use of ozone results in formation of bromate in bromide-containing water, which cannot be separated using RO.	Chlorine (Biocide)	0.5–6	0.25–4
		Hypochlorite	0–15	2
		Calcium Hypochlorite	NR	NR
		Hydroxides	10–40	NR
		Ozone	NR	NR
Coagulant	Improved filtration of suspended particles. Enhanced removal of solids and silt during coagulation.	Ferric Chloride	0.8–25	NR
		Aluminum Chloride	NR	NR
		Polyelectrolyte	0.2–4	NR
		pH Control	NR	NR
Antiscalants	To prevent scale formation on RO membranes, heat-exchanger surfaces, inside tubes, etc. Antiscalants have low toxicity, thus having a low environmental impact. However, their poor degradability results in a long residence time.[190]	Sulfuric Acid*	6.6–10	NR
		Polyphosphate	NR	2.2–2.5
		Phosphonate	1.4	NR
		Polyphosphonate	NR	1–3
		Sodium Hexametaphosphate	2–10	NR
		Carboxylic-rich Polymers	NR	NR
		Polycarboxylic Acid	NR	1.5–2
		Polyacrylic Acid	2.9	NR
		Polymaleic Acid	NR	NR
Anti-foaming	To reduce foaming in distillation plants, antifoaming agents like polyglycols are added to the feedwater, which are not toxic but are poorly biodegradable. Adverse effects are not to be expected with regard to a low dosage level and sufficient dilution following discharge.[191]	Polyglycol	Not applicable for membrane technologies.	NR
		Polyethylene Glycol		NR
		Polypropylene Glycol		0.035–0.15
		Acylated Polyglycol		NR
		Fatty Acids (Detergent)		NR
		Fatty Acid Esters (Detergent)		NR
Anti-corrosion	Corrosion inhibitor. Prevention of oxidative corrosion. Reduces residual chlorine.	Benzotriazole derivatives	NR	NR
		Sodium Bisulfite*	3–19	NR
		Sodium Metabisulfite*	NR	NR
		Ferrous Sulfate	NR	1–3
		B-ethyl phenyl ketocyclo-hexylamino hydrochloride	NR	25
Cleaning	Used for periodic system cleaning and chemical-enhanced backwashing.	Citric Acid	NR	NR
		Sodium Hypochlorite	NR	NR
		Caustic cleaners	NR	NR

* Chemicals included in dechlorination process

8.0. Desalination Process Energy Intensity

The desalination process consumes more energy than any other component in the desalination system. Energy requirements for desalination have steadily declined over the past 40 years due to technological advances and research on energy reduction for desalination plants. This report categorizes desalination processes into three divisions of desalination: thermal, membrane, and hybrid technologies. Table 8-1 summarizes the typically applicable water sources and maturity level for several technologies within each category. Alternative energy sources such as wind, solar, and geothermal also have been incorporated recently into newer desalination plants to further reduce carbon emissions.

Membrane-based technologies are pressure-, concentration gradient-, or electric potential-driven. They physically separate the feedwater components using a membrane barrier. Membrane-based technologies usually require mechanical or electrical energy. Applications of this technology include reverse osmosis (RO), forward osmosis (FO), and electrodialysis (ED). Reverse osmosis is the technology used primarily in large commercial seawater desalination plants but it is also used on smaller scales and for brackish water.[192]

Thermal technologies use phase change to separate salts from the feedwater. Vacuum components are sometimes incorporated as well to increase evaporation at lower temperatures.[193] In thermal technologies the 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). The resulting water vapor is then condensed to produce freshwater. The thermal energy extracted from the vapor during condensation is then reused to pre-heat the incoming feedwater. Multi-effect distillation (MED), multi-stage flash distillation (MSF), mechanical vapor compression (MVC), thermal vapor compression (TVC), and humidification-dehumidification (HDH) are all applications of this technology.

Hybrid processes involve a combination of membrane and thermal technologies in a single or multiple units to produce pure or potable water. Membrane distillation (MD), FO, or combinations of RO with MSF or MED are all emerging hybrid technologies that are yet to be proven at large scales. Forward osmosis must be paired with a thermal or membrane technology to regenerate the draw solution. If paired with a thermal technology, the system is considered a hybrid technology. If paired with a membrane technology, such as RO and ED, it is considered a purely membrane-based technology.

Energy Recovery Devices (ERD) are used to capture the energy within the RO concentrate stream leaving the desalination unit operation. These ERDs are incorporated in modern desalination plants due to their ability to capture nearly 76%–96% of the concentrate pressure energy.[194] Energy recovery from the concentrate is most desirable when the RO plant operates at low recovery (typically less than 50%). At high recovery, energy recovery is less efficient, but such devices are increasingly being employed in even small RO plants.

Table 8-1. Desalination Technologies' Technological Maturity and Typical Applicability to Water Sources

Technology Maturity	Desalination Technology	Brackish Water	Seawater	Commercialization/Use Comments
Established	Reverse Osmosis (RO)	X	X	Widely used worldwide for both brackish water (see Section 12.4.1) and seawater (see Section 8.2.1.1)
	Nanofiltration (NF)	X		Normally used as a pretreatment process, but being piloted for desalination (see Section 12.4.3)
	Electrodialysis (ED)	X		Used commercially for brackish water desalination (see Section 12.4.2)
	Multi Stage Flash (MSF)		X	Used commercially worldwide for seawater desalination, but no plants in the U.S. (see Section 8.2.2.1)
	Multi Effect Distillation (MED)		X	Used commercially worldwide for seawater desalination, but no plants in the U.S. (see Section 8.2.2.2)
	Vapor Compression (VC)		X	Commercial technology (see Section 8.2.2.3)
Emerging	Capacitive Deionization (CDI)	X		Best for use at low salinities (< 5,000 ppm). Traditionally used for residential-scale water softening (see Appendix B.2.2.2)
	Forward Osmosis (FO)* coupled with Membrane Desalination	X	X	Commercialized emerging technology; no large plants yet commissioned. Limited industrial applications such as the treatment of oil- and gas-produced water and municipal wastewater (see Section 8.2.1.2)
	Forward Osmosis (FO)* coupled with Thermal Desalination	X	X	
	Membrane Distillation (MD)		X	Currently commercial technology at small scale
	Humidification-dehumidification (HDH)**		X	Older concept, but now commercially available emerging technology; no large plants yet commissioned (see Section 8.2.2.4)

*FO requires an additional thermal separation step and might instead be considered a "pretreatment" but in literature it is referred to as a desalination stage process; see Section 8.2.1.2 for more information on FO.
**HDD is not included in this report, but it will be reviewed for Phase 2.

8.1. Energy Requirements for Seawater Desalination

Table 8-2 presents the reported low and high energy intensities for various membrane, thermal, and hybrid technologies for seawater desalination. Where possible, the table provides a breakdown of electrical (kWh_e) and thermal ($kWh_{e,equiv}$) energy requirements for each technology. Thermal energy intensity values in this report are electrical equivalents. Total energy intensity is also reported in electrical equivalent (also denoted by $kWh_{T,equiv}$). Energy requirements are reported as found in the literature; further analysis on these values will be conducted during Phase 2. Where "NR" is indicated, a breakdown was not reported or found. Additional notes on the intensity values are provided below the table. See Table A-3 through Table A-6 in Appendix A for full details on the referenced values and full findings from referenced sources on the energy intensity of the desalination unit operation.

Table 8-2. Seawater Desalination Unit Operation Energy Intensity Summary

Technology Type	Desalination Unit Operation Technology	Reported Range					
		Low Energy Intensity			High Energy Intensity		
		Electric (kWh_e/m^3)	Thermal ($kWh_{e,equiv}/m^3$)	Total ($kWh_{T,equiv}/m^3$)	Electric (kWh_e/m^3)	Thermal ($kWh_{e,equiv}/m^3$)	Total ($kWh_{T,equiv}/m^3$)
Membrane	Reverse Osmosis (RO)[195]	1.58	0	1.58	7.5	0	7.5
	Forward Osmosis (FO-RO)[196]	5.98	0	5.98	21.5	0	21.5
Thermal	Multi-stage Flash (MSF)[197]	2.5	7.5	10	35	12	47
	Multi-effect Distillation (MED)[198]	1.5	4	5.5	2.5	20.1	22.6
	Mechanical Vapor Compression (MVC)[199]	7	0	7	17	0	17
	Thermal Vapor Compression (TVC)[200]	1.6	14. 5	161	1.8	14.5	16.3
Other	Hybrid technologies*[201]	NR	NR	7.3	NR	NR	9.6
	Membrane Distillation (MD)[202]	0.75	175	175.8	1	350	351

Notes below are provided for the energy intensity values from the references cited (key information including saline water intake flow rate and salinity, recovery, product water output flow rate and salinity, temperature of incoming energy stream, and technologies used were sought and are provided below to the extent reported in the original reference):

NR means that a breakdown between electrical and thermal energy requirements was not reported.
RO: Low-intensity value – lab-scale testing as part of the Affordable Desalination Collaboration; seawater intake at 42.5% recovery and 0.244 m^3/m^2/day production of potable water; High-intensity value – single pass RO.
FO-RO: Low-intensity value – 35,000 ppm TDS feedwater and 50% recovery. High-intensity value – ~37,000 ppm and 75% recovery. FO has not yet been demonstrated for seawater desalination at a large scale. FO needs to be coupled with a secondary direct desalination process for draw solution regeneration. The energy intensities reported for FO in this table include the RO energy requirements for draw solution regeneration.
MSF: Low-intensity value – typical unit size 90,000 m^3/day; includes integration of waste heat; top brine temperature of 120°C. High-intensity value – 30,000–100,000 ppm TDS feedwater salinity; < 10 ppm TDS product water quality.
MED: Low-intensity value – typical unit size 22,700 m^3/day; includes integration of waste heat; top brine temperature maintained at 70°C. High-intensity value – < 20 ppm TDS product water quality.
MVC: No additional notes.
TVC: Typical unit size 10,000–30,000 m^3/day; about 10 ppm TDS product water quality; top brine temperature ranges from 63°C to 70°C.
Hybrid Technologies: Low-intensity value – for a MVC/MED hybrid process. High-intensity value – for a RO/MED hybrid process.
MD: Production rate of 50 m^3/day; feed temperatures from 60°C to 100°C and cooling < 40°C. Membrane desalination has not yet been demonstrated for seawater desalination at a large scale.

8.2. Description of Technology or Process Energy Use

The main energy requirements during the desalination unit operation are electricity for the membrane desalination processes or heat for the thermal desalination processes. Electricity is used to provide power to the pumps to convey water throughout the desalination unit operation. For membrane processes, pumping energy is also required to pressurize the water to overcome the osmotic pressure. For thermal processes, heat is required to separate freshwater from the seawater (or draw solution in the case of FO) through evaporation.

8.2.1. Membrane Technologies

8.2.1.1. Reverse Osmosis

Reverse osmosis is one of the most widely used and commercially available methods for water desalination worldwide. Since the 1970s, the energy intensity of seawater RO has decreased due to improvements in membranes, integration of energy recovery devices, and high-efficiency pumps.[203] Improvements in pretreatment since the 1980s and 1990s have also increased the energy efficiency of RO.[204] Many references are available for the current energy intensity for RO, providing a range of values between 1.58 $kWh_{T,equiv}/m^3$ for lab-scale demonstration to 7.5 $kWh_{T,equiv}/m^3$ for double pass RO systems.[205] See Table A-3 in Appendix A for full details on the referenced values and full findings from referenced sources on the energy intensity of the desalination unit operation using RO technology and seawater feed.

The energy intensity will depend largely upon the plant specifics, including the effectiveness of the pretreatment process, the recovery, number of passes, energy recovery technologies used, and equipment age.

8.2.1.2. Forward Osmosis

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.

In FO, the freshwater in the pre-treated seawater is pulled across a membrane by a draw solution or an osmotic agent. The external energy requirement to overcome frictional resistance between the two sides of the membrane is 29–44 psi. For comparison, RO pressures can be as high as 1,100 psi.[206] After the freshwater has passed through the membrane, it is combined with the osmotic agent and must be separated through an additional step which requires additional process energy. In this step, the draw solution is separated (regenerated or concentrated) from the freshwater. Draw solution regeneration is done through a thermal process (e.g., thermal stripping) or another membrane separation process (e.g., RO, ED, or MD); both of these processes require additional energy input. This means that the FO process alone cannot produce fresh water; it depends on a secondary desalination method for draw solution regeneration. Even if draw solution regeneration is optimized, the efficiency of an optimal draw regeneration process and other mature direct desalination approaches are unlikely to differ significantly, meaning the energy efficiency of direct desalination, for example, using RO, will be superior.[207]

Little published energy intensity data was found for FO. Similarly, actual data from operating FO desalination plants (e.g., Modern Water's FO desalination plant in Oman) is not readily available. For the FO process only (excluding draw regeneration), the minimum energy requirement is reported to be 2.5 kWh_e/m^3 for feedwater salinity of 35,000 ppm and 50% recovery. The highest value reported is 15 kWh_e/m^3 for a feedwater salinity of ~37,000 ppm and 75% recovery. The sources have also reported RO energy intensities of 3.48 kWh_e/m^3 and 6.5 kWh_e/m^3, respectively, needed for draw solution regeneration. Therefore, energy intensity of a FO process including draw regeneration using RO ranges from 5.98 $kWh_{T,equiv}/m^3$ to 21.5 $kWh_{T,equiv}/m^3$ for feedwater salinities/water recoveries of 35,000 ppm/50% and – 37,000 ppm/75%, respectively.[208]

A critical consideration often not discussed in the literature is the composition of the draw solution. This will impact the energy requirements of draw regeneration and the posttreatment processes required. Moreover, it will dictate whether or not the draw solute can be used for potable water production.

8.2.2. Thermal Technologies

8.2.2.1. Multi-stage Flash

Multi-stage flash distillation is the most commonly applied thermal desalination method in the Middle East.[209] The feedwater goes through several units of MSF processes, known as *stages.* The feedwater is heated with steam in a concentrate heater, where the top concentrate temperature is about 108°C–112°C.[210] The incoming cooler feedwater serves as a coolant and condenses water vapor from the concentrate. The resulting liquid fresh water is then collected and sent to the next stage. The process is shown below in Figure 8-1.

Energy consumption for MSF includes the thermal energy requirement (steam) as well as the electrical energy for water conveyance. Multi-stage flash vessels operate under partial vacuum; therefore, additional electrical energy or steam is required to create the partial vacuum. The pressure of the MSF system's first stage is maintained just below the water saturation vapor pressure, and the pressure drops during each stage to accommodate the system temperature drops. Additionally, non-condensable gases are removed from the last stage. Energy efficiency can be increased by regenerative heating and preheating of the seawater feed to the desalination unit operation with condensed water vapor.[211] The number of stages is equivalent to the recovery of the desalination plant. Increasing the number of stages will lower the energy consumption. A typical MSF unit has 19 to 28 stages, while the latest MSF technology has 45 stages.[212] A gained output ratio (GOR) is a measure of how much thermal energy is consumed to produce a unit of product water. It is the ratio of the mass of water produced to the mass of steam consumed (e.g., a GOR of 10 means that 10 kg of water was produced from 1 kg of steam). The higher the GOR value, the lower the energy consumption of the process because it means that there is higher recovery for a given amount of steam input.[213] The total equivalent energy consumption of the MSF unit ranges between 19.58 and 27.25 $kWh_{T,equiv}/m^3$ for GORs of 8 and 12, respectively.[214]

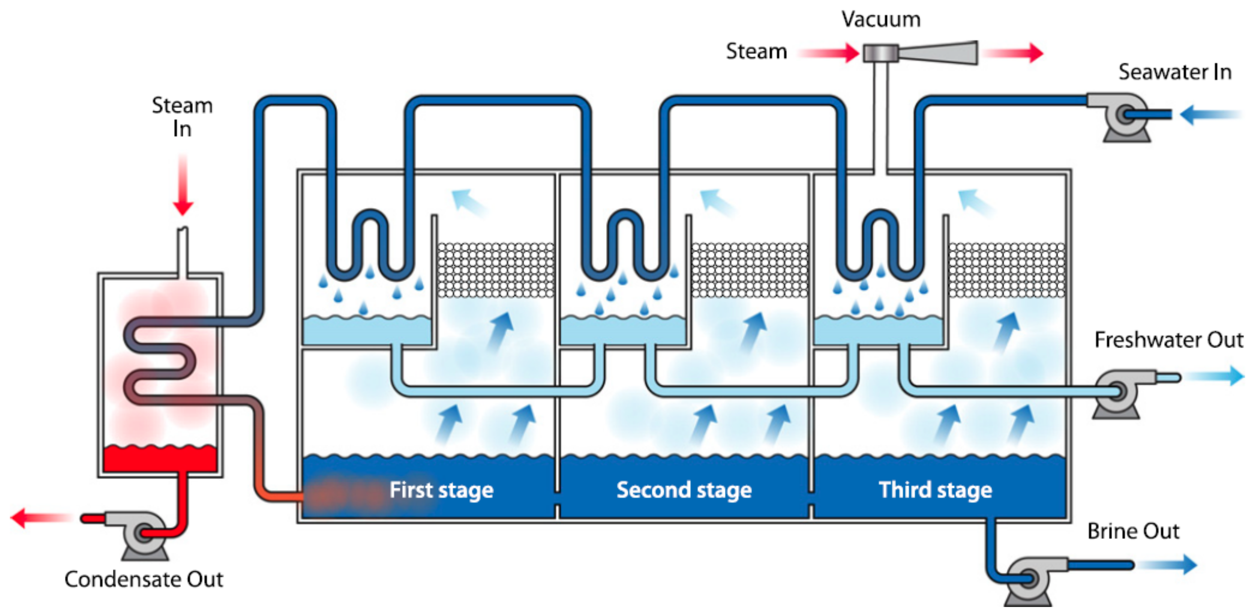


Figure 8-1. MSF Process Diagram[215]

See Table A-4 in Appendix A for full details on the referenced values and full findings from referenced sources on energy intensity of the desalination unit operation using seawater feed and MSF technology.

8.2.2.2. Multi-effect Distillation

Multi-effect distillation uses a series of stages, or effects, to vaporize and condense seawater to produce freshwater. Each successive effect operates at a lower pressure and temperature. Saline feedwater enters the first effect and is evaporated using non-contact steam. The water vapor is collected and used as the heat source to evaporate saline feedwater in the next effect, where the pressure (and boiling point) is lower. The process is repeated through all the effects in the system. A basic diagram of the process is found in Figure 8-2.

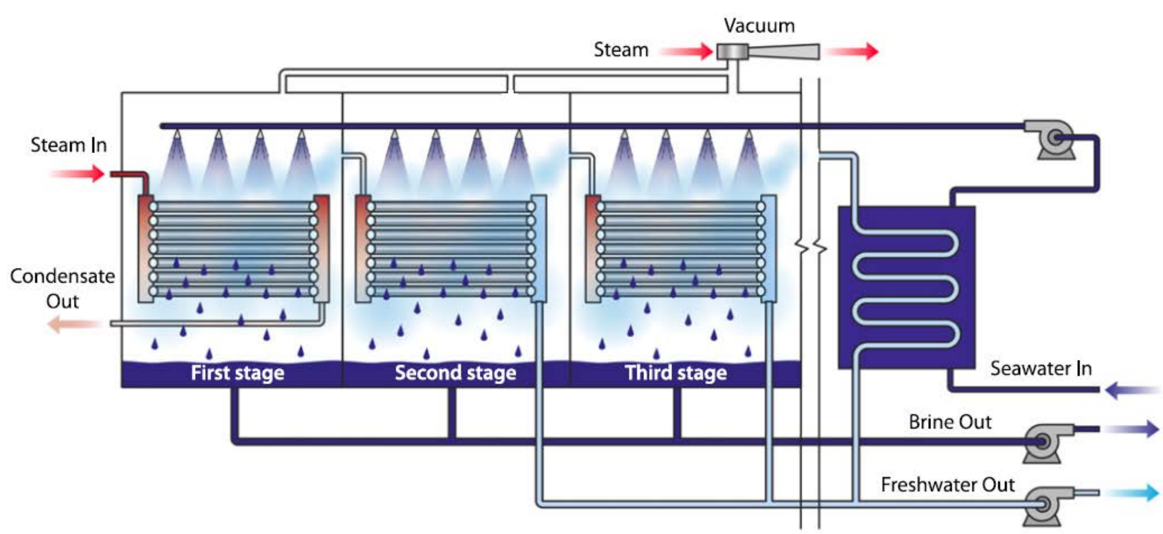


Figure 8-2. MED Process Diagram[216]

Lower-grade steam at temperatures as low as 60°C, can be used as heat input for MED, leading to higher efficiency; this also allows the use of lower-cost heat exchange materials (such as specialty aluminum alloys) which permit more effects and higher GOR at an acceptable capital cost.[217] Electricity is required for pumping to convey water and create the vacuum; however, the pumping power requirements for MED are lower compared to MSF.[218] Minimal pretreatment before the desalination unit operation is required to produce high-quality product water. While MED has previously lagged in unit size and commercial acceptance compared to MSF, two plants were recently built in Saudi Arabia with capacities of 68,200 m^3/day (15 MGD) and 800,000 m^3/day (211 MGD).[219]

The MED process has recently become more popular due to its lower electrical energy consumption and is considered state-of-the-art (SOA) when combined in configuration with thermal vapor compression (TVC)—this is discussed in more detail in Section 8.2.2.3.

Sources report the energy intensity for MED ranges from 5.5 $kWh_{T,equiv}/m^3$ to 22.6 $kWh_{T,equiv}/m^3$ of equivalent electricity.[220] See Table A-5 in Appendix A for full details on the referenced values on seawater MED desalination unit operation energy intensity. The wide range in energy intensities is likely due to waste heat integration, which is commonly recovered at facilities. One author (Ghaffour 2015) reports the energy intensity of MED with the integration of waste heat as 5.5–9 $kWh_{T,equiv}/m^3$.[221]

8.2.2.3. Vapor Compression

Desalination plants using vapor compression rely on the heat generated by the compression of water vapor to evaporate sea or brackish water. Two methods are employed: mechanical vapor compression (MVC) or thermal vapor compression (TVC). The feedwater enters the VC process through a heat exchanger, and vapor is generated in the evaporator and compressed by either mechanical or thermal means. Compressing the vapor raises its temperature by a sufficient amount to serve as the heat source for distillation. The concentrated concentrate is removed from the evaporator vessel by the concentrate recirculating pump. This flow is then split, and a portion is mixed with the incoming feedwater and the remainder is rejected. Figure 8-3 shows both types of VC desalination. Mechanical vapor compression uses electricity to drive the compressor, whereas in TVC, a steam jet creates the lower pressure. These units are usually used in small- and medium-sized applications. Mechanical vapor compression capacity ranges between 100 and 3,000 m^3/day, and TVC capacity ranges between 10,000 and 30,000 m^3/day.[222] When used in a configuration with MED, TVC is able to operate in larger installations (unit sizes approach 76,000 m^3/day).

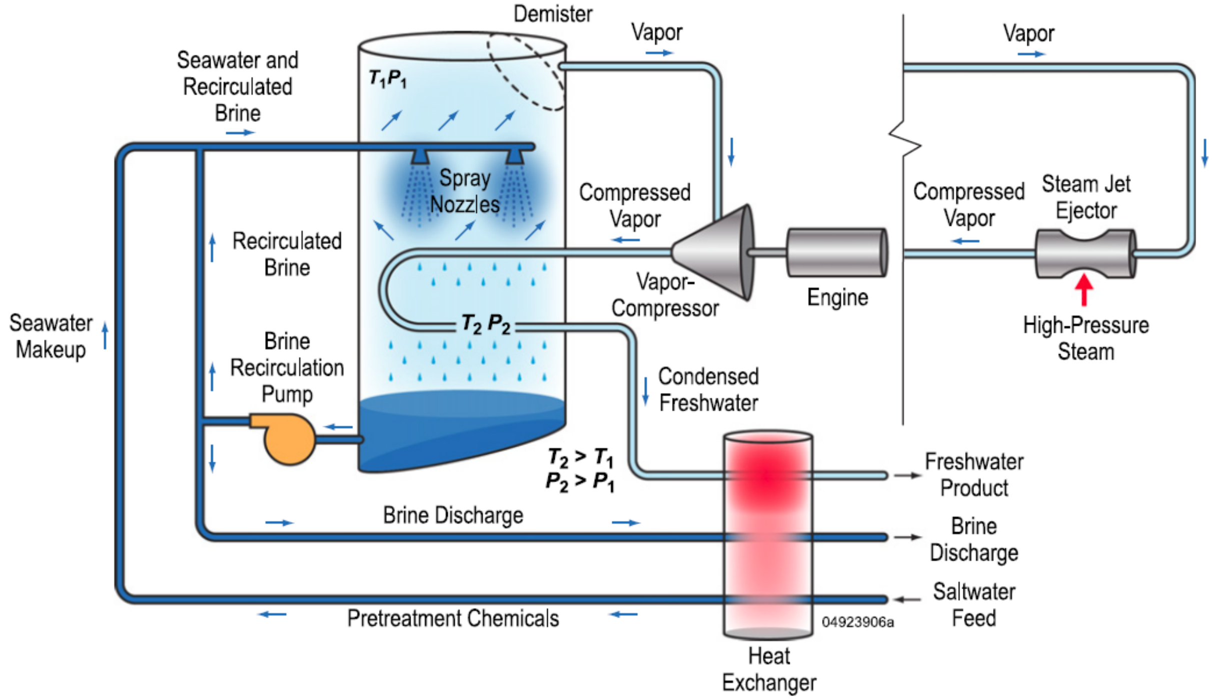


Figure 8-3. Vapor Compression (MVC and TVC) Process Diagram[223]

Thermal vapor compression accounts for less than 10% of desalination plants globally today. It has an energy intensity of about 16.3 $kWh_{T,equiv}/m^3$.[224] Mechanical vapor compression has an energy intensity range between 7 $kWh_{T,equiv}/m^3$ and 17 $kWh_{T,equiv}/m^3$.[225] See Table A-6 in Appendix A for full details on the referenced values on seawater MVC desalination unit operation energy intensity.

8.2.2.4. Humidification-dehumidification

Humidification-dehumidification desalination is a thermal process that utilizes the vapor-carrying capacity of air at an applicable temperature range; the vapor-carrying capacity increases with increasing temperatures.[226] Seawater is fed into the system, where it is passed through a stream of dry air (the humidification step). The air, now carrying water vapor, passes through a heat exchanger where the product water is condensed from the vapor (the dehumidification step).[227] Before the humidification step, it is necessary to heat either the air or the seawater depending upon their starting temperatures. Operating temperature is typically between 50°C and 90°C.[228]

Some of the challenges involved with HDH desalination are the large amounts of evaporation heat required in addition to the pumping energy needed; the large heat transfer area required; and the lower product water quality due to the presence of condensed pollutants.[229] The approach behind the HDH process is actually very old, with the newly commercialized technology based on a revised technique.[230] Because commercialization of HDH desalination technology has been recent (especially in comparison to RO), and there are no large plants in operation, limited published literature sources were found. However, it will be considered more during Phase 2, due to the possibility of thermal energy sources such as waste heat, solar, or geothermal.

8.2.3. Hybrid/Emerging

There are numerous hybrid and emerging seawater desalination technologies that are being developed. Hybrid technologies incorporate a combination of the conventional desalination processes to achieve lower energy intensity, cost, and environmental impacts for the production of potable water. This report focuses on the technologies that are commercially available and that facilities use today (e.g., RO, MSF, MED, and VC). Further research will be conducted on these technologies for potential inclusion in Volume 2. Hybrid and emerging technologies that will be further explored are: MED/TVC; MED or MSF with RO; FO with thermal draw regeneration; NF with RO, MSF, or MED; HDH; and membrane distillation (MD).

8.2.4. Energy Recovery Devices

Energy recovery devices incorporated in a pressure-driven desalination system offer significant energy-reduction improvement opportunities. Energy recovery has the potential of recovering the pressure that would have otherwise been lost in the concentrate stream enabling significant overall energy savings. As more concentrate energy is recovered and reused in the system, lower inputs of electrical energy are required for the desalination system.[231]

Commercially available ERDs have efficiencies (the percent of energy recovered from the concentrate stream) ranging from 55%–95%.[232] More than 60% energy savings can be realized when ERDs are integrated with seawater reverse osmosis.[233] For pumping, the use of pressure exchangers, turbo-chargers, turbine-assisted boost pumps, or another energy recovery technology could reduce energy requirements by 10%–20%.[234] The efficiency of ERDs is dependent on concentrate flow rate and pressure, and will be lower for high water recovery.

Table 8-3 summarizes the energy recovery technologies and type of ERDs commercially available and their range of efficiencies. Each technology has a specific flow, pressure, and energy recovery range. For more information regarding energy recovery, refer to Appendix B.1.3.2.

Table 8-3. Summary of Energy Recovery Devices and Efficiency Ranges[235]

Energy Recovery Technology	Energy Recovery Device (ERD)	Recovery Efficiency*
Hydraulic to mechanical assisted pumping	Pelton Wheel	80%–85%
	Francis Turbine	76%
	Reverse Running Pump	NR
Hydraulically driven pumping in series	Hydraulic Turbocharger	85%
	Pelton Drive Pump	87%
	Hydraulic Pressure Booster	NR
Hydraulically driven pumping in parallel	Pressure Exchanger	> 90%
	Dual Work Exchange Energy Recovery	96%

* *Recovery efficiency* refers to the efficiency of recovering the energy in the concentrate stream and not the input energy into the desalination unit operation.[236]

8.3. Incorporating Renewable Energy

Renewable energy sources such as solar thermal, solar photovoltaic, wind, and geothermal technologies have the potential to reduce the energy cost of desalination systems, as well as their environmental footprint. These renewable resources are now proven technologies and remain economically promising for regions with electric grid or CO_2 emissions constraints. As the technologies continue to improve, fresh water becomes scarce, and fossil fuel energy prices rise, renewable energy desalination will become more economically viable.[237] This section will provide a high-level overview of renewable energy integration with desalination systems. Further analysis will be performed and incorporated into Volume 2.

In 2009, the most commonly paired renewable energy and desalination technologies out of 131 identified installations using renewable sources was photovoltaics with RO, accounting for 31% of the installations. Reverse osmosis powered by wind energy accounted for 12%, solar-powered MED accounted for 9%, and solar-powered MSF accounted for 7%.[238]

Table 8-4 shows the possible applications of renewable energy sources with conventional desalination technologies. Table 8-5 shows examples of capacity and energy intensities for selected combinations. The information in Table 8-5 is based on a survey of 131 plants constructed between 1974 and 2009. Thermal energy technologies such as solar thermal and geothermal tend to combine with thermal desalination processes, while renewable energy technologies such as photovoltaics and wind power tend to pair with desalination processes that require mechanical or electrical power.[239]

Table 8-4. Renewable Energy Sources' Application to Commercial Desalination Technologies[240]

Renewable Energy Source	Type of Energy	Desalination Technology					
		MSF	MED	TVC	MVC	RO	ED
Geothermal	Heat	X	X	X			
	Electricity				X	X	X
Solar PV	Electricity				X	X	X
Solar Thermal	Electricity				X	X	X
	Solar Collector	X	X	X			
Wind	Electricity				X	X	X
	Shaft				X	X	

Table 8-5. Renewable Energy and Desalination Combination Capacity and Energy Intensity[241]

	Desalination Technology			
	Solar Thermal – MED	PV-RO	Wind-RO	Wind - MVC
Typical Capacity	> 5,000 m^3/day	< 100 m^3/day	50–2,000 m^3/day	< 100 m^3/day
Energy Intensity	Thermal*: 33 $kWh_{e,equiv}/m^3$ Electrical: 1.5 kWh_e/m^3	Electrical: 4–5 kWh_e/m^3	Electrical: 4–5 kWh_e/m^3	Electrical: 11–14 kWh_e/m^3

*Value in reference assumed to be thermal and converted to electrical equivalent here

8.3.1. Thermal Desalination Processes

8.3.1.1. Solar Thermal Energy

Low-grade (< 90ºC) and high-grade (> 90ºC) solar thermal energy can be coupled with various desalination technologies. Solar stills, solar multi-effect humidification (MEH), and solar membrane distillation are examples of low-grade solar thermal utilization. Using concentrating solar power (CSP) such as parabolic troughs, Frensel mirror reflector, power tower, and dish engine in combination with RO, MSF, and MED are examples of utilizing high-grade solar thermal energy.

A direct application of low-grade solar thermal in a desalination facility is through a solar still. A solar still consists of a shallow basin covered by a transparent roof acting as a condenser. Solar radiation is trapped in the still, causing the water to evaporate.[242] Solar stills have many limiting factors, such as low energy efficiency, low recovery, intermittent water production, high costs and footprints, and small total capacities of less than 0.1 m^3 per day.[243] Another direct application of low-grade solar thermal energy is through solar MEH. Solar MEH consists of a solar-powered evaporator where air is humidified and a condenser where distilled water is recovered. The process occurs under atmospheric conditions by an air loop saturated with water vapor.[244]

The primary aim of CSP technologies (high-grade solar thermal energy) is to generate electricity; however, a number of configurations enable CSP to be combined with various desalination methods. The parabolic trough system has been cited as a leading candidate for CSP/desalination coupling, and two types of desalination technologies, MED and RO using steam-powered pumps, have been cited as the leading candidates for CSP coupling.[245]

8.3.1.2. Geothermal Energy

Geothermal systems can provide a stable and reliable source of electricity and heat for thermal and membrane desalination technologies. Geothermal energy is continuous and predictable, making thermal storage unnecessary.[246]

Geothermal reservoirs are generally classified as being either low temperature (< 150°C) or high temperature (> 150°C). High-temperature reservoirs are the most sought for commercial electricity production, and these can be used to power RO, ED, and MVC plants. The direct use of moderate and high temperatures is suitable for thermal desalination technologies. In addition, a high-pressure geothermal source allows the direct use of shaft power on mechanically driven desalination.[247]

8.3.2. Electromechanical Desalination Processes

Electricity generated through solar photovoltaic (PV) cells or wind turbines can provide a direct energy source for RO operations. The disadvantages to PV-powered desalination plants are the high cost and the low capacity factor of PV cells.[248] A set of batteries may be incorporated for stand-alone operations to ensure continuous runtime.[249] Wind-powered RO systems are more suitable for islands and exposed coasts, as wind energy is more predictive in those sites compared to inland sites.[250] Even though wind energy can be scaled more easily than PV energy, there are few existing examples of wind energy coupled with desalination due to the economic challenges.

8.4. Other Relevant Considerations from Framework

Table 8-6 provides a list of chemicals that are added primarily for RO membrane cleaning during the desalination process.

Table 8-6. Chemicals Added for Seawater Desalination[251]

Chemical Added	Purpose
Citric acid	Cleaning of RO membrane
Detergents (type not specified)	Cleaning of RO membrane
Caustic soda	Cleaning of RO membrane; enhanced boron removal
Biocides	Cleaning of RO membrane
Alkaline cleaning solutions (pH 11–13)	Cleaning of RO membrane
Acidified solutions (pH 1–3)	Cleaning of RO membrane
Oxidants	Cleaning of RO membrane
Complexing agents	Cleaning of RO membrane

Table 8-7 lists characteristics of RO, MSF, MED, and MVC technologies that can affect the system's energy intensity.

Table 8-7. Characteristics of Seawater Desalination Technologies[252]

Performance Factor	Reverse Osmosis	Multi-Stage Flash	Multi-Effect Distillation	Mechanical Vapor Compression
Operating Pressure	55–80 bar	See below	See below	0.3 bar
Steam Pressure	-	2.5–3.5 bar	0.2–0.4 bar	-
Top Concentrate Temperature	-	90ºC –120ºC	60ºC –70ºC	-
GOR Value	-	4–12	3–15	20–40
Recovery	35%–50%*	25%–50%	0%–65%	~50 %
Lifetime	25–30 years	20 years	20 years	20 years

9.0. Post-treatment Energy Intensity

After the desalination unit operation, the water is corrosive due to its purity and low pH, and it must be treated and stabilized prior to water system integration to meet transport and drinking water specifications. For the seawater desalination plants in the United States, the post-treatment unit operation involves the addition of conditioning chemicals (e.g., limestone, fluoride), as well as disinfection to ensure that the product water is acceptable for drinking. Figure 9-1 shows the post-treatment steps (including remineralization, disinfection, and fluoridation before the water is distributed) at the seawater desalination plant in Carlsbad, California.

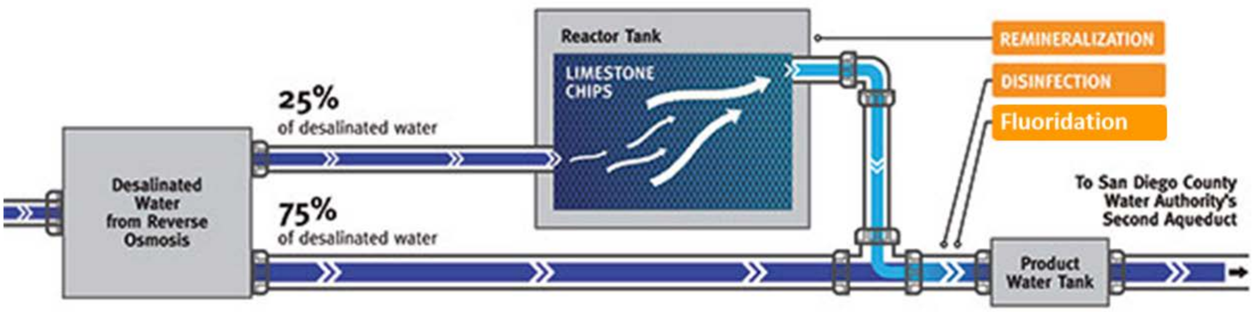


Figure 9-1. Post-treatment at the Carlsbad, California, Seawater Desalination Plant[253]

9.1. Energy Requirements for Seawater Post-treatment

The low-salt-content water leaving the desalination unit operation is referred to as the "permeate" for a membrane process or simply "product water." The primary use of energy in post-treatment involves pumping the product water through pipes and process equipment. For remineralization, this can involve elevating the water to allow it to trickle down through a limestone reactor tank, or moving it through a lime slaking system.[254] Desalination processes may require multiple post-treatment systems depending on the intended use of the water, which will contribute to variations in the reported energy intensity. This can include treatments to reduce corrosiveness (which can damage pipes in water distribution systems), adjust pH and CO_2 content (to ensure scaling prevention), and disinfect the water if it is intended for consumption.[255] To reduce boron and chloride to acceptable levels, part or all of the product water may also go through one or more RO passes, adding to the total energy consumption.[256] Post-treatment of the product water can result in total energy requirements of 0.07 $kWh_{T,equiv}/m^3$.[257] Post-treatment energy expenditures can range between 2% and 13% of the total requirement for a seawater desalination plant.[258]

Table 9-1 provides a summary of the findings on energy intensity for the post-treatment unit operation. Energy requirements are reported as found in the literature; further analysis on these values will be conducted during Phase 2. See Table A-7 in Appendix A for full details on the referenced values and full findings from referenced sources on post-treatment energy intensity.

Table 9-1. Seawater Desalination Post-Treatment Energy Intensity Summary

Technology	Reported Range	
	Low Energy Intensity	High Energy Intensity
	Total[a] ($kWh_{T,equiv}/m^3$)	Total[a] ($kWh_{T,equiv}/m^3$)
Remineralization[259]	0.04	0.07
Boron Removal[260]	0.08	0.42
Disinfection[261]	0.044	0.072

[a] Energy consumption for post-treatment processes is electric only; there is no thermal energy consumption.
Remineralization: Lime and carbon dioxide post-treatment for a demonstration plant (with a study scaling up to 50 million gallons per day).
Disinfection: From a study in Northern and Central Coast of California.

9.2. Description of Technology or Process Energy Use

9.2.1. Remineralization

The product water has a low amount of TDS, making the water corrosive. To meet the requirements for drinking water, this water must undergo remineralization.[262] Remineralization reintroduces or supplements the product water with certain levels of minerals, including calcium, magnesium, zinc, copper, chromium, manganese, and potassium.[263] The remineralization processes includes either direct addition of calcium-containing chemicals (e.g., lime) and magnesium, addition of calcium and magnesium through dissolution of limestone and dolomite, or mixing with the source water or other fresh water sources (blending).

The most common remineralization method is to dissolve limestone into the desalinated water (which must first be acidified with CO_2).[264] This is the process used in the Carlsbad, California, plant (shown in Figure 9-1). Energy consumption in this process is mainly for pumping the product water to a height to allow it to flow through the limestone reactor tank (typically 30 feet, or 10 meters).[265] An alternative method is to use hydrated (or slaked) lime instead of limestone; a small amount of energy is required for lime slaking.[266]

Carbon dioxide with the excess lime is used to add alkalinity to the product water. It can stabilize the product water (i.e., make it non-corrosive). The aggressive water can obtain a more positive Langelier saturation index (LSI), which is a corrosion potential index. Another method of determining product water stability is the calcium carbonate precipitation potential (CCPP), which is a measure of calcium carbonate deficit or excess in the product water. However, calculating the CCPP is more complicated than LSI, and can only be done through iterative computer permutations rather than with an analytical equation.[267] Calcium carbonate adjustment could be used to combat this corrosion potential. The mechanism for this corrosion control is the deposition of calcium carbonate onto the pipe walls conveying the desalinated water.[268]

In 2008, the Affordable Desalination Collaboration used a lime and CO_2 post-treatment method at its test facility in Port Hueneme, California. Based on the testing, the energy intensity was 0.07 $kWh_{T,equiv}/m^3$, and projected energy intensity for larger facilities of 10 - 50 million gallons per day could be reduced to 0.04 $kWh_{T,equiv}/m^3$.[269]

Blending incorporates the product water with other sources that can contribute minerals to the final product water. The source for the blending water depends on the natural minerals present in the product water and the finished water product requirements. When product water is blended with small levels of seawater, minerals such as sodium, potassium, calcium, and magnesium are added to meet drinking water standards. Seawater as a source for blending with product water is limited, as it can affect the corrosiveness and taste if more than 1% is used.[270] The product water becomes stabilized after blending. Blending is not recommended if the product is drinking water, as there is little control over the final water quality.[271] If blending is used, distillation process water out (product water) is blended with finished water usually with a bypass stream during the desalination process.[272]

9.2.2. Disinfection

Disinfection of desalination unit operation water is required in order to protect the eventual consumers of the drinking water from contamination that may be introduced when it is distributed, stored, or further treated.[273] It prevents bacteria growth in the water distribution system. Typically disinfection involves the addition of chlorine (generally the least expensive method), though other methods include on-site sodium hypochlorite generation or treatment with bulk hypochlorite.[274]

9.2.3. Boron and Chloride Removal

There are specific requirements on boron and chloride content in potable water that poses a separation problem in desalination systems, as there is limited rejection of these chemicals during the desalination process. The WHO guideline for boron content for safe drinking water is 2.4 ppm.[275] To remove boron from the product water, parts of the water go through one or more RO passes, which adds energy consumption to the entire system. The boron rejection rate will depend on various parameters including pH, temperature, and salt concentration.[276] Boron removal processes can include: SWRO then brackish water reverse osmosis (BWRO); SWRO with boron selective ion exchange resin (BSR); SWRO with a hybrid BSR/BWRO process; SWRO with electrodialysis reversal (EDR); and single-pass SWRO with high rejection boron membranes.[277]

10.0. Concentrate Management and Disposal Energy Intensity

Desalination plants create discharge containing the various unit operations' by-products, the pretreatment filter backwash water, and membrane cleaning solutions. Concentrate is the largest by-product of the plant and the greatest challenge in management and disposal.[278] The concentrate produced by seawater desalination can be 1.5 to 2 times higher in salinity than standard seawater, which may lead to harmful effects in marine environments if proper concentrate management is not used.[279] The high saline concentrate needs to be properly disposed while maintaining the environmental and health standards regulated by federal and state agencies.

Seawater desalination concentrate disposal can fall into five different categories: surface water disposal, sewer disposal, deep well injections, evaporation ponds, and land application.[280] However, no references of seawater desalination facilities using these disposal options were found; instead, surface water disposal, especially disposal to the sea, is the most common and low-cost method for concentrate discharge. A permit is required to use this disposal method, and generally, concentrate is no longer disposed into inland surface water. Several states forbid disposal in certain surface water sites for environmental and safety concerns.

Zero-liquid discharge is a more recent concentrate management method to recover more water from the concentrate and lower the amount of liquid waste that causes damage to aquatic environments.[281] These systems evaporate the concentrate, produce distilled water, and dispose the salt slurry.[282] Zero-liquid discharge includes concentrators and vapor compression crystallizers,[283] and is an expensive and energy-intensive process more likely to be used in brackish water desalination. Zero-liquid discharge can be used in seawater desalination if salt recovery is desired and economical.

10.1. Energy Requirements for Concentrate Management

Table 10-1 provides a summary of the findings on energy intensity for the concentrate management and disposal unit operation. Energy requirements are reported as found in the literature; further analysis on these values will be conducted during Phase 2. Energy requirements for surface water discharge are rarely reported. However, reported energy requirements for other methods (concentration and crystallization) are much higher. See Table A-8 in Appendix A for full details on the referenced values and full findings from referenced sources on post-treatment energy intensity.

Table 10-1. Seawater Desalination Concentrate Management Energy Intensity Summary

Technology	Reported Range	
	Low Energy Intensity	High Energy Intensity
	Total[a] ($kWh_{T,equiv}/m^3$)	Total[a] ($kWh_{T,equiv}/m^3$)
Surface Water Discharge[284]	0.035[b]	0.105[b]
Concentrators[285]	15[c]	26.4[d]
Crystallizers[286]	50[d]	70[d]

[a] Additional research will be conducted to identify thermal energy requirements for concentrate management technologies, particularly for brine concentrators.
[b] kWh/m^3 concentrate pumped will be dependent on distance and elevation of the discharge location.
[c] kWh/m^3 processed concentrate
[d] kWh/m^3 feed concentrate

10.2. Description of Technology or Process Energy Use

10.2.1. Surface Water Discharge

Surface water discharge is the most common disposal practice for U.S. seawater desalination plants, as it requires a low amount of energy compared to alternatives. All except one U.S. seawater desalination plant employ this practice. Newer desalination plants use cooling water from nearby power plants or wastewater treatment plants to dilute the concentrate before it is discharged. The cooling water or effluent is able to account for several receiving disposal areas, as some seawater does not have enough kinetic energy to provide sufficient mixing and dispersion of the concentrate.[287]

As noted, there are few published surface water discharge energy intensities. The energy required is to mix cooling tower water, seawater, or wastewater before it is pumped back into the ocean.

10.2.2. Zero Liquid Discharge

Brine concentrators and crystallizers are often combined into a single system where the slurry from the concentrator is fed to the crystallizer. This single system is referred to as zero liquid discharge. The ZLD disposal methods are not as common, due to the high energy consumption and associated significant greenhouse gas emissions. However, ZLD eliminates liquid waste, reducing aquatic environment damage compared to conventional disposal methods.[288] Zero liquid discharge also offers the potential to provide an additional revenue stream if a market can be found for the concentrated salts.

10.2.2.1. Concentrators

Concentrators reduce the volume rejected from the desalination unit operation and recover parts of the waste as distilled water. The volume of concentrate can be reduced to about 2% of the feedwater flow. The concentration process uses heat exchangers, deaerators, and vapor compression to convert the liquid concentrate to concentrated slurry. About 95% of the concentrate can be recovered as high-purity distillate, with less than 10 ppm of TDS concentration.

Mechanical vapor compression concentrators are energy intensive. The electrical energy requirements are typically 20 to 25 $kWh_{T,equiv}/m^3$, with even higher energy intensities reported as well. They can reach salinity concentrations of 250,000 ppm with a water recovery of 90%–98% as well as produce product water with TDS levels lower than 10 ppm.[289]

10.2.2.2. Crystallizers

Crystallizer technology reduces concentrate or concentrate slurry into a transportable solid through forced circulation evaporation.[290] The concentrate is fed into the crystallizer and joins recirculating concentrate. The feed is pumped to a heat exchanger where the waste is heated by a vapor compressor. The recirculating concentrate enters the crystallizer vapor body at an angle and swirls in a vortex. As small amounts of concentrate and water evaporate, crystals begin to form. The system creates highly soluble salts and distilled water that is then fed back to the desalination feed or exit stream.[291] A crystallizer reduces the slurry to a wet cake that can easily be disposed of; this is the only waste steam from the crystallizer system.[292]

Energy consumption can be nearly three times more than that of concentrators, as crystallizers treat feed brines with much higher salinity and viscosity. [293] Energy intensities can range from 50 to 70 $kWh_{T,equiv}/m^3$.[294]

11.0. Desalination System Techno-Economic Analysis

This section outlines a methodology to determine the unit production cost (UPC) of the potable water leaving the desalination system and at suitable conditions for water system integration. The approach presented here for calculating the UPC of potable water is identical to the approach used in the literature for determining the levelized cost of electricity (LCOE). Therefore, UPC can also be referred to as levelized cost of water (LCOW), which is reported in dollars per cubic meter of potable water ($\$/m^3$).

Cost categories to determine LCOW are: fixed cost (FC), variable cost (VC), and energy cost (EC). These three cost categories are consistent with the economic characteristics of each unit operation of the desalination process introduced in the boundary analysis framework. Section 4.0 of this report provides a detailed breakdown of these cost categories and their relative importance for each unit operation. Table 11-1 provides an overview of these three main categories.

Table 11-1. Three Main Cost Categories for Determining the LCOW

Cost Category	Units	Definition
Fixed Cost (FC)	$\$/m^3/day$	Capital expenditure for permitting, plant construction, equipment purchase, and cost of capital amortization (interest payments). FC is reported as dollars per plant capacity in cubic meters per day.
Variable Cost (VC)	$\$/m^3$	Cost of labor, chemicals, maintenance, and equipment replacement. VC is reported in dollars per volume of water produced in cubic meters.
Energy Cost (EC)	$/kWh	Also referred to as *fuel cost,* it is the cost of purchased energy from outside of the plant boundaries to run the desalination system. Depending on the source of energy, this could be the cost of purchased electricity, steam, or fuel (i.e., natural gas). EC is typically reported in dollars per energy consumed in kilowatt-hours. Knowing the energy intensity of the desalination process (kWh/m^3), this number can be converted to the same units as VC.

Economies of scale also play a role in determining the LCOW. Data from available capital cost databases indicates that FC per unit of water produced decreases as the plant size increases. Figure 11-1 shows the capital cost for different desalination technologies and plant capacities. It can be seen that the data points found in the literature follow a power law relation (the dotted lines), and the cost decreases with increasing capacity. Larger plants can also run more efficiently; therefore, requiring lower energy per unit of water produced, which results in lower EC. Lower FC and EC for larger plants leads to a lower LCOW.

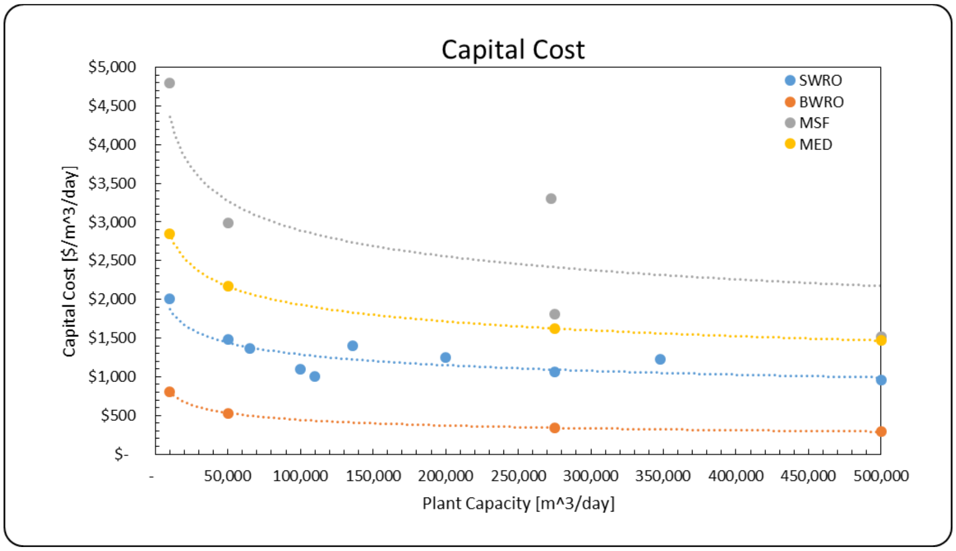


Figure 11-1. Capital Cost for Different Desalination Technologies and Plant Capacities[295]

In addition to the three main cost categories introduced in Table 11-1, parameters summarized in Table 11-2 are also used to determine a realistic LCOW.

Table 11-2. LCOW Calculation Parameters

Cost Parameter	Unit	Description
Plant Capacity (PC)	m^3/day	PC is the maximum designed freshwater output of the desalination plant. Plant capacity is reported in volume of potable water produced per day (365 days/year).
Capacity Factor (CF)	%	CF indicates the fraction of the time during which the plant is operating and producing potable water.
Fuel Escalation (FE)	%	FE accounts for energy source cost increases that occur above the inflation rate.
Degradation Factor (DF)	%	DF is the annual decline in maximum plant's capacity.
Plant lifetime (t)	years	t is the number of years during which the plant can operate economically compared to alternatives. Plants older than the year "t" are assumed to be retired.
Interest or discount rate (r)	%	r is the rate at which the capital has been borrowed to pay for plant's fixed costs.

Equation 8 uses the parameters in Table 11-1 and Table 11-2 to calculate the LCOW. The LCOW that is calculated by Equation 8 is simply the price ($/m^3) at which the product water needs to be sold for the project to break even by the end of its lifetime (t).

$$LCOW = \frac{FC \times PC + \sum \frac{[FC \times (1+FE) + VC \times PC \times (1-DF)^t]}{(1+r)^t}}{\sum \frac{[PC \times CF \times 365 \times (1-DF)]^t}{(1+r)^t}}$$

Equation 8: Levelized cost of water as a function of the parameters listed in Table 11-1 and Table 11-2

Through further data collection on desalination costs, the LCOW for various desalination system configurations will be calculated using the methodology prescribed above as part of the ongoing research effort.

12.0. Brackish Water Desalination Summary

Both phases of this study focus on seawater desalination to provide drinking water. However, brackish water desalination will also be considered. Highlighted here are notable differences and additional considerations when evaluating brackish water desalination systems compared to seawater desalination systems.

12.1. Brackish Water Desalination Overview and Comparison to Seawater Desalination

The discussion on the thermodynamic minimum in Chapter 3 applies to brackish water as well. Figure 3-1 shows the difference in minimum energy requirement for separation of pure water from seawater at 35,000 ppm TDS and from brackish water at 25,000 ppm TDS using a reversible process as a function of percent recovery. For 50% recovery, the minimum energy requirement for brackish water at 25,000 ppm TDS is about 0.7 kWh/m^3 and about 1 kWh/m^3 for seawater. It should be noted, however, that brackish water systems can achieve higher percent recoveries (around 75%–80%) due to lower concentrate production and pressure requirements resulting from the lower TDS in the feed.

Table 12-1 provides a summary of the best available and most representative options for the five desalination unit operations for a brackish water desalination system. Reverse osmosis is a commonly used desalination process for brackish water desalination due to its low energy requirements. The lower energy consumption is attributable to the lower salinity reducing the osmotic pressure of the feedwater leading to lower operating pressures. Other differences compared to a seawater desalination system include the concentrate management unit operation. Where surface water discharge would typically be used for a seawater desalination system, in a brackish desalination system that option is usually not available because most brackish water desalination plants are inland with little access to coastal areas. Brackish water plants that typically use wells for intake usually use deep well injection for the disposal as well. Other methods can include sewer disposal and evaporation ponds. These methods are of higher cost and energy consumption compared to surface water disposal for seawater desalination. However, brackish water desalination will generally produce less concentrate than seawater desalination due to the lower salinity of the feedwater, and will operate at much higher recovery ratios to maximize the product water output and reduce the volume of concentrate for disposal.

Table 12-1. Brackish Water Desalination System Energy Intensity Summary

Unit Operation	Process	Low Energy Intensity	High Energy Intensity
		Electric (kWh$_{T,equiv}$/m^3)	Electric (kWh$_{T,equiv}$/m^3)
Intake	Sub-Surface Intake	Information Unavailable	Information Unavailable
Pre-treatment	Cartridge Filtration[296]	0.0425	0.122
Desalination	Reverse Osmosis[297]	0.3	3
	Electrodialysis and Electrodialysis Reversal[298]	0.5	1.8
	Nanofiltration[299]	<1	
Post-treatment	Chlorination	Information Unavailable	Information Unavailable
	Boron Removal[300]	0.07	
	Remineralization	Information Unavailable	Information Unavailable
Concentrate Management	Deep Well Injection	Information Unavailable	Information Unavailable

12.2. Intake

Over 80% of brackish water desalination plants in the United States use subsurface intake systems from wells. The water is typically from a deep, confined aquifer with low to medium salinity (600 to 3,000 ppm) and is usually not connected to a surface water source. Vertical wells in particular are the most common method of subsurface intake for brackish water.[301]

Extraction of water from underground aquifers primarily requires energy for pumping. The amount of energy consumed in raising well water depends on the location of the water source relative to the location of discharge and also on the frictional resistance to flow. Energy consumption by groundwater pumps in California has been reported to range between 0.24 and 0.76 kWh$_{T,equiv}$/m^3.[302] Intake pumping for RO treatment plants can require 0.05 to 1 kWh$_{T,equiv}$/m^{3}of electrical energy.[303]

Surface water options for brackish water desalination include rivers, lakes, reservoirs, streams, and estuaries. These sources are located in coastal areas but have a lower salinity than seawater. Further, their salinity is not constant and changes with the tides (lower salinities during low tide) and seasonally (highest in winter).

12.3. Pre-Treatment

Brackish water desalination systems that treat groundwater use minimal pretreatment to remove particulates. Brackish groundwater has low concentrations of suspended solids and organic matter, but would still need to remove or prevent precipitation of dissolved constituents such as dissolved iron, sulfides, manganese, and sparingly soluble salts. If these components are left in the system, they can create particulates that can foul the RO membranes.[304] Brackish water from wells can be directly pumped to the RO unit through a cartridge filter after dosing with antiscalant.[305] Filtration protects the membrane from large debris, while the addition of pre-treatment chemicals controls scaling and fouling.[306] More information on brackish water pretreatment processes can be found in Appendix B (Section B.2.1.).

12.4. Brackish Water Desalination Processes

Brackish water is typically desalinated using membrane technologies such as reverse osmosis, nanofiltration, electrodialysis, or electrodialysis reversal. Thermal technologies are used primarily for seawater desalination and rarely discussed for brackish water desalination.[307] Membrane-based desalination technologies are more advantageous for brackish water desalination over thermal technologies, due to the lower energy consumption at low salt concentration.[308] A brief description of energy intensity of brackish water RO is found below; please refer to Appendix B (Section B.2.2.) for more information describing the brackish water desalination processes including NF and ED/EDR.

12.4.1. Brackish Water Reverse Osmosis

For BWRO, energy intensity is comparatively lower than seawater RO because the energy required for the desalination is proportional to the feedwater salinity.[309] The lower salinity levels in brackish water reduce the osmotic pressure of the feedwater, which then reduces the operating pressure of the BWRO plant. Brackish water RO uses feed pressures ranging from 145 to 218 psi, while SWRO uses feed pressures as high as 1,200 psi.[310] According to Fritzman, Löwenberg, Wintgens, and Melin (2007), the product water recovery is limited by risks of scale precipitation, but generally range from 75%–80%.[311]

12.4.2. Electrodialysis and Electrodialysis Reversal

Electrodialysis is an electrochemical separation process that operates at atmospheric pressure and uses direct electrical current to move salt ions selectively through a membrane, leaving fresh water behind. A schematic of an ED unit is shown in Figure 12-1.

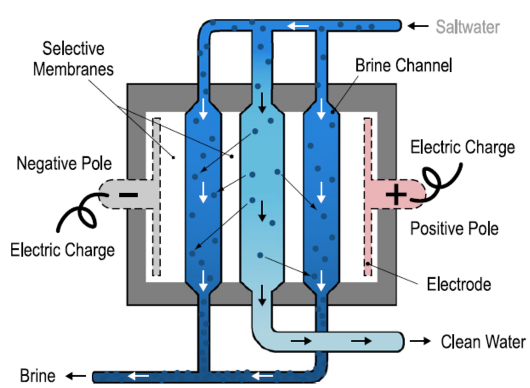


Figure 12-1. Schematic Diagram of an ED Unit[312]

In an ED system, cation and anion-selective membranes are placed in parallel to form channels. When brackish water flows between these channels and the electrodes placed around the ED vessel are charged, positive salt ions travel through the cation-permeable membrane toward negative electrodes, and negative salt ions travel through the anion-permeable membrane to the positive electrode, which results in the removal of salinity from the water. This creates alternating channels — a concentrated channel for the concentrate and a diluted channel for the product water. An ED plant's typical capacity can be as high as 145,000 m^3/day.[313] The cost of ED increases significantly with salinity and is typically not used in seawater processes.[314] Energy consumption for brackish water ED has been reported to be between 0.5 $kWh_{T,equiv}/m^3$ and 1.8 $kWh_{T,equiv}/m^3$ (75% recover with feedwater salinity ranging from 1,000 to 5,000 ppm).[315]

Over time, precipitant can build up on the concentrate sides of the ED membranes. In EDR, the polarity of the electrodes is switched periodically to prevent the buildup of precipitant on the membranes. This polarity reversal increases the life of the electrodes and helps to clean the membranes.

12.4.3. Nanofiltration

Nanofiltration is a membrane-based technology that uses membranes with a looser barrier layer than that of RO, but it will reject high molecular weight species and multivalent ions. Particulates will still be removed since there are no distinct pores as there are in microfiltration and ultrafiltration membranes. Nanofiltration operates with a hydraulic driving force of 50–250 psi and was originally intended for water softening and removal of organics. It is usually used on low TDS water with the intention of removing some of the hardness and/or removal of color due to large organic compounds. Recoveries of 80%–85% are common for a NF system.[316]

Nanofiltration can be part of a composite system for purification (e.g., as part of the pretreatment unit operation);[317] however, in a pilot project operated by the Long Beach Water Department, a two-stage NF process has been used to generate high-quality drinking water from seawater.[318] The two-pass NF system is able to remove 99.5% of the salinity and can provide greater flexibility than other systems. The second pass can reject boron at a higher rate. The recovery for this process is 30%–40%, which is low in comparison to recovery for RO desalination; however energy consumption is much lower, and energy recovery is possible with recovery devices.[319] Nanofiltration energy consumption has been reported as less than 1 $kWh_{T,equiv}/m^3$ (recovery rate, feedwater/product water salinity, and flow rate not provided in reference).[320]

12.4.4. Energy Recovery Devices

For RO brackish water desalination, energy recovery devices have reduced energy demand and are finding greater use in balancing hydraulic and pressure balance between stages. Brackish water desalination plants use the same devices for energy recovery (such as pressure exchangers and turbine systems) as the seawater desalination plants do.

12.5. Post-Treatment

Degasification or decarbonation, stripping, scrubbing, corrosion control, and disinfection are common post-treatment operations used for brackish water desalination. Additional information regarding brackish water post-treatment can be found in Appendix B (Section B.2.3).

12.6. Concentrate Management

Disposal options for brackish water desalination plants are limited and associated with high costs and environmental damage. Direct disposal into surface water or the sea or mixing with a wastewater plant's effluent prior to disposal into surface water are the desired methods for brackish water plants due to the low cost. Brackish water desalination often occurs inland, which would require large amounts of piping to transport the concentrate directly to the sea.[321] Other disposal options, when disposal to the sea is not available, can be discharge to a river or reservoir, sewage discharge, evaporation ponds, or deep well injection (below active aquifers).[322] Zero liquid discharge is the most environmentally friendly option, as the concentrate is processed to produce more desalinated water and dry salts, but the high cost and energy-intensive nature of the process make ZLD less favorable for brackish water desalination plants.[323] More information regarding brackish water concentrate management and disposal options can be found in Appendix B (Section B.2.4).

Discharging the concentrate to a sanitary sewer is the predominant method for concentrate management for small brackish water desalination plants. It is only suitable for small volumes of concentrate because of the high TDS content of the concentrate. The concentrate water quality is compliant with the typical requirements for discharging into a sewer, therefore no specific concentrate pretreatment is needed.[324] Mixing concentrate with reuse water has been done with careful attention to the total salinity. In this case, the concentrate can become a revenue stream for the facility.

All sizes of brackish water desalination plants can use deep well injection. Deep well injection takes the concentrate and injects it into a confined, deep underground aquifer that is separated from the brackish water aquifer above it. The depth of the wells can vary from 500 to 1,500 meters.[325]

The sole energy requirement for evaporation ponds is to pump the concentrate to the pond.[326] However, concentrators, which are often paired with evaporation ponds for ZLD, are estimated to have an energy consumption of 22.5 to 35.6 $kWh_{T,equiv}/m^3$ of concentrate treated.[327]

A BWRO brackish water desalination facility in Tracy, California, utilizes a concentrator to evaporate the produced concentrate, concentrating it by 97% to return drinking water back to the facility; the remaining concentrate is then sent to an evaporation pond. As noted in Section 10.2.2, this type of concentrator is energy intensive; for this particular facility the energy intensity for the unit (which utilizes a mechanical vapor recompression system) is 21 $kWh_{T,equiv}/m^3$ concentrate.[328]

13.0. Scenarios

Phase 2 of this research will determine the thermodynamic minimum, practical minimum, state-of-the-art, and current typical energy intensities for various desalination system configurations. These values will be presented in units of energy consumed per volume of potable water produced, which measures energy productivity and is useful to understand and compare desalination system efficiencies. However, it does not convey impact if used alone. To predict energy consumption, CO_2 emissions, and water and energy grid integration impacts, the energy intensity metrics will be applied to various desalination uptake scenarios in the United States.

13.1. Regional Characteristics

Various characteristics of the region proposed to be served with desalinated water will be considered when identifying uptake scenarios. These include geography, water stress, energy infrastructure, air emissions, water costs, and purpose for desalination. Each is described in further detail below.

13.1.1. Geography

Desalination systems serving populations closer to the source of saline water will consume less energy for conveyance of intake water and concentrate. Not only should distance between water source and the population center be considered, but also topology should be evaluated. Pumping over elevations will increase pumping energy consumption. Geographic location will determine the best option for concentrate disposal—injection into the ground, conveyance to the sea, disposal as solids, or some other option. As a result, for brackish water desalination facilities, geography is a significant driver for system design, total cost of water, and siting. Also, the protection of the marine ecosystems impacted by the desalination plants' intake and outfall will influence plant siting and design considerations.

13.1.2. Water Stress (existing or projected)

Regions that are water stressed (e.g., southwestern United States and California) will require additional water capacity to ensure resiliency. These regions are more likely to have implemented water efficiency and conservation strategies, although more savings may be realized through further efforts such as greater water reuse. Incorporating saline water supplies may be necessary for these regions to ensure a sufficient and resilient water supply. A region may become water stressed due to prolonged droughts, overuse or contamination of existing water supplies, or population growth that will be unsupported by existing water availability.

13.1.3. Energy Infrastructure

Large-scale desalination plants will require an energy infrastructure to support them. If the regional electric grid cannot provide enough power for an RO plant, additional or alternate electricity generation will have to be considered. Furthermore, the ability to balance the electric grid or provide ancillary services will improve the cost justifications for the plant. For example, desalination offers the flexibility to store energy as water (e.g., through elevated storage). This provides a potential solution to grid balancing and renewable energy intermittency. Finally, co-location—where a thermoelectric power plant and the desalination facility share infrastructure such as seawater intake—offers opportunities for reductions in capital cost and therefore total cost of water.

13.1.4. Air Emissions

The impact of the desalination plant on air emissions, particularly CO_2, will influence the ability to site the plant. Plants sited in regions with existing air emissions regulations or CO_2 mandates may require a clean energy source to power the plant.

13.1.5. Water Cost

For desalination to be competitive with freshwater, wastewater reuse, and conservation measures in regions with freshwater availability, it should be able to produce water at a cost to the consumer that is comparable to water from existing/conventional sources, such as groundwater or surface fresh water. The difference between the costs of desalination when operated at the various energy intensities versus the cost of water from existing/conventional sources may affect desalination uptake. Cost will not be the only factor affecting the choice between desalination and conventional sources. For example, improved resiliency through diversification of water sources may be a consideration. Further, cost will not be a factor in regions with insufficient or exhausted freshwater resources. Israel, for example, does not have low-cost desalination, but gets the bulk of its water from desalination due to necessity.

13.1.6. Purpose

Some geographies may require desalination in order to add capacity to their existing water sources, whereas others may be seeking to replace existing water sources. The purpose of the desalination plant will affect system integration and determine if new wastewater capacity needs to be added or if existing capacity is sufficient. This consideration is not unique to desalination, and is relevant to any water supply expansion.

13.2. Uptake Scenarios

With these considerations, the following is a list of uptake scenarios that may be used in Phase 2. Further refinements may be made and additional scenarios added. The scenarios are grouped under “seawater” and “brackish water” scenarios. Scenarios will not be limited to their group, and optimum balances between use of seawater and brackish water for any given scenario may be evaluated.

13.2.1. Seawater Scenarios

- Supplying all populations within a certain distance (e.g., 10 miles) of a seawater coastline
- Supplying (all or a percentage of) public water for all water-stressed regions (current and projected) in the United States through seawater desalination
- Supplying all populations with existing water costs that are above the existing cost of water produced through seawater desalination. This scenario can also be calculated using the projected cost of water at practical minimum or state-of-the-art energy intensities
- Supplying regions with large renewable energy resources, but insufficient energy

storage capability

- Supplying all populations within the water distribution network of retired coal or operating thermal power plants. Under this scenario, the desalination plant would be co-located with the power plant.
- Supplying all U.S. public water supply through seawater desalination. While not practical or appropriate, this provides a maximum to which to compare other scenarios.

13.2.2. Brackish Water Scenarios

- Supplying all population centers with populations over one million people with brackish or seawater desalinated waters
- Supplying (all or a percentage of) public water for all water-stressed regions (current and projected) in the United States through brackish water desalination
- Supplying all populations with existing water costs that are above the existing cost of water produced through brackish water desalination. This scenario can also be calculated using the projected cost of water at practical minimum or state-of-the-art energy intensities
- Supplying small distributed communities with access to brackish groundwater, as their sole water source

14.0. Energy-Water Bandwidth Study Scope

Through the research and data gathering in support of Phase 2, several findings have been made that will be further explored in the development of Volume 2 and the supporting analysis. Some of these findings include the following:

- Determining the best technology options for a given desalination system is complex, and will depend on many factors including LCOW, feedwater characteristics, output water quality, and desired recovery.
- The energy intensity of a desalination system will be dependent on feedwater characteristics, output water quality, input thermal energy sources, and desired recovery.
- The data on energy and total cost of water is available in the literature. However, it is seldom reported in a consistent manner (e.g., consistent system boundaries and input/output water quality). Greater harmonization of reported data is required.
- Chemicals must be added during pre- and post-treatment. The choice of chemicals used can reduce the energy intensity of the desalination process. However, a trade-off is the need to recover and/or safely dispose of the same chemicals.
- While RO has become the dominant technology for seawater and brackish water desalination, several other technology options appear promising. For seawater desalination, the use of FO in combination with another desalination process is heavily studied; however, although it is promising for several industrial wastewater applications, FO is unlikely to compete with RO for seawater desalination. For brackish water, ED is already established and competitive with RO in the range of salinities from 1,000 to 5,000 ppm.[329]
- The energy intensity of the desalination unit operation for RO membranes has been reduced over the years and is approaching thermodynamic limits for crossflow RO desalination. However, advances in pretreatment, high-pressure pumping, pressure energy recovery, improved operational practices, and development of fouling resistant membranes offer further opportunity for energy reduction.
- The integration of renewable energy and water storage, particularly as a means to build desalination systems that can support and balance the electric grid and to reduce CO_2 emissions, is promising.

Additionally, through collecting the information presented in this volume, the authors identified several questions or areas where additional research and development could lower the energy intensity and total cost of water from desalination. These include, but are not limited to, the following:

- What is the maturity level and performance of energy recovery devices, including maintenance and component lifetime, as well as their range of applicability and efficiency with respect to plant capacity?
- How can mineral scaling, fouling, and concentrate polarization for ultrahigh permeability membranes be reduced? What would be a target flux per unit of surface area of membrane to achieve water recovery using ultrahigh permeability membranes such that

product water is generated at cost equivalent to the cost from ground/surface freshwater sources?
- What are the challenges to developing fouling, oxidation, and/or scale-resistant membranes?
- What are the opportunities for greater performance of pressurization pump and motor, including advanced motor technologies to meet pump requirements?
- How can the manufacturing costs of desalination system components be lowered, including: first-time cost for RO membranes, extending membrane lifetime and maintaining design throughput, and reuse of cartridge filters?
- What are the barriers to desalination as a means for greater recovery and direct (or indirect) reuse of municipal wastewater?
- What are the barriers to integrating renewable energy sources with desalination facilities? Can desalination serve as a "water battery" and enable: (1) better integration of renewable energy sources for grid balancing and (2) lowering the total cost of water by creating additional revenue mechanisms through demand response?
- How can the capital costs of staged RO desalination be reduced?
- Analogous to the financing schemes that have in-part enabled greater uptake of solar energy, are there financing mechanisms for lowering desalination amortization costs?
- How do the environmental impacts and respective mitigation costs for saline water desalination compare to conventional water environmental impacts and mitigation costs? Examples of possible comparative analysis could include:
    - Disposal of treated municipal wastewater and its potential impact, when compared to desalination concentrate, or
    - Desalination intake versus diverting rivers or groundwater withdrawals
- How can increasing water source diversity, and subsequently improving water infrastructure resiliency, be factored in when comparing total water costs across water sources (i.e., what would be the cost if Los Angeles, California, lost partial access to water for one summer)?

Some of these questions will be further researched to the extent possible in Phase 2 of this research.

The information summarized here will be further reviewed and distilled for use in Phase 2. The bandwidth study will seek to evaluate the current typical (CT), state-of-the-art (SOA), practical minimum (PM), and thermodynamic minimum (TM) energy intensities for several saline water desalination technologies, including the following:

- Membrane: Electrodialysis, RO, nanofiltration, FO-RO
- Thermal: multi-stage flash, multiple effect distillation, vapor compression
- Hybrid technologies processes: FO with thermal or membrane process, HDH

To contextualize the findings and assess impact, several seawater and brackish water uptake scenarios will be selected based on the outline presented here. The scenarios will be used to evaluate the energy and CO_2 emissions implications associated with greater uptake of desalination in the United States under various energy-intensity scenarios (CT, SOA, and PM).

The impact will be assessed within the context of the energy and CO_2 intensity of existing conventional freshwater treatment and supply.

Phase 2 of this research will identify opportunities for performance improvement for intake, pretreatment, post-treatment, and concentration management as well. Where quantitative analysis may not be possible for each area, a qualitative review of the issues will be sought. While some of the advances in these areas will not affect the energy intensity of the overall desalination process, they will affect the cost of operation.

Phase 2 will also consider reported capital and operational cost ranges associated with the desalination technologies and systems evaluated. Cost range metrics may be developed as well, and used in addition to the levelized cost of water framework outlined here. However, the inclusion of results will depend on the ability to gather additional information and reconcile regional and facility/system-specific variations in the data. These comparisons will allow for an evaluation of “pipe parity,” or the cost needed to provide water from the source to the water system. This concept will be expanded upon in Volume 2.

Appendix A – Seawater Energy Intensity Findings Tables

A.1. Intake Unit Operation Energy Intensity Findings

Table A-1. Range of Referenced Seawater Desalination Intake Energy Intensities

Intake Technology	Reported Range[a] Low Energy Intensity Total ($kWh_{T,equiv}/m^3$)	Reported Range[a] High Energy Intensity Total ($kWh_{T,equiv}/m^3$)	Notes
Open-ocean intake[330]	0.05	-	Reference calculated value assuming a 500 m distance to the plant, 3 m/km head loss, 94% pump efficiency, and 82% motor efficiency 0.0001 $kWh_{T,equiv}/m^3/m$
Subsurface intake - beach well[331]	0.16	-	Value was calculated assuming five wells all 20 m deep, 94% pump efficiency, and 82% motor efficiency
Screened, open-ocean intake[332]	0.45	0.58	Values are for a 3 mm screen, with 200 feet of total dynamic head. Low energy intensity is projected for a 50 MGD operating plant with 80% pump efficiency; high energy intensity is actual testing value from a facility in California in 2008 with 70% pump efficiency. Motor efficiency is 95% for both values. 0.0075–0.0095 $kWh_{T,equiv}/m^3/m$
Intake pumping[333]	0.05	1	Source noted that the variation is due to the magnitude of variation in local differences (distance water must travel). For a RO desalination plant, the intensity is noted as 0.25 $kWh_{T,equiv}/m^3$.
Screened, open-ocean intake[334]	0.08	0.11	Values are specific for a feasibility study for a desalination facility in Santa Cruz, California, but provide context on ranges of energy intensity. Low value is to pump water 70 feet (40 feet above sea level, 20 feet of suction lift, 10 feet of head loss

Intake Technology	Reported Range[a]		Notes
	Low Energy Intensity Total ($kWh_{T,equiv}/m^3$)	High Energy Intensity Total ($kWh_{T,equiv}/m^3$)	
			through a 0.75 mile pipeline) and high value is to pump 90 feet (40 feet above sea level, 20 feet of suction lift, 30 feet of head loss through a 2-mile pipeline). 0.0037–0.0040 $kWh_{T,equiv}/m^3/m$
Sub-surface intake – offshore radial collector wells [335]	0.14	-	Value is to pump water 120 feet (40 feet above sea level, 50 feet of suction lift, 30 feet of head loss) through a 2-mile pipeline 0.0038 $kWh_{T,equiv}/m^3/m$
[a] Energy consumption for intake processes is electric only; there is no thermal energy consumption.			

A.2. Pre-treatment Unit Operation Energy Intensity Findings

Table A-2. Range of Referenced Seawater Desalination Pre-treatment Energy Intensities

Pre-Treatment Technology	Reported Range[a] Low Energy Intensity Total ($kWh_{T,equiv}/m^3$)	High Energy Intensity Total ($kWh_{T,equiv}/m^3$)	Notes
Membrane filtration (microfiltration/ ultrafiltration)[336]	0.11	0.26	Pretreatment affects the specific energy consumption
Ultrafiltration[337]	0.24	0.40	Low energy intensity is projected for a 50 MGD operating plant; high energy intensity is actual testing value from a California facility in 2008 using an ultrafiltration system (0.01 micron, and a water flux of 0.815 m^3/m^2/day, 20 gallons per square feet per day [gfd])
Conventional pretreatment*[338]	1.04	–	From a case study on pretreatment at a reverse osmosis (RO) desalination plant in the United Arab Emirates, assuming a recovery of 40%
Conventional pretreatment*[339]	0.27	0.49	Values from two different RO desalination plants. Low value has an intake seawater salinity of 35 g/L and high value has an intake seawater salinity of 39 g/L.
Pressure sand filter[340]	0.13	0.26	Pressure sand filter pretreatment for iron and manganese removal; would be necessary for a specific situation based on seawater conditions from a sub-seafloor (slant well) intake.
Dissolved air flotation and filter system[341]	0.40	0.53	Pre-treatment to removed higher levels of suspended solids (filter) and algae (dissolved air

Pre-Treatment Technology	Reported Range[a] Low Energy Intensity Total ($kWh_{T,equiv}/m^3$)	High Energy Intensity Total ($kWh_{T,equiv}/m^3$)	Notes
			floatation) from the feedwater from a screened, open-ocean intake
Flocculation[342]	0.0024	0.0026	Based on a surface water treatment plant, 1–100 MGD.
Sedimentation[343]	0.0023	0.0037	Based on a surface water treatment plant, 1–100 MGD.
Chlorination[344]	0.00053	0.0021	Based on a surface water treatment plant, 1–100 MGD.
Flocculation, coagulation, and filtration[345]	0.011	0.12	Study of California statewide
Cartridge filter (CF)[346]	0.02	–	In a beach well intake scenario
Disc filter (DF), ultra-filtration (UF), cartridge filter (CF)[347]	0.28	–	DF, UF, or CF in an open intake scenario
Chlorination[348]	Negligible	Negligible	N/A
Dissolved air flotation[349]	0.09	0.11	N/A
Granular media filtration[350]	0.05	–	Single-stage gravity granular filtration process
Membrane filtration[351]	0.2	0.4	Energy intensity will depend on the type of membrane system (pressure or vacuum)

[a] Energy consumption for pretreatment processes is electric only; there is no thermal energy consumption.
* Conventional pretreatment normally consists of rotating screens for coarse pre-filtration, chlorination, acid addition, coagulation, flocculants, single- or double-stage sand filtration, addition of sodium bisulfite (to remove residual chlorine) and antiscalants, and cartridge filtration.[352]

A.3. Desalination Unit Operation Energy Intensity Findings

Table A-3. Range of Referenced Seawater Reverse Osmosis Desalination Energy Intensities

Reference	Reported Range[a] Low Energy Intensity Total ($kWh_{T,equiv}/m^3$)	High Energy Intensity Total ($kWh_{T,equiv}/m^3$)	Notes	% Recovery
(Birkett, 2011)[353]	2.5	3	Includes energy recovery devices	Not specified
(Cooley, Ajami, & Heberger, 2013)[354]	2.1	3.2	Range of energy consumption of 15 global plants for the reverse osmosis process (67% of total energy use). Capacity for the low intensity is 60,000 m^3/day and for the high intensity is 230,000 m^3/day	Not specified
(Dundorf, MacHarg, Sessions, & Seacord, 2009)[355]	1.58	2.35	Values are from a demonstration plant in Southern California using commercially available equipment. Low value is using an extra low energy (XLE) membrane at 6 gfd (0.244 m^3/m^2/day) for single-pass RO with a pressure exchanger. High value is at the most cost effective operating point (i.e., 0.367 m^3/m^2/day (9 gfd), 50% recovery for the HR membrane and XLE membrane, and 0.244 m^3/m^2/day (6 gfd), 50% recovery for the HR membrane).	Low value: 42.5% High value: 50%
(Elimelech & Phillip, 2011)[356]	3	4	Authors notes as state-of-the-art energy intensities.	Not specified
(Fritzmann, Löwenberg, Wintgens, & Melin, 2007)[357]	2	7	–	40% to, at most, 60%
(Ghaffour, Missimer, & Amy, 2013)[358]	3	4	Includes energy recovery system	45%, up to 60% if 2nd stage is applied
(Gude, Nirmalakhandan, & Deng, 2010)[359]	5	9	Potable water quality TDS <500 ppm;	Not specified

Reference	Reported Range[a] Low Energy Intensity Total ($kWh_{T,equiv}/m^3$)	High Energy Intensity Total ($kWh_{T,equiv}/m^3$)	Notes	% Recovery
			Membrane pore size: 0.1–3.5 nm, <45 ºC feed temperature	
(Lattemann & Höpner, 2008)[360]	2	7	Range depends upon the type of energy recovery utilized at plant; low range includes a piston-type accumulator and low-pressure pump.	Not specified
(McGovern & Lienhard, 2014)[361]	2.5	-	Energy requirement of energy-efficient reverse osmosis plants	50%
(Ng, et al., 2015)[362]	3.5	7.5	Low energy intensity is the efficient benchmark and high energy intensity is for a double-pass RO.	Not specified
(Vince, Aoustin, Bréant, & Marechal, 2008)[363]	3.5	7	Low value is the lowest range with energy recovery (3.5–4.5 $kWh_{T,equiv}/m^3$); high value is highest in range without energy recovery (5.5–7 $kWh_{T,equiv}/m^3$).	40%
(Voutchkov, 2013)[364]	2.5	4.0	Best-in-class SWRO plants use between 2.5 and 2.8 $kWh_{T,equiv}/m^3$ of fresh water, while the industry average is approximately 3.1 $kWh_{T,equiv}/m^3$.	Reference notes typical RO desalination plant recovery of 40%–45%.
(National Research Council, 2008)[365]	2.5	7	Moderate reliability; typical single-train capacity of <20,000 m^3/day; <45°C operating temperature	35%–50%

[a] Energy consumption for SWRO desalination processes is electric only; there is no thermal energy consumption.

Table A-4. Range of Referenced Seawater Multi-stage Flash Desalination Energy Intensities

Reference	Reported Range						Notes	% Recovery
	Low Energy Intensity			High Energy Intensity				
	Thermal ($kWh_{e,equiv}/m^3$) [kJ/kg]	Electric (kWh_e/m^3)	Total ($kWh_{T,equiv}/m^3$)	Thermal ($kWh_{e,equiv}/m^3$) [kJ/kg]	Electric (kWh_e/m^3)	Total ($kWh_{T,equiv}/m^3$)		
(Ng, et al., 2015)[366]	19.4	5.2	24.6				1 kWh of electricity production is accompanied by emissions of carbon and sulfur gases and the rejection of >1 kWh of waste heat to the environment	Not specified
(Ghaffour, Missimer, & Amy, 2013), (Ghaffour, 2015)[367]	7.5	2.5	10	12	4	16	Includes integration of waste heat	Not specified
(Gude, Nirmalakhandan, & Deng, 2010)[368]	22.9[a] [250]	3.5	26.4[a]	27.5[a] [300]	5	32.5[a]	Distillate TDS < 20 ppm; feed temperature 60°C–120°C	Not specified
(Semiat, 2008)[369]			8.4			17	High value includes taking energy losses into consideration; GOR of 10; for a desalination plant integrated with a power plant; 35°C–120°C for exiting steam	40%
(Fritzmann, Löwenberg, Wintgens, & Melin, 2007)[370]	12	35	47				Product water quality is <10 ppm TDS	Not specified
(Birkett, 2011)[371]			2.5			3	High reliability guaranteed performance on all feedwaters.	Not specified
(National Research Council, 2008)[372]	22.9[a] [250]	3	25.9	30.3[a] [330]	5	35.3	Very high reliability; <120°C operating temperature; typical single train capacity	35%–45%

Reference	Reported Range						Notes	% Recovery
	Low Energy Intensity			High Energy Intensity				
	Thermal ($kWh_{e,equiv}$/ m^3) [kJ/kg]	Electric (kWh_e/ m^3)	Total ($kWh_{T,equiv}$/ m^3)	Thermal ($kWh_{e,equiv}$ / m^3) [kJ/kg]	Electric (kWh_e/ m^3)	Total ($kWh_{T,equiv}$/ m^3)		
							of <76,000 m^3/day	
(Lattemann & Höpner, 2008)[373]	12.5	3.5	16				Maximum operating temperature of 120°C	
(Voutchkov, 2013)[374]	9.5	3.2	12.7	11.0	4.0	15.0	Feedwater heated to 90°C–115°C; product water TDS of 10 to 25 ppm; concentrate is 5°C–15°C warmer discharge; steam pressure of 253–355 kPa	Typical recovery is 19%–28%.

[a] Thermal portion provided by source in kilojoules per kilogram (kJ/kg) is multiplied by 33% and converted from kJ/kg to $kWh_{e,equiv}/m^3$. 33% is the factor representing the efficiency of the U.S. electric grid.

Table A-5. Range of Referenced Seawater Multi-effect Distillation Desalination Energy Intensities

Reference	Current Typical / State-of-the-Art						Notes	% Recovery
	Low Energy Intensity			High Energy Intensity				
	Thermal ($kWh_{e,equiv}/m^3$)	Electric (kWh_e/m^3)	Total ($kWh_{T,equiv}/m^3$)	Thermal ($kWh_{e,equiv}/m^3$)	Electric (kWh_e/m^3)	Total ($kWh_{T,equiv}/m^3$)		
(Ghaffour, Missimer, & Amy, 2013)[375]	4	1.5	5.5	7	2	9	Includes integration of waste heat	Not specified
(Gude, Nirmalakhandan, & Deng, 2010)[376]	13.8[a] [150]	1.5	15.3[a]	20.2[a] [220]	2.5	22.7[a]	Assumes 1 kWh electricity production results in 0.96 kg of CO_2 emissions; distillate TDS < 20 ppm; feed temperature 60°C–120°C	Not specified
(Lattemann & Höpner, 2008)[377]	6	1.5	7.5				Operate at temperatures <70°C	Not specified
(Semiat, 2008)[378]			5.6			13	Assumes efficient heat usage; GOR of 10; for a desalination plant integrated with a power plant; 35°C–100°C for exiting steam	50%
(Ng, et al., 2015)[379]	16.4	3.8	20.2					Not specified
(Voutchkov, 2013)[380]	4.5	1.2	5.7	6.0	1.8	7.8	Maximum brine concentrate temperature of 62°C to 75°C; product water TDS of 10 to 25 ppm; concentrate is 5°C–15°C warmer discharge; steam pressure of 0.2–0.4 atm	30%–50%

[a] Thermal portion provided by source in kilojoules per kilogram (kJ/kg) is multiplied by 33% and converted from kJ/kg to $kWh_{e,equiv}/m^3$. 33% is the factor representing the efficiency of the U.S. electric grid.

Table A-6. Range of Referenced Seawater Mechanical Vapor Compression Desalination Energy Intensities

Reference	Reported Range[a]			
	Low Energy Intensity Total ($kWh_{T,equiv}/m^3$)	High Energy Intensity Total ($kWh_{T,equiv}/m^3$)	Notes	% Recovery
(Miller, Shemer, & Semiat, 2015)[381]	11	12	N/A	Not specified
(Plappally & Lienhard, 2012)[382]	8.0	17.0	Values irrespective of their size	Not specified
(National Research Council, 2008)[383]	8	15	High reliability; typical single train capacity of <36,000 m^3/day; <70°C operating temperature	23%–41%
(Voutchkov, 2013)[384]	8.0	12.0	N/A	Not specified

[a] Energy consumption for SW MVC desalination processes is electric only; there is no thermal energy consumption.

A.4. Post-treatment Unit Operation Energy Intensity Findings

Table A-7. Range of Referenced Seawater Desalination Post-Treatment Energy Intensities

Technology	Reported Range[a]		Notes
	Low Energy Intensity Total ($kWh_{T,equiv}/m^3$)	High Energy Intensity Total ($kWh_{T,equiv}/m^3$)	
Remineralization[385]	0.04	0.07	Lime and carbon dioxide post-treatment for a demonstration plant (with a study scaling up to 50 million gallons per day).
Disinfection[386]	0.044	0.072	Study in Northern and Central Coast of California
Disinfection and Pumping[387]	–	0.52	Includes pumping required for distribution and disposal
Boron Removal[388]	0.08	0.42	Variation of single-pass boron removal and boron removal with second-pass BWRO
[a] Energy consumption for post-treatment processes is electric only; there is no thermal energy consumption.			

A.5. Concentrate Management Unit Operation Energy Intensity Findings

Table A-8. Range of Referenced Seawater Desalination Concentrate Management Energy Intensities

Technology	Reported Range* Low Energy Intensity Total ($kWh_{T,equiv}/m^3$)	Reported Range* High Energy Intensity Total ($kWh_{T,equiv}/m^3$)	Notes
Concentrators[389]	15[a]	25[a]	Evaporate 90%–98% of the concentrate; reduce concentrate volume 10 to 50 times. Concentrate salinity produced by the system can reach 20,000 to 100,000 ppm.
Crystallizers[390]	50[b]	70[b]	Recovery of salts and reuse of the liquid separated from the concentrate is almost 100%. Unit processing capacity is 50 to 500 m^3/day.
Concentrators[391]	15.9[b]	26.4[b]	Powered by electrically driven vapor compressors
Crystallizers[392]	52.8[b]	66[b]	Can be exposed to corrosive environments that require expensive materials
Surface Water Discharge[393]	0.035[c]	0.105[c]	N/A
Concentrators[394]	20[b]	25[b]	Reach salinity concentrations of 250,000 ppm and water recovery of 90%−98%
Crystallizers[395]	52[b]	66[b]	Commonly operated in forced-circulation mode. Can treat higher salinity and viscosity feedwaters than concentrators

* Energy consumption for seawater mechanical vapor compression desalination processes is electric only; there is no thermal energy consumption.
[a] kWh/m^3 processed concentrate
[b] kWh/m^3 feed concentrate
[c] kWh/m^3 concentrate pumped

Appendix B – Additional Information on Desalination System and Technologies

There are many references available that provide a detailed introduction to desalination in general and the technologies used both today and in the past. This appendix provides a brief overview of energy recovery devices and brackish water systems. For readers who wish to learn more about the basics of desalination and each of the five unit operations (intake, pretreatment, desalination, post-treatment, and concentrate management) please refer to the following references for more details and an overview:

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B.1. Energy Recovery Devices

B.1.1. Pressure Energy Recovery Systems

Pressure exchangers are able to harness, transfer, and reuse the energy applied for salt separation at efficiencies of 93%–96%, reducing the overall amount of electric energy used for seawater desalination.[396] For brackish water desalination, where recoveries are higher and concentrate flow rates are lower, pressure exchangers will have less of an impact on energy consumption.

Pressure exchangers can directly transfer pressure from the concentrate to the feed seawater. The process involves several ducts that operate in parallel. Feedwater enters a duct which is closed by a valve. Another valve opens and gives way to the concentrate entering the duct at a high pressure. The pressurized feed then exits the duct and mixes with the feed from the high-pressure pump and is taken to the reverse osmosis (RO) process. The pressure exchangers require additional equipment such as high-pressure circulation pumps.[397]

Work exchangers use pistons and valves to transfer energy from the concentrate stream to the RO feed. A booster pump pressurizes the feed to the required pressure. Work exchangers have higher efficiency compared to pressure exchangers (and turbo chargers, described below), but they are not as popular in desalination systems due to their high cost and size limitations.

B.1.2. Centrifugal Energy Recovery Systems

Centrifugal energy recovery systems take potential energy from the concentrate and convert it to mechanical energy. The recovered energy is supplied to the feed pump or applied directly to the feedwater. The system can be either a Pelton wheel or a turbocharger, the latter being the more dominant energy recovery method.

Pelton wheel energy recovery devices (ERDs) have high-pressure concentrate enter the turbine though the inlet nozzle. The steam from the high-pressure water drives the rotor producing rotational power to a shaft connecting the turbine and high-pressure pump. The main electric motor is assisted by this ERD in driving the high-pressure bump. Concentrate is then discharged at atmospheric pressure.[398]

Turbochargers use a pump and a turbine section that contain either a single stage impeller or a rotor. The turbine rotor converts hydraulic energy from the concentrate stream into mechanical energy. The pump section converts the mechanical energy back to pressure energy that is supplied to the feed stream. The entire feed is pressurized by high-pressure pumps driven by an electric motor. The feed pressure is then increased by the turbocharger to the inlet pressure of the RO process.[399]

B.2. Information on Brackish Water Desalination

B.2.1. Pre-Treatment

B.2.1.1. Chemical Addition

Surface waters need clarification to turbidity of <1 nephelometric turbidity units (NTU) and silt density index of <3–4. Coagulant, sand or multimedia filters are used. Filtration through activated carbon should be avoided if possible due to propensity for microbial growth. Microfiltration and ultrafiltration are also used, especially for brackish municipal wastewater.[400]

Chemical additions to the water before desalination helps mitigate scaling or fouling that can occur during the desalination process. Calcium carbonate, calcium sulfate, and barium carbonate are examples of major scalants in brackish water. Silica is also a concern at higher recoveries. Antiscalant chemicals can be added to the feedwater or a nanofiltration system can be incorporated upstream of the RO system.[401]

Antifoulants acting as anticoagulants for colloidal foulants and dispersants for colloidal coagulates are specifically developed for colloidal sulfur, silica and microbial slime in brackish water.[402] Anticoagulants assist in the removal of finer debris and microplankton from the source water.[403]

B.2.1.2. Cartridge Filtration

Cartridge filtration is usually the only source of filtration for brackish water desalination plants that use well intake systems. Cartridge filters are fine microfilters ranging from 1 to 25 micrometers (µm) used as a screening device between the intake wells and the RO process. They can capture particulates in the feedwater that have passed through the previous pretreatment systems. The RO membranes are able to prevent premature fouling and other damages using these cartridge filters.[404]

B.2.1.3. Media Filtration

In media filtration, suspended and colloidal particles are removed by their deposition on the surface of filter grains while the water flows through them. The most common media filters are sand and anthracite. The effective grain size for a fine sand filter is in the range of 0.35–0.5 millimeters (mm), and 0.7–0.8 mm for an anthracite filter. In comparison to single sand filter media, dual-filter media with anthracite over sand permit more penetration of the suspended matter into the filter bed, thus resulting in more-efficient filtration and longer runs between cleaning.[405]

B.2.2. Desalination Processes

Table B-1 below provides a summary of the range of brackish water desalination unit operation energy intensities as found in the literature. The sections below describe the desalination processes in more detail. Thermal desalination technologies are generally not used for brackish water desalination, and this section focuses on electricity-powered membrane technologies.

Table B-1. Range of Referenced Brackish Water Desalination Energy Intensities

	Reported Range			
Process	Low Energy Intensity ($kWh_{T,equiv}/m^3$)	High Energy Intensity ($kWh_{T,equiv}/m^3$)	Notes	% Recovery
ED[406]	0.5	1.8	Low intensity is for 1,000 ppm feedwater High intensity is for 5,000 ppm feedwater	75
BWRO[407]	0.6	1.7	Feedwater and product water salinity and flow rates not reported	NR
BWRO[408]	0.5	2.5	Feedwater and product water salinity and flow rates not reported	NR
BWRO[409]	0.5	3	Feedwater and product water salinity and flow rates not reported	50–90
CDI[410]	0.14	–	2,000 ppm feed to 186 ppm product water. Percent recovery refers to the stored electrical energy.	70
NF[411]	<1		Feedwater and product water salinity and flow rates not reported	50–90
BWRO[412]	0.3	2.8		85–95

B.2.2.1. Brackish Water Reverse Osmosis (BWRO)

A two-stage RO system increases the water recovery and improves the permeate quality, as high-salinity brackish waters typically use two-stage RO systems.[413] The first-stage permeate usually contributes 75%–85% of the total permeate flow; second-stage RO system produces the remaining 15%–25% of the total RO system permeate flow.[414]

Energy Recovery Devices

A Francis turbine (reverse running pump) converts the concentrate energy into kinetic energy for the feed pump motor. The turbine is connected directly to the motor shaft. The turbine begins to turn once the plant flow has reached 40% of its design level. Francis turbines often have vertical high-pressure pumps built into the system. It is mainly used in brackish water RO desalination plants.[415]

B.2.2.2. Capacitive Deionization (CDI)

Capacitive deionization is an emerging technology for brackish water desalination. It is an electrosorption process where an electric field gradient drives the removal of salt ions from the feedwater. The electrodes are made from porous materials such as carbon-based aerogels which have high salt storage capacity.[416] After an external power supply charges the electrodes, cations and anions are attracted to the anodic and cathodic electrode, respectively, and are stored in their respective electrodes. The feedwater is separated from the salt ions and is sent to the post-treatment process. The potential difference is reversed and the electrodes then regenerate by releasing the absorbed ions. The ions leave the electrode pores and are ideally flushed out to the concentrate stream.[417] However, ions may instead be attracted to the other electrode and not be flushed out with the backwash. In a lab setting, tests showed CDI could desalinate 2,000 ppm salinity brackish water to 186 ppm product using 0.14 $kWh_{T,equiv}/m^3$.[418]

B.2.3. Post-Treatment

B.2.3.1. Water Quality Polishing

In some brackish water RO facilities, chlorine is typically used in pretreatment for disinfection; the presence of chlorine in the water causes the formation of disinfection by-products, which are not effectively fully removed by the RO membrane. Thus it is necessary to perform water quality polishing, to treat specific compounds such as boron, silica, or N-Nitrosodimethylamine (NDMA).[419] Theses polishing processes might include ion exchange, granular activated carbon filtration, or additional RO passes, although this usually only is required for industrial applications of the product water.[420]

B.2.3.2. Stabilization

Stabilization is the most common approach for post-treatment of brackish water. Permeate must be re-hardened to prevent corrosion of pipes in the distribution network. The pH value and CO_2 content need to be adjusted for scaling prevention, and permeate water needs further disinfection. Stabilization provides corrosion control for metallic pipelines by adding caustic hydroxide alkalinity. Blending the desalinate water with freshwater supplies is a cost-effective option for stabilization to provide sufficient levels of calcium hardness and alkalinity.[421]

B.2.3.3. Hydrogen Sulfide Stripping

Air stripping is required for brackish waters, especially if hydrogen sulfide is present in the source water or the source water is from an aquifer. Hydrogen sulfide can be removed though a packed tower or an air stripping process.[422] These waters contain odorous gases that fail to meet standards for human consumption, and current RO and electrodialysis (ED) systems do not remove these gases. The desalinated water is passed through a tower filled with contact media, while air enters the opposite direction, stripping the dissolved gases. Air stripping also aerates the finished water product, improving the taste as well.[423] Aeration in brackish water has an energy intensity of 0.113 $kWh_{T,equiv}/m^3$.[424] Surface discharge of concentrate may require a hydrogen sulfide removal step (as well as on the permeate) to minimize air quality complaints.

B.2.3.4. Degasification or Decarbonation

Alkalinity control is vital to prevent scaling during the distribution process. Carbon dioxide can pass unhindered through the RO membrane, and can be a converted to its bicarbonate form. This form of decarbonation can recover the desired amount of alkalinity in the desalinated water. This process is also able to control the pH of the permeate.[425]

B.2.3.5. Boron Removal

Brackish water needs to use a different method for boron removal compared to seawater desalination. The two most common methods are boron selective ion exchange resins or special RO membranes operating at higher pH levels for boron removal.[426]

B.2.4. Concentrate Management and Disposal

B.2.4.1. Sewer Discharge

Discharge to a wastewater collection system is the lowest-cost disposal method, especially if the system is in the vicinity of the plant site.[427]

B.2.4.2. Deep Injection Wells

The injection wells are usually constructed in the same manner as the intake wells (see Section 12.2). The wells are multi-cased to prevent the borehole from caving and to house the tubing. The injection tubing transports the concentrate from the surface to the injection zone. A packer seals the outside of the tubing to ensure isolation of the injection zone from any other bodies of water. Injection well pumps might be used if the concentrate head does not provide sufficient discharge pressure. A set of monitoring wells is also included to overlook any possible migrations of the concentrate to adjacent aquifers.[428]

B.2.4.3. Evaporation Ponds

Evaporation ponds are shallow basins where concentrate evaporates due to solar irradiation. The minerals that do not evaporate are precipitated into salt crystals and later disposed offsite. Solar ponds, specifically, are deep lagoons with high-salinity water that collect solar energy and convert it to electrical energy. They are designed to retain heat and have a lower evaporation rate than conventional evaporation ponds.[429]

B.2.4.4. Land Application

Land application of brackish desalination concentrate can be used for lawns, parks, golf courses, or crop land. There is typically a need for addition of dilution water if the total dissolved solids of the brackish water concentrate is greater than 5,000 ppm prior to land application. Due to the seasonal demand for irrigation, a back disposal or storage is also necessary for year-round operation. The key concerns with land application of brackish water concentrate include the influence of concentrate on the soil and vegetation, potential contamination of groundwater, and runoff to surface water. The allowable salinity will depend on the tolerance of target vegetation, percolation rates, and the ability to meet the groundwater quality standards.[430]

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