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Sustainability Analysis: Large-scale Desalination Implications for Coastal California

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This Master's Project

Sustainability Analysis: Large-scale Desalination Implications for Coastal California

by

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Abstract

In response to prolonged drought, desalination is gaining popularity as an alternative water production method for fresh water. However, water desalting technology poses concerns; the process is energy intensive, creates brine waste, and has the potential to damage sensitive coastal ecosystems. Significant research is available on the technological, economic, and energy efficiency aspects of desalination, while only a small percentage of the current literature focuses on environmental impacts. This research analyzes the desalination literature holistically in terms of both energy consumption and environmental impacts by conducting 1) a historical and current state review of the sector, 2) a technology analysis of current energy standards, and 3) a case study and gap analysis of environmental impacts. This study found that the sustainability of a desalination plant design is heavily dependent on several indicators like renewable energy availability, feedwater intake design, brine disposal method, coastal hydrological conditions, and proximity to sensitive ecosystems. Outcomes for this research include a quantitative/qualitative sustainability index tool, additional sustainability considerations, and design recommendations specific to coastal California for mitigating energy intensity and coastal damage. These findings inform state, regional, and local water stakeholders on the potential impacts of incorporating desalination into a community's water portfolio.

1. Introduction

Due to prolonged drought, climate change, and increases in water use throughout the state, California faces water distribution concerns. These concerns affect rural communities, fish & wildlife, farmers in the Central Valley, and communities with vulnerable water supplies. Increased focus on conservation and emergency measures has reduced consumption, but the state's water portfolio remains reliant on groundwater and snowmelt from northern California's Sierra Nevada mountain range. The 2020-2022 water years experienced dry winters followed by high summer temperatures, low reservoir levels, and increased risk of land subsidence from heavy groundwater pumping (California Department of Water Resources, 2022). As water managers consider alternatives, desalination appears as a solution to freshwater insecurity both nationally and at the state level (DSTC, 2019).

Desalination is the process of removing salts and other suspended minerals from feedwater in order to produce freshwater. Desalinated water can be used for either municipal potable water, for non-potable household use, or for irrigation (Aliku, 2017; Shemer & Semiat, 2017). Plants can also range from small units processing less than 10 gallons per day to massive industrial sites supplying entire cities with fresh water (Al-Karaghouli & Kazmerski, 2013). Areas of the globe with limited surface or groundwater resources often are entirely reliant on desalination technology to meet water needs; common regions using desalination are the Middle East North Africa (MENA) region, rocky islands, and parts of southern Europe bordering the Mediterranean Sea (Ayaz et al., 2022, Ali et al., 2022).

Desalination technology adds a secure and relatively economical supply stream of freshwater, fulfilling Sustainable Development Goal 6.1 of "By 2030, achieve universal and equitable access to safe and affordable drinking water for all (Bianchelli et al., 2022; United Nations, n.d.)." However, increased desalination intensity has the potential to cause environmental harm; large-scale processing can increase salinity levels and temperatures in discharge areas (Elsaid et al., 2020, Ahmad & Baddour, 2013), create a threat to marine life during intake (Al-Kaabi & Mackey, 2019), and introduce chemical byproducts to the surrounding environment (Belkin et al., 2017). This technology also generates a significant power demand for often overburdened utility grids, potentially increasing reliance on fossil fuels for electricity generation (Fornarelli et al., 2018). Recent advances have made the process more energy efficient, but it is unclear what the environmental impact of large-scale desalination infrastructure would be in conjunction with the true energy consumption.

1.1 Research Justification

The motivation for this research project stems from water availability tensions in California. Desalination appears as a solution to alleviate water distribution issues and reduce reliance on shrinking aquifers; tapping into the vast expanse of seawater seems an irresistible option for arid coastal regions. However, other large water infrastructure projects, such as proposals for the Central Valley Project (Grimaldo et al., 2021), have underscored how innovative ideas can lead to unintended and sometimes damaging consequences - the disruption of California's rivers contributed to the decline of economically important species like the Delta smelt. With incomplete evidence on the environmental effects of desalination, this research brings together the available knowledge, highlights existing gaps, and creates a sustainability-focused scale for decision makers.

Within the topic of desalination, some areas are studied more extensively than others (Jones et al., 2019). Energy intensity, technological capabilities, and the economics of desalination implementation are better understood than concerns around long-term environmental damage. A 2019 review found that while interest in desalination has grown exponentially since 1995, only a small fraction of published articles address the environment (see Figure 1). This research intends to connect both technology-based energy consumption and ecological concerns.

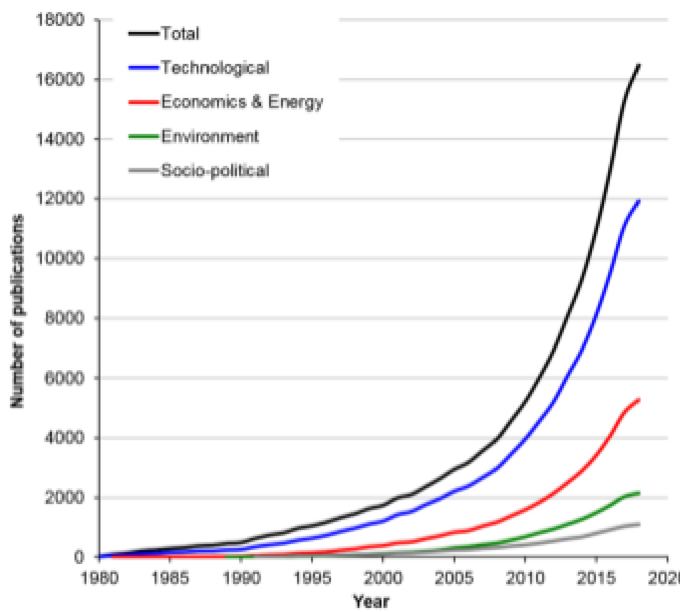


Figure 1: Published desalination works by topic category. Jones et al, 2019.

1.2 Research Questions & Hypotheses

Considering that all water procedurement pathways have potential for positive and negative impacts, more research is needed to connect disparate factors related to desalination implementation. This study seeks to answer the question: How can California water managers incorporate desalination sustainably, considering both the energy costs and environmental impacts? In order to address this question fully, subtopics are also considered, each with discrete objectives. Because this topic spans a broad range of related subtopics, “energy” and “environment” are split into two distinct areas, then synthesized into a scaled desalination sustainability index (see Figure 2). This method is specifically tailored to the current information available; after addressing each unique subquestion, this study brings together two previously disparate areas of desalination research. This method will also provide a decision framework for California water managers and stakeholders.

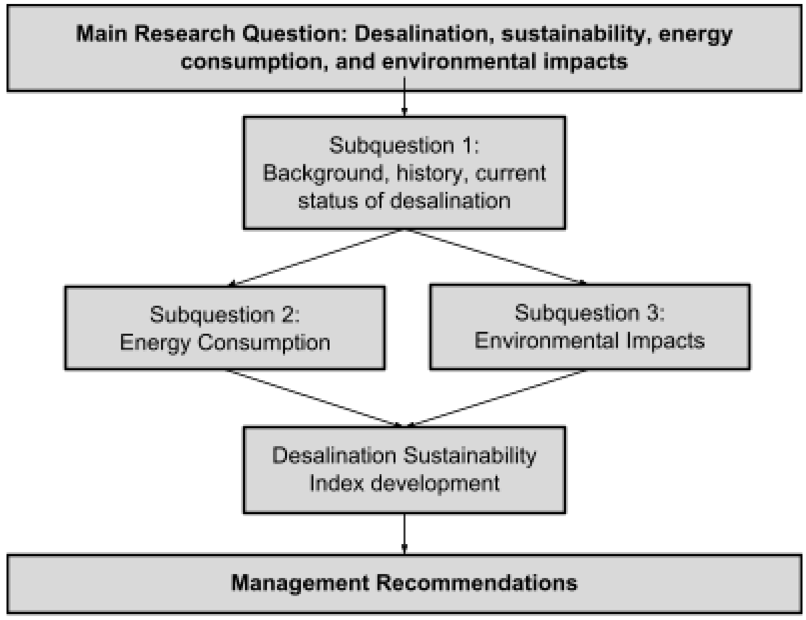


Figure 2: Subquestion Connectivity. Energy and Environment represent two arms of this research project, and are both incorporated into development of a sustainability index and management recommendations.

One hypothesis is that research and design efforts are already underway to solve desalination’s energy intensity issue. Based on an initial review of the literature, there is a wealth of knowledge on the carbon footprint of desalination and the cost of water based on the technology and salinity content. However, it is also clear that relatively fewer studies have been conducted on the environmental effects of desalination activities, specifically around the long-term effects on aquatic plants and wildlife. One can suspect that there is consequently less knowledge available on potential damage to ecologically sensitive areas, although there is some emerging work on the subject.

Another hypothesis is that sustainable desalination is more suited for smaller, affluent coastal communities because of size, cost, and environmental mitigation factors. Efficient and sustainable desalination may be less available for communities with stretched resources or limited renewable energy sources, when compared to currently installed water production methods. However, communities in resource-scarce areas often have few choices when considering their water portfolio. Based on location and proximity to freshwater sources, desalination may actually be a more viable choice when comparing the energy and environmental costs of transporting water from other areas of the western United States.

2. Research Methods

Each research subquestion (refer to Figure 2) will require a unique method in order to adequately address the topic. All subquestions strive to center sustainability indicators to produce a visual sustainability index. This relative scale index can be used by water managers to evaluate the appropriateness of a desalination design and siting plan, using the major indicators for sustainability like energy consumption levels and waste management practices. Sustainability refers to obvious factors like the two examples shown here, but also refers to less apparent factors like circular economy connections and land use footprint; an expanded definition of sustainable activities will be established.

First, this research includes a review of desalination literature using keywords to provide background of currently available technology. Appendix A clarifies how terms will be used in this research, as much of this historical analysis introduces the current desalination landscape. Reviewed publications will be limited to those published within the last two decades to ensure the most updated information is analyzed. Knowing that there is a wide range of uses based on scale, this review will be limited to publications relating to large-scale desalination plants with applications for municipal potable water use only; research does focus on microgrids or industrial wastewater treatment (Bales et al., 2021), but neither of which are areas that will significantly affect state water supplies. Large scale refers to designs that are sufficient for coastal towns and cities, in the millions of gallons a day (MGD) range.

The energy subtopic includes a technology analysis and synthesis of emerging innovations in regards to energy consumption specific to desalination. This section will avoid a descriptive narrative focused solely on technical details; rather, the focus is to investigate sustainability indicators related to desalination and illustrate the variability in energy consumption based on a wide range of processes. Portions of this subquestion will expand on newer, emerging processes, but the majority of the processes analyzed will be commercially available, well-studied methods applicable to coastal desalination designs. The environment subtopic will utilize case studies to illustrate desalination’s interaction with the coastal environment (marine and benthic study areas). When available, case studies of other desalination plants will be included. However, as some effects of desalination have not been researched extensively, comparisons will need to be made with similar water purification or transportation methods. Addressing this subquestion will not focus on the alternatives to desalination processes, but rather will evaluate gaps in the current desalination literature surrounding environmental impacts to the coastal ecosystem.

Based on subquestions 2 and 3 (see Figure 2), the synthesis asks, “How can California implement desalination as a sustainable technology while also taking into account both energy and the environment?” Noam Lior defines “sustainable activities” in his 2017 article as those which, “*...describe a logical process that takes carefully into account all relevant consequences within time and space boundaries that are large enough to ensure satisfactory existence for us and other humans, and for our and their descendants* (Lior, 2017)”. This definition will be used to determine which indicators or factors could have a major effect on desalination outcomes in terms of energy and environment impacts. Based on the results of the analysis, a desalination sustainability index will be set out for decision makers and stakeholders considering a large-scale coastal project. This will include specific questions to ask and a relative index system giving a theoretical sustainability ranking for aspects of a specific project.

3. Background

3.1 Historical Context

Although large-scale commercial interest did not begin until the mid 20th century, rudimentary desalination techniques have been utilized for centuries. One of the first recorded instances of using a “de-salting” technique was in pre-industrial Japan on fishing vessels using boiling water and clay pots (Greenlee et al., 2009). Solar stills, or designs using the direct energy of the sun for evaporation and condensation, were the first developed style and are still in use even today for resource-limited communities (Aliku, 2017). Prior to the advent of membrane technology, ocean-going vessels relied on stored water, limited solar stills, fermented liquids, or frequent port calls to obtain safe water for drinking (Greenlee et al., 2009). Once reverse osmosis (RO) technology became available, ships and submarines now had limitless raw material to convert seawater to potable water on demand. This advancement was critical for sustained at-sea voyages, and large vessels are often relied upon during coastal humanitarian crises for supply of safe drinking water.

Globally, many countries are reliant on desalination due to limited surface and groundwater resources. This is especially true for regions located near the Arabian Gulf, the Mediterranean Sea, and rocky islands with limited rainwater catchment (Shemer & Semiat, 2017; Janowitz et al., 2022; Kariakarakos et al., 2022). Almost 50% of the global desalination capacity is sited in the Middle East North Africa (MENA) region due to extreme surface water scarcity (Elsaid et al., 2020). Most were constructed during the first wave of desalination development; as such, many of the designs from the 1960's were large, less efficient compared to today's standards, and used intense heat rather than electricity. These advancements did allow development in desert areas never before capable of supporting large populations; however, doing so also took a toll on supporting water bodies (Del-Pilar-Ruso et al., 2014). Many plants built prior to the 1970s utilized thermal technology, but are less popular

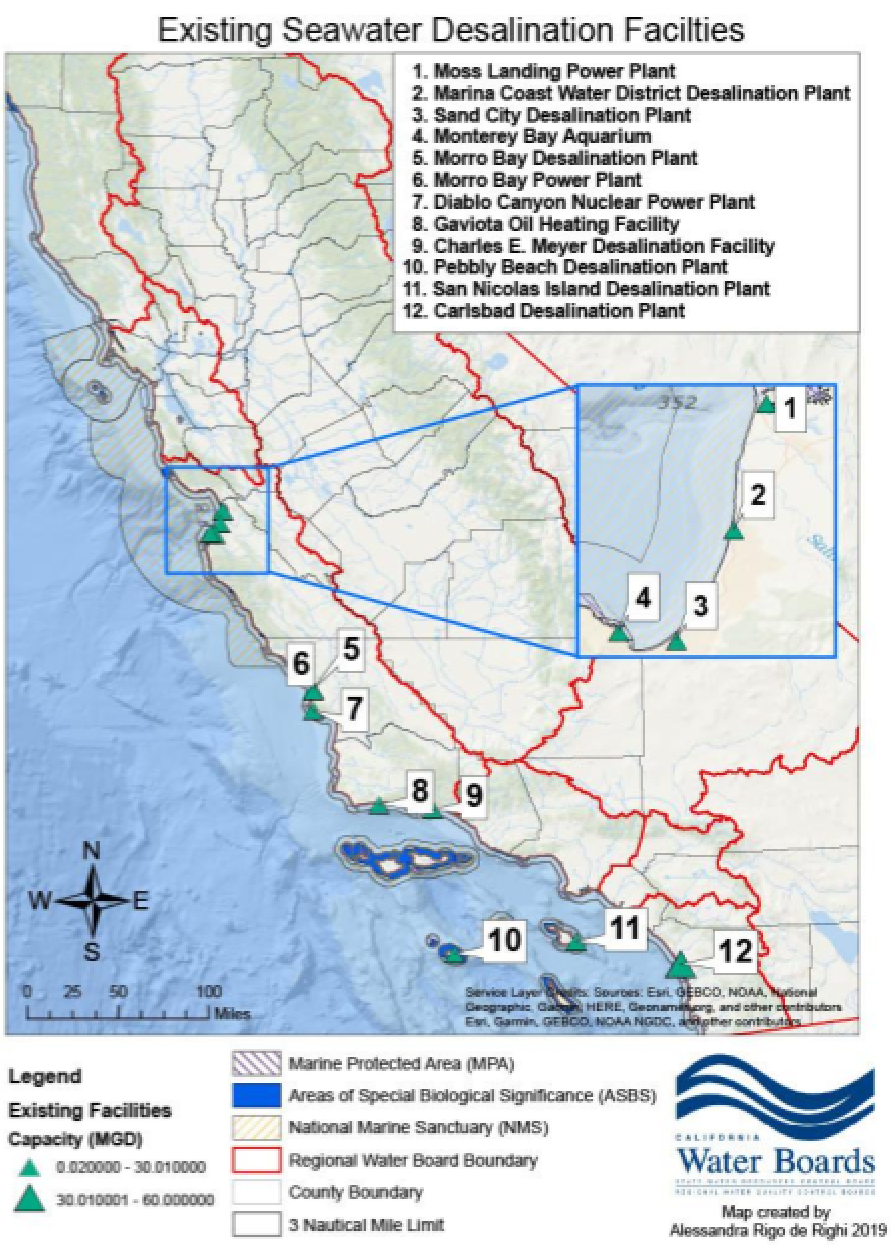


Figure 3: Illustrated description of major California desalination plants in operation. California State Water Board, 2019.

than membrane designs now due to lower operating costs and reduced fossil fuel consumption (Elsaid et al., 2020). Because of inefficiencies noted with utilizing heat for desalination and global commitment to reduce fossil fuels, research and use of strictly thermal designs are waning as indicated by rising interest in membrane and electricity-based technologies (Jones et al., 2019).

In California, there are currently 12 desalination plants supplying water for municipal and commercial purposes; these plants are located along the central and southern coastal regions of the state (see Figure 3 and Table 1). Although some small-scale designs had been implemented for agriculture and desalination plants continued to rise in popularity, regulation for large-scale desalination was not implemented until after 2000 (SWRCB, 2019). Influences on California's need for more fresh water include the expansion of urban populations located in desert climates and intensifying agricultural practices. Dubbed the nation's salad bowl, California's agricultural footprint is over 24 million acres of farm and ranchland. California is the leading state for agricultural exports at 12% of the nation's total commodities and accounts for over $50 billion dollars in agricultural sales (CDFA, 2022). The state's high productivity exacts a comparable water toll - approximately 40% of the state's water supply is devoted to growing food (Public Policy Institute of California, 2018). To diversify the state's water portfolio and relieve mounting dependence on transported water, Southern California has built or proposed several high-need, large-capacity facilities (Table 1); these facilities are intended to serve medium to large communities in the coastal area in an effort to reduce pressure on inland water resources.

Table 1: Location and description of selected major California desalination activities. (SWRCB, 2021)

Desalination Project Name	**Description**	**Feedwater Quality**	**Production** MGD = million gal/day	**Location**
Claude "Bud" Lewis Carlsbad	Pretreatment (filter), pretreatment (microfiltration), RO, ERD, post-treatment + brine dilution w/SW	Seawater	50 MGD	Carlsbad
Charles E. Meyer	Pretreatment (filter), RO, post-treatment + brine dilution w/city WW	Seawater	2.8 MGD	Santa Barbara
Santa Catalina Island	Improvements in progress, completion date: 12/31/2024	Seawater	0.33 MGD	Santa Catalina Island
Sand City Coastal	Pretreatment (filter), RO, post-treatment + injection well	Seawater / Brackish well	0.30 MGD	Monterey Peninsula

Chino Basin Desalter Authority	2 desalters: Groundwater intake, RO + Ion Exchange (IO) for nitrate, TDS, and VOC removal, brine processing via Inland Empire Brine Line (IEBL).	Brackish	34.7 MGD	Chino / Jurupa Valley

3.2 Current State

For established technologies, desalination for freshwater production is categorized as either thermally based, membrane based, or based on an electric field for separation (Miller et al., 2015). Other forms of desalination or auxiliary processes not in mainstream use are considering emerging technologies and are yet untested in large capacity plants. Additionally, desalination processes can also be categorized by the quality of the feedwater, either as either brackish (salinity of 3-10 g/L or 3,000-10,000 ppm) or seawater (salinity greater than 10 g/L or 10,000 ppm) (Elsaid et al., 2020). Desalination plants are composed of two major components: a power generation component to fuel the plant's operating needs and a desalting technology component which separates the freshwater from salts and minerals (Miller et al., 2015).

A well-studied and commonly used parameter for desalination technology is determination of the recovery ratio (RR). This calculation is the proportion of potable water produced compared with feedwater required as intake (Jones et al., 2019). Table 2 displays generalized RRs for common methods of desalination.In regards to membrane based technology, the RR is a function of feedwater quality to include turbidity and salinity (Jones et al., 2019). Although some methods have improved over time, the RR for a typical RO desalination plant without the addition of a filtration step or pre-treatment is approximately a 2:1 recovery, or two units of feedwater for every one unit of potable water. (Jones et al., 2019).

Table 2: Expected Recovery Ratios (RR) for selected desalination types, seawater (SW) and brackish water (BW). Jones et al, 2019.

Type	RR - SW/BW
Multi-Stage Flash (MSF)	0.22/0.33
Multi-Effect Desalination (MED)	0.25/0.34
Nanofiltration (NF)	0.69/0.83
Reverse Osmosis (RO)	0.42/0.65
Capacitive Deionization (CDI)	0.90/0.97
Electrodialysis (ED)	0.86/0.90

Thermal desalination uses heat to convert saltwater to freshwater using evaporation and condensation steps. These techniques are considered more energy intensive and result in a higher outfall temperature (Chen et al., 2021). Thermal desalination plants also require two forms of energy input; electrical energy is used for water pumping action and heat energy is used for raising the intake feedwater temperature (Nassrullah et al., 2020). Although most desalination development is moving away from thermal techniques due to high operating costs, there is some benefit to utilizing heat for desalination - using heat is generally more appropriate for turbid or high salinity feedwater, like the seawater found in the Arabian Gulf (Elsaid et al., 2020). Location of desalination plants also determines whether thermal processes are viable - if sited next to other industrial processes, thermal designs can incorporate heated wastewater for feedwater. Similarly, if sufficient geothermal energy is available, then the use of thermal desalination is relatively more energy efficient than utilizing electricity alone (Gude, 2019).

Multi-stage Flash (MSF) desalination plants (see Figure 4, diagram (c)) were some of the first commercial, large-scale methods of thermal desalination developed in the 20th century, mainly in the Arabian Gulf region. Feedwater is "flashed," or quickly heated to a phase-changing temperature; steam then condenses onto tubes, collecting into a reservoir. The resulting brine is again flashed to steam, and stages are repeated up to 30 times to pull all available fresh water out of the heated brine solution (Hanshik et al., 2016). As the second most commonly used method of desalination, many aging MSF plants are still in operation and are co-located with industrial power plants (Al-Karaghouli & Kazmerski, 2013). Multi-Effect Distillation (MED) and Mechanical Vapor Compression (MVC, or VC) (see Figure 4, diagram (b) and (c)) are follow-on thermal innovations designed to utilize energy more efficiently. MED uses multiple effects (stages) similar to MSF, but heat energy from steam is transferred to subsequent effects, requiring less energy and pressure with a higher recovery rate. MVC is the most modern and energy efficient form of thermal technology due to its ability to recoup latent heat from pressurized water vapor and apply it to the incoming feedwater. Some versions of MVC technology are able to produce desalinated water using a vacuum pressure method and electricity alone (Hanshik et al., 2016; Ahmed et al., 2020, Lin, 2020).

Membrane desalination, on the other hand, uses electricity solely to pump water against an osmotic pressure gradient. First developed in the late 1950's (Habib & Weinman, 2021), feedwater is pumped using hydraulic pressure through a semipermeable membrane, separating water molecules from charged ions (see Figure 4, diagram (a)). Reverse osmosis (RO) is the most popular method with over 60% of all desalinated water produced via this method (Ahmed et al., 2020), although nanofiltration (NF) is a emerging low pressure alternative for brackish feedwater (Elsaid et al., 2020). Membrane desalination is relatively new compared with thermal processes, yet most desalination designs now use at least some form of a membrane. One reason is that total energy consumption is lower, requiring no thermal energy for phase change; also, the resulting brine temperature is lower, minimizing the negative impacts of brine discharge to the natural environment (Ahmed et al., 2020).

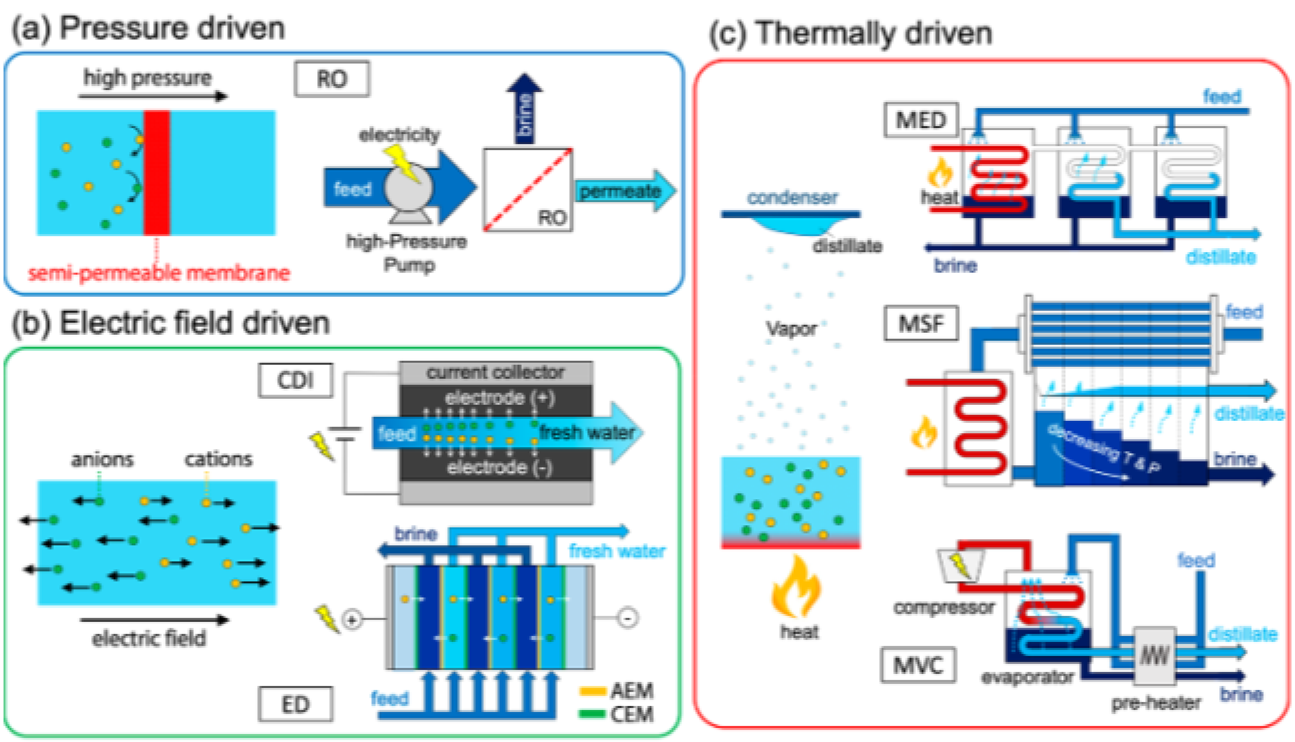


Figure 4: Illustrated description of major desalination processes by category: pressure, thermal, and electric field desalination. Lin, 2020.

A drawback to membrane technology is that the quality of the feedwater has a direct impact on maintenance cost, energy requirements, and the resulting freshwater quality. Membranes, because of high pressure exerted on fine semi-permeable structures, are prone to fouling (Adda et al., 2022). Feedwater with a high salinity content is more likely to damage the RO membrane over time and require increased pumping energy per unit of freshwater produced (Hanshik et al., 2016). RO systems will often utilize a filtration system ahead of the desalting mechanism to produce high quality feedwater or will utilize intake systems which naturally filter seawater (infiltration galleries, beach wells, etc.) (Kim et al., 2015). Lastly, since membranes are designed to overcome osmotic pressure with hydraulic pressure, increased salinity and turbidity require either a higher applied hydraulic pressure or multiple passes to obtain a potable water product (Ahmed et al., 2020).

While not currently a major component for large-scale desalination, the use of an applied electrical potential difference to desalt feedwater has projected growth for future commercial use. These desalination methods are also referred to as charge-based separation technologies (CST) (Kyriakarakos et al., 2022). CSTs are often incorporated into a membrane-based design to increase efficiency and reduce energy consumption. Since salt ions possess a charge, placing electrodes along a gradient can separate water molecules from salt and mineral ions in a way similar to a battery (see Figure 3, diagram (b)). The most common CST methods are Capacitive Deionization (CDI) and Electrodialysis (ED). CDI incorporates high capacity anodes and cathodes and is commonly used for brackish water desalination (Gary et al., 2017); ED, on the other hand, uses multiple passes or re-circulation to reach the desired product water quality (Ghazi et al., 2022). Due to the relatively new emergence of CST methods, upfront and operating costs for both CDI and ED are preventative for large-scale implementation at this time, although interest is expanding (Ghazi et al., 2022).

In the near future, many countries see freshwater scarcity as a looming crisis and national security issue. The Kingdom of Saudi Arabia (KSA) is facing almost complete depletion of groundwater, a resource which currently supports their agricultural industry; in response, KSA's Ministry of Environment, Water, and Agriculture set a goal of at least 90% water from desalination by 2030 (Ali et al., 2022). China, a country with 41% of the population living in coastal provinces, has also invested in large-scale desalination to meet water demand. The Chinese government indicated that the membrane technology industry was strategically important and desalination capacity is still growing (Zhu et al., 2019). Faced with increasing tourism demands, Greece has recently investigated the use of seasonal desalination plants to alleviate water scarcity on the arid/semi-arid islands with limited water storage capacity (Kariakarakos et al., 2022). In Australia, Sydney operates a desalination plant on an intermittent basis to accommodate fluctuations in water supply, thus alleviating drought while conserving resources (Kelaher & Coleman, 2022).

In California specifically, future desalination research, design, and implementation has been incorporated into the state's 2020 water resilience portfolio as a viable water supply source; the addition of desalination to the Governor's water plan is aimed at maintaining and diversifying the state's limited water resources (California Department of Water Resources, 2020). The 2020 Safe Drinking Water Plan for California also includes plans for desalination technical and financial resources allotted to disadvantaged communities and predicts an increased need for desalination capabilities due to climate change effects and increasing population demand (State Water Resources Control Board, 2021).

3.3 Cost & Accessibility

The monetary cost of desalinated water is often variable based on the type, operating costs, and location of the desalination plant. However, the final cost of water for the end consumer is largely dependent on the cost of energy for the local area; energy costs can account for 20-50% of the produced water costs (Ahmad et al., 2020). A 2018 white paper by Joe Williams concluded that modern desalination in California addresses the water resource concern and, due to the relative inexhaustibility of Pacific Ocean feedwater, converts water demand into an embedded energy availability concern. The water and energy connection converges two distinct sectors via "nexus-thinking," a term commonly used to manage conflict and overlap in resource sectors traditionally controlled with distinct and separate mechanisms (Williams, 2018). Increased dependence on desalination would then increase dependence on California's energy resources.

Knowing that water cost and energy consumption are related, different methods of fresh water production can be compared using energy consumption as a proxy for end-user water costs. In a case study of San Diego County's water portfolio, conservation plus five methods of fresh water supply were compared in terms of kilowatt hours per mega liter (kWh/ML). Desalination represents the highest energy consumption method

Table 3: Energy consumption needs in kilowatt hours per mega liter (kWh/ML) for selected fresh water production in San Diego, CA. Williams, 2018.

Method	kWh/ML
Increased conservation	0
Re-use of non-potable sources	500
Re-use of potable sources	2,800
Colorado River transfer	2,500
State Water Project transfer	4,100
Desalination	6,000

by far when compared with other locally available water production methods (see Table 3).

Energy costs, and therefore desalinated water costs, are connected with the availability of renewable energy - as global commitments to reducing greenhouse gas (GHG) emissions increase, the cost of energy produced with fossil fuels will likely increase as well (Roth & Tal, 2022). However, the current landscape of energy costs indicates that renewable energy used for desalination (i.e. a steady, reliable source of energy from a carbon-emitting grid) often increases costs despite incentives or carbon credits. A 2020 study found that solar as a renewable energy source was cost-competitive with conventional grid energy sourcing until the addition of photovoltaic (PV) battery storage. Concentrated solar production (CSP) was also found to increase the price of water at the time of the study. Many analyses of desalinated water future costs will add in the rising cost of using GHG-emitting fossil fuels - under that consideration, PV and CSP with storage is likely to be more cost effective in the future. Storage is not currently competitive, so large scale desalination using only renewable energy leads to higher water costs at this time (Kettani et al., 2020).

In the current literature, desalination is often touted as a solution for water scarcity issues in resource-poor areas (Ahmed et al., 2019). Almost 6 billion people could be without access to clean water by 2050 due to a changing climate and an unfair burden from GHG emissions (Bianchelli et al., 2022; Ahmed et al., 2020). However, the justification that desalination could benefit resource-scarce communities appears to be valid only on the surface. A study in 2019 found a high prevalence of desalination plants were located in high income countries and a starkly low prevalence were located in low income countries, some of which are likely to experience or are currently experiencing water crisis. While the concept of desalination as a solution for environmental justice imbalances is tempting, the most current research indicates that communities with limited financial resources are not investing in this technology (Jones et al., 2019)

There are several reasons why desalination might not be accessible or palatable for every community, regardless of energy availability or environmental suitability. First, the upfront discal costs of desalination are substantial (Vasquez et al., 2022). Burdens associated with plant construction and maintenance are incorporated into the consumer's cost of water, as alluded to previously. Second, desalination conducted in a sustainable way is a long term investment, requiring years of permitting and research when other close-term solutions may be more readily available (increased groundwater or surface water pumping). Lastly, communities can be hesitant to support industrial projects that could cause damage to the natural environment, affect the community's livelihoods (fishing and tourism), or incur an environmental justice burden (Heck et al., 2018;Vasquez et al., 2022). For example, the Monterey Bay project approved November 2022 will be located in Marina, CA, but is projected to service water needs for the more affluent Pebble Beach, Pacific Grove, and other Monterey Peninsula enclaves which currently use water from the diminishing Carmel River. Publicly recorded comments and language in Appeal A-3-MRA-19-0034 indicated that residents felt the burden of industrial water production was unfairly placed and would increase the local cost of water regardless of service area (California Coastal Commission, 2019).

4. Energy Consumption

4.1 Minimum Energy Threshold

Seawater desalination requires more energy than other freshwater production sources, including brackish water desalination as seen in Figure 5 (Kiehbadroudinezhad et al., 2022). Compared with traditional surface water treatment, seawater desalination requires at least eight times the kilowatt hours per cubic meter of water (kWh/m^3). There are several reasons for such a high minimum energy threshold - breaking the ionic bonds between water molecules and

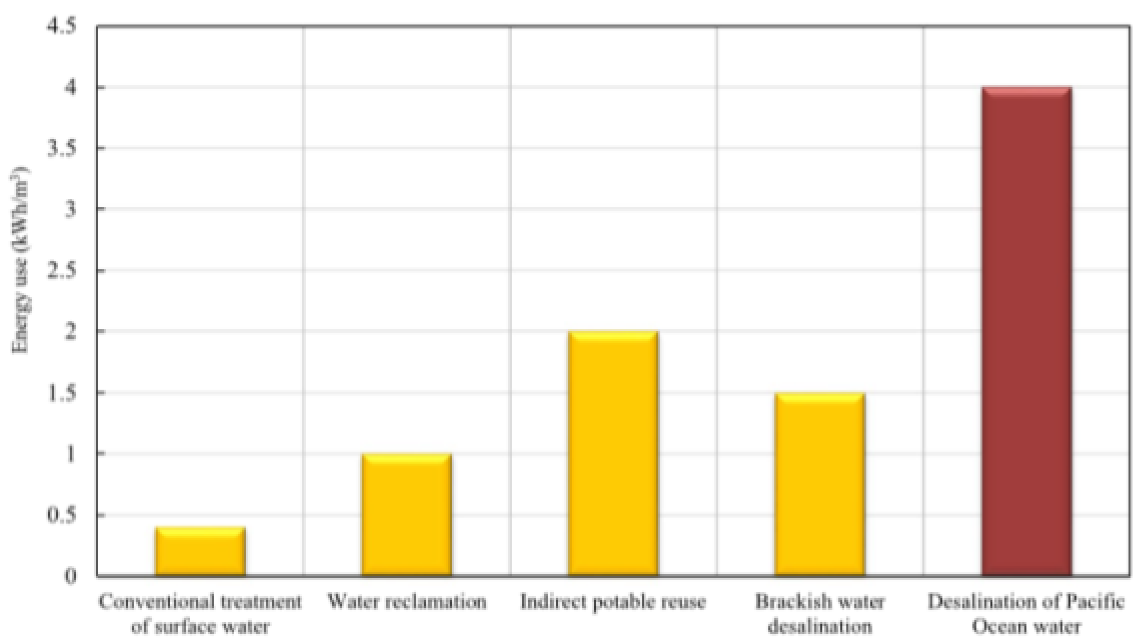


Figure 5: Estimated energy consumption levels for freshwater supply alternatives. Kiehbadroudinezhad et al, 2022.

cations/anions in seawater requires a high amount of energy, even if using reverse osmosis (Gary et al., 2017). Thermal desalination also requires a phase change from liquid to vapor and the amount of heat energy required for that phase change is dependent on the feedwater temperature (Ahmed et al., 2020).

In the last decades, progress has been made to reduce energy needs for RO specifically. Measured in kWh/m^3, specific energy consumption (SEC) refers to the amount of energy needed in the primary processes to produce a unit of mass (Kim and Hwang, 2022). Since the 1970s, the SEC requirement for RO has decreased from approximately 16 kWh/m^3 to 2 kWh/m^3. (Panagopoulos, 2020). However, this SEC estimate only accounts for average feedwater salinity and turbidity, and only includes the primary processes of desalting; additional processes such as pre-treatment, losses from friction, and brine disposal/processing increase energy consumption. Although the SEC is commonly used as a theoretical average for desalination comparisons, the actual energy consumption (AEC) accounts for energy consumption in practice (Panagopoulos, 2020). Estimated AEC ranges expressed in kWh/m^3 for common desalination methods as well as auxiliary processes likely to increase consumption are shown in Table 4.

Table 4: Estimated actual energy consumption ranges for select desalination processes, both primary and auxiliary. Energy is expressed in kilowatt hours per cubic meter of water (kWh/m^3). Lee et al, 2019; Panagopoulos, 2020; Soliman et al, 2021; Nassrullah et al, 2020.

Process	Type	AEC (kWh/m^3)
MSF	Thermal	20 - 27
MED	Thermal	14 - 21
SWRO	Membrane	4 - 6
BWRO	Membrane	1 - 3
ED - high TDS	Membrane + Electric Field	3 - 6
ED - low TDS	Membrane + Electric Field	1 - 3
SWRO + FO	Membrane + Pretreatment	6 - 19
SWRO + NF	Membrane + Pretreatment	2 - 6
Membrane Crystallization	Brine Processing	39 - 73

4.2 Energy Efficiency Variations

Because membrane desalination operates on the principle of osmotic pressure being overcome by applied hydraulic pressure, the amount of energy needed to produce a unit of freshwater is proportional to the osmotic pressure of the feedwater, and the accepted maximum salinity for effective RO is approximately 70 g/l or 70,000 ppm (Panagopoulos, 2020). The more salt and minerals contained in the feedwater, the greater the SEC required to separate these ions from the water molecules. Thus, the local salinity and the turbidity levels of intake seawater have a direct effect on energy efficiency of the desalination process. For locations such as the Arabian Gulf, the SEC for membrane desalination is higher than SEC for the same process in the Pacific Ocean. Similarly, high turbidity waters pumped from closer to shore require more energy to desalinate than waters using infiltration or from deeper, less turbid waters (Rachman et al., 2014).

Because the resulting brine solution from membrane desalination has not lost osmotic pressure, the brine contains energy. This energy can be recouped using Energy Recovery Devices (ERDs), a broad category of tools and techniques designed to harness latent osmotic, hydraulic, and heat energy. Since the energy differential between concentrated brine waste and the produced freshwater is high, there's an electrical current that can be used to generate Salinity Gradient Energy (SGE) to capture Giibs free energy (He & Wang, 2017, Lee et al., 2019, Seyfried et al., 2019). Pressure Retarded Osmosis (PRO) is an increasingly common method of generating electricity from a salinity gradient in order to power the desalting process, thus requiring less energy input (Seyfried et al., 2019). There is also an opportunity for membrane desalination processes to recover hydraulic pressure in the form of potential energy. Since pumping water through the membrane is the largest source of energy consumption, energy in the form of pressurized brine leaves the desalting step carrying a significant amount of latent energy with it. ERDs such as Pelton turbines and isobaric devices recapture brine pressure and apply it to incoming feedwater; these processes can recover as much as 40% of the RO energy typically lost with no ERD implementation as seen in Figure 6 (Ahmed et al., 2020).

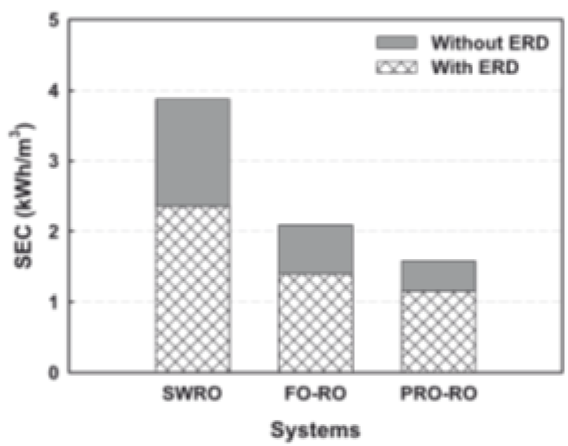


Figure 6: Comparison of SWRO, FO-RO, and PRO-RO systems with Energy Recovery Devices (ERDs). Kim et al, 2015.

Thermal desalination also has a way of recovering energy that would otherwise have been lost after desalting - the brine waste still contains heat and pressure. Top Brine Temperature

(TBT) is a major determinant in the energy consumption of a thermal plant (Hanshik et al., 2016). The higher the TBT, the more freshwater is produced per unit of energy consumed. Instead of discharging the heated brine with embedded TBT energy, ERDs in the form of heat exchangers are used to prime feedwater; this increases the temperature of the feedwater at the beginning of the thermal cycle, thus reducing the overall energy consumption (Hanshik et al., 2016). Thermal desalination plants also can use waste heat from co-generation sites like industrial power wastewater and nuclear plant cooling water. This can have a significant impact on overall energy consumption, as TBT can be supplemented with latent heat recapture (Elsaid et al., 2020).

It warrants attention that several emerging technologies reduce both the energy consumption and the environmental impacts of desalination. One such technology is wave-action desalination, which converts the mechanical energy of waves acting on a buoy to electrical power to run membrane distillation (Kim and Hwang, 2022). Another option that is currently in development is using halophilic bacteria and algae to process the salts found in seawater (Gao et al., 2021). While theoretically possible on a small scale or with very specific conditions, emerging technologies such as wave-action and bio-desalination have yet to prove their applicability for medium or large scale water production.

4.3 Hybrid Systems

Due to rapid development of unique desalination processes and techniques, interest is growing in combining approaches to improve performance (Sahu, 2021). Hybridization of desal technologies uses the beneficial parts of traditionally stand-alone processes to increase recovery rates, reduce fouling and scaling, and boost energy efficiency (Ahmed et al., 2020). Many emerging technologies have recovery rates as high as 90%, but must be coupled with more robust technologies like RO (Sahu, 2021). Examples of commonly used hybrid systems include filtration + RO, FO + RO, PRO + RO, and CDI + RO (Ahmed et al., 2020; Sahu, 2021; Shaffer et al., 2015; Lee et al., 2019).

Due to high propensity for fouling, RO designs will include a filtration step (see Figure 7) to improve water quality before reaching the RO membrane. Filtration at different levels (micro-, ultra-, and nano-) is often necessary due to poor feedwater quality or varying ocean conditions. Nanofiltration (NF) is a popular method for removing particulates, organics, and hardness prior to entry into the RO system (Adda et al., 2022). NF utilizes a highly engineering filtering tube, allowing only minimal salt content to pass through. It is capable of removing scalants and bacteria, is a lower cost system than other forms of pre-treatment, and requires less energy than active methods like FO and PRO. Unfortunately, adding NF adds complexity to the desalination design, which is often difficult to scale past small systems (Adda et al., 2022).

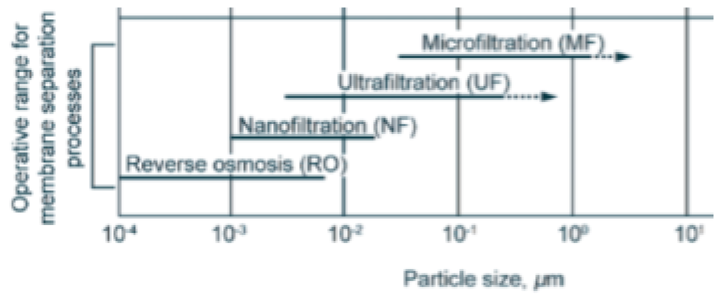


Figure 7: Operative range of membrane technologies compared with dissolved, colloidal, and suspended materials. Aliku, 2017.

Other pretreatment steps include pressure retarded osmosis (PRO) placed ahead of RO (Kim et al., 2015). Forward Osmosis (FO) also uses osmotic pressure to allow water permeation, but does not need the addition of hydraulic pressure like RO or PRO. When an FO step is added prior to RO, high-salinity feedwater is optimized for the desalting system (Shaffer et al., 2015). By negating the need for hydraulic pressure and using only osmotic pressure to reduce salinity, fouling is reduced and the SEC for the system is reduced to 1.1kWh/m^3 (Kim et al., 2015). However, these measures, especially PRO, still require chemical maintenance to prevent inorganic fouling through the use of anti-scalants, which can increase the financial costs. Additionally, active salinity reduction techniques like FO have been found to increase energy consumption to as much as 6-19 kWh/m^3 for RO plants (Lee et al., 2019; Shaffer et al., 2015).

4.4 Renewable Energy

Acknowledging that desalination will most likely remain an energy intensive process regardless of technological improvements, the carbon footprint can be reduced by using renewable energy in place of fossil fuels. Specifically for regions lacking viable water alternatives like Israel, KSA, or desert regions of Australia, renewable energy is viewed as essential for sustaining desalination activities in the future (Roth & Tal, 2022; Fornarelli et al.,

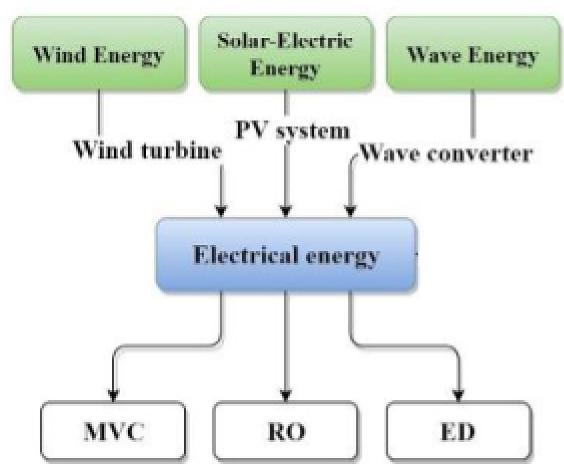


Figure 8: Applicability of renewable energy sources desalination. Mito et al, 2019.

2018). While some forms of renewable energy are inappropriate for water-scarce regions (hydroelectric) or are not guaranteed to be accessible from coastal areas (geothermal), several renewable energy sources are a suitable complement for desalination plants and are readily available on most coasts (see Figure 8). Those sources include wind, wave action, and solar energy production methods (Mito et al., 2019).

The applicability of renewable energy for desalination is dependent not only on local availability of sun, wind, and waves, but also on the local energy grid. Desalination, especially membrane processes, requires a constant and smooth source of energy while in operation. The variability of solar and wind energy complicates the consistent operation of a membrane system. Some regions incorporate renewable energy into the local grid system, negating the need for additional power supply. Some governments, both country and state, have set ambitious renewable energy goals, such as California's commitment to 100% renewable and zero-carbon electricity by 2045 (SB 100, 2018). However, if the local electricity grid is unable to support the additional load, supplemental power must be supplied. To address concerns with variable power, a desalination plant will operate a variable speed pump or use a modular design to allow for peaks and dips in production based on energy availability (Mito et al., 2019). Alternatively, plants may opt to utilize a hybrid system composed of multiple renewable sources, or carbon-based grid energy as a backup for renewable power (Ghazi et al., 2022).

Solar power relies on the availability of clear skies and strong solar irradiation to produce electricity via PV cells. Energy is only produced during daylight hours, is most effective during midday when the sun's rays are strongest, and experiences seasonal variations. The use of a Rankine cycle also captures solar energy to power a steam turbine; the resulting recovery ratio for produced water was above the expected 2:1 ratio for seawater reverse osmosis (SWRO) at approximately 0.70 recovery (Zewdie et al., 2021). More research is needed on Rankine cycles to determine if this technology can be applied for large-scale demand.

The interface for wind turbines is through electricity generation for hydraulic pumps, although mechanical turbines for desalination pumps have been proposed (Gonzalez et al., 2019). Wind power depends on consistent, strong winds and years of wind data to determine appropriate siting, height, and design for maximum exploitation; wind farms can be located inland or offshore, depending on land availability and local regulations. Many of the wind-powered desalination plants in use currently are small in scale and suitable for only remote areas. One alternative is to connect wind-powered energy farms to the local grid transmission network, thus offsetting the additional desalination electricity load and avoiding construction of additional transmission infrastructure (Gonzalez et al., 2019).

Wave action or tidal action exploitation is still in a nascent development stage, and has not been applied commercially. Several small-scale and pilot operations beginning in the 21st century focused on developing viable forms of oscillating wave energy capture (Kim & Hwang, 2022). Conceptually, this form of energy capture would require offshore floating platforms to convert water movement (energy transferred from ocean winds) into electricity, similar to current designs for offshore wind energy production.

One of the biggest concerns for the future is the problem of energy storage. Since renewable energy sources are heavily dependent on environmental conditions, water production may not be readily available at night or in the absence of wind. Currently, energy storage in the form of batteries for solar and wind power are cost prohibitive (Kyriakarakos et al., 2022) and that the theoretical amount of battery storage required for large-scale desalination energy would not be feasible. Battery technology required for large-scale, commercial renewable energy storage must improve in the future and be cost effective prior to implementation with desalination.

5. Results: Environmental Impacts

As large-scale desalination plants have been in use since the 1950s (Darwish, 2011), some understanding has been gained on how desalination affects the surrounding natural environment. However, most ecological studies have focused on the short-term effects of feedwater intake and brine discharge in the Mediterranean Sea and Arabian Gulf. Both of these large, semi-enclosed water bodies support high capacity desalination plants which have been in operation for decades (Paparella et al., 2022). But there is less certainty in the current literature of long term environmental effects and the sustainability of building more and larger sites; the dynamic nature of coastal environments as well as the co-siting of other continuously discharging industrial plants can make studying the desalination outcomes challenging. Based on a review of published literature, desalination production interacts with the coastal environment in four major ways: through feedwater intake, brine discharge, GHG emissions, and water displacement (Kelaher & Coleman, 2022; Williams, 2019; Cornejo et al., 2014; Le Quesne et al., 2021).

5.1 Feedwater Intake

As seawater is taken into the desalination plant, an opportunity exists for marine biota to become impinged (held by water pressure against screens), entrapped (unable to swim out intake structures), or entrained (carried with intake through screens and into plant) in the feed water intake (Missimer & Maliva, 2018: Foster et al., 2012). These processes of impingement, entrapment, and entrainment are collectively referred to in this research as IM&E impacts. It should be noted that intake fouling by marine organisms is not a desalination-specific issue; other industrial processes such as power generation, water purification, and freshwater conveyance also utilize intake systems in natural lakes, rivers, and oceans (Grimaldo et al., 2021). As such, significant design work has already been completed to reduce the IM&E impact. Traditional desalination intakes were vertical pipes from a beachhead and provided only minimal protection for marine life (Hussian et al., 2019). However, newer designs focus on slow flow, escape areas, fine mesh screens, and prevention of entry. In general, marine organisms face a greater threat from direct intakes (open water pipes and screens) than from indirect intakes (water filtration through seabed) (Figure 9).

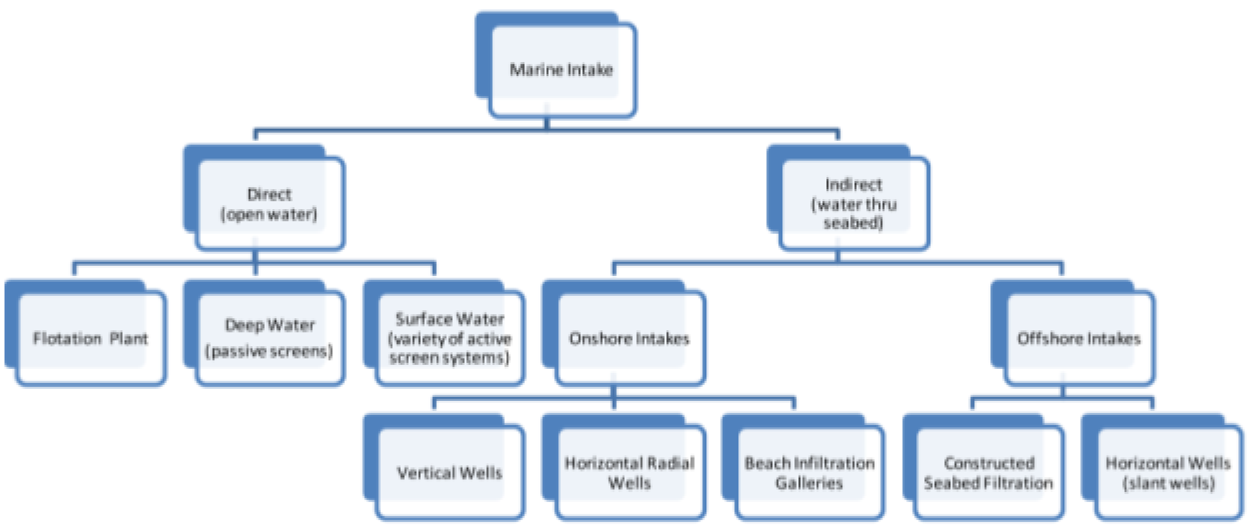


Figure 9: Selected intake designs from ocean environments. Foster et al, 2012.

Other than varying construction designs for intake systems, there are innovative options for preventing IM&E impacts. Reducing intake velocity to less than 0.15 m/s can have a positive effect on aquatic mortality, and measures like fish return systems can prevent harm to marine organisms (Hussain et al., 2019). One example technique utilizes a fish's natural tendency to swim away from dangerous situations; a vertical cap is placed on a vertical intake pipe, creating a change in flow direction. As fish associate horizontal flow with dangerous and unusual conditions, marine organisms capable of sensing intake changes will swim away. When combined with screened low-velocity intakes, fish have an opportunity to leave the area prior to entrapment (Foster et al., 2012). Another example is to place intakes far from shore (greater than 5 km) and at a distance from high bioproductivity areas (Bayoumi et al., 2021); however, one drawback would that artificial structures could encourage new habitat, drawing marine life to intakes (Kelaher et al., 2022).

One perspective on IM&E impacts is that the annual loss of biomass from desalination direct intake would be minor compared with the survival rate of the organisms as a species, citing a mortality report prepared for the California State Water Resources Control Board (Foster et al., 2012). The basis for this theory is that fish in the larval stage, zooplankton, and other tiny biota would be able to maintain high populations despite additional takings associated with feedwater intake mortality. But the full SWRCB report, using the Huntington Beach Generation Station as a case study, indicated that the level of IM&E mortality would indeed affect local fish populations and quantified the expected loss of biomass (Foster et al., 2012). A 2018 review of desalination intakes and outfalls noted that mortality losses for fish larvae may be location dependent (Missimer & Maliva, 2018). The literature is unclear as to what factors would mitigate direct intake IM&E such that takings would be negligible to the species as a whole, and more research is recommended.

As alluded to above, differences in expected IM&E mortality could be based on the location of the intake; if intakes were sited in areas of naturally low bioproductivity such as in open ocean environments, the impact to marine life could be minimal. Le Quesne et al. summarized that population level effects from impingement and entrainment were not visible. However, the study did conclude that most studies focused only on individual plants and failed to take into account the cumulative effect of multiple mortality sources like co-sited intakes, overfishing, and climate change (Le Quesne et al., 2021). The contradictions raised by both the SWRCB report, the 2018 review, and the Le Quesne paper cast doubt on if appropriately designed desalination feedwater intakes are potential sources of long-term environmental harm; more study is needed to determine best practices for obtaining negligible levels of IM&E mortality.

It should be noted that designs incorporating IM&E mitigation measures are not only beneficial for ecosystem health, but also to prevent fouling, a major concern for sensitive membranes used in reverse osmosis desalination systems (Elimelech and Phillip, 2011). A review by Hussain et al. in 2019 found that subsurface, indirect intake systems were an effective physical pretreatment strategy while also avoiding the major IM&E impacts associated with direct intake systems. By preventing debris, suspended solids, and entrained organisms from entering the treatment system, energy costs will decrease and reduce the need for intensive chemical pretreatment steps like the addition of anti-scalants and biofilm preventers (Imbrogno et al., 2017).

5.2 Outfall & Brine

At the completion of the desalting process, brine is created as a waste product effluent. Brine is a highly concentrated saline solution with varying levels of chemicals, minerals, turbidity, and organic matter as seen in Table 5; if produced via thermal technologies, brine can also contain heat as a waste product (Khan et al. 2021; Fallatah et al., 2021; Breunig et al., 2013). While brine can be disposed of or processed through other methods, the most common disposal method is through ocean discharge. Depending on the plant and local regulatory conditions, this discharge may be with or without post-treatment to reduce constituents to acceptable levels. Understanding how the different constituents affect coastal ecosystems is often difficult to tease out, as not all desalination discharge is comparable and not all ecosystems are affected the same manner.

Table 5. Common constituents found in desalination waste streams. Elsaid et al., 2020; Fallatah et al., 2021; Khan et al., 2021; Zhou et al., 2013.

Brine Constituent	Associated Processes	Description
Salts	All	Concentrated salt ions from water removal to include Ca^{+2},Mg^{+2}, K^{+}, and Na^{+}. Combined concentration range is 39-61 g/L in brine discharge, 33-37 g/L in the Pacific Ocean.
Coagulants, flocculants	Membrane	Chemicals such as iron oxides, used to remove suspended solids. Added as a pretreatment step to maximize membrane lifespan.
Anti-scalants	Membrane, Thermal	Acidification to prevent scale damage to membranes and thermal equipment. Can affect pH of brine discharge if not neutralized in post-treatment.

Disinfectants, biocides	Membrane, Thermal	Chlorine is used as a biocidal agent to prevent fouling. Disinfectants and free chlorine are commonly neutralized prior to discharge using sodium metabisulfite (SMBS). Residual prior to post-treatment is 0.1-0.25 ppm.
Organic Matter (OM) / TSS	Wastewater from industrial processes	When the waste stream is mixed or received from wastewater processes, brine may be contaminated with OM.
Inorganic Content	Membrane, Thermal	Trace amounts of heavy metals and minerals to include lithium, copper, chromium, and iron.
Heat	Thermal	Present only in thermal discharge, based on TBT and use of heat energy recapture. Brine can be as high as 10 degrees above ambient seawater temperatures.

The US EPA limits saline discharges to waters of the United States (WOTUS) to within +/- 2 parts per trillion (ppt) of the receiving body's salinity levels (State Water Resources Control Board, 1975), while the EU limits salinity discharges to no more than 38.5 ppt in protection of *Posidonia oceanica* (seagrass) meadows habitats (Gacia et al., 2007; Bleninger & Jirka, 2011). However, if the mixing zone is not appropriate for the discharge, the heavier brine concentrate settles to the ocean floor. This creates a dense, high salinity pool relative to the surrounding area which resists mixing (Ahmad & Baddour, 2014) and can have an effect on local biodiversity. Osmoconformers (species unable to control cellular osmosis) such as echinoderms are less likely to thrive in high salinity (Kelaher et al., 2022; Missimer & Maliva, 2018), although there is some evidence of an adjustment period for areas not exceeding 39 ppt salinity (Gacia et al., 2007; de-la-Ossa-Carretero et al., 2016; Sandoval-Gil et al., 2023). A study in the Mediterranean Sea found increased salinity content in benthic (bottom of a waterbody) sediments near desalination outfalls, indicating a continued presence of saline brine in the environment after discharge, leading to a short-term population increases in halophilic (salt-loving) bacteria (Frank et al., 2019).

Another study also conducted in the Mediterranean Sea compared sentinel taxa population counts of *Polychaetes* and amphipod species before and after diffuser installation. Use of a diffuser spreads the outfall discharge over a larger three-dimensional area and will reduce salinity concentrations per cubic meter at discharge point (see Figure 10). Diffusers will also prevent higher salinity levels from remaining trapped on the ocean floor, thus unable to mix with the less dense, lower salinity water above. A phenomenon discovered by this decade-long research project is that the ratio of sensitive species to opportunistic species in the presence of increased salinity was different than areas unaffected by desalination discharge. This difference was noted prior to diffuser implementation, and the effect slowly lessened over the span of several months as salinity levels normalized around diffuser-equipped outfalls.

This study also found that areas around brine discharge areas experienced a higher ratio of salt-tolerant species when accounting for differences in habitat and sand type; this effect was only short-term, as communities recovered within months of a salinity change (Del-Pilar-Ruso et al., 2014). Also, some organisms like nematodes are not only unaffected by slight increases in salinity, but appear to thrive in increasingly saline waters (de-la-Ossa-Carretero et al., 2016). Thus, areas of increased salinity could create unintended advantages for hardier or invasive species, atleast over a short term period. Also important to note is that while localized effects can be seen in the areas surrounding brine outfall diffusers, the effects are typically localized to the immediate area only; for this reason, outfalls should be placed with consideration to sensitive habitat locations (Le Quesne et al., 2021).

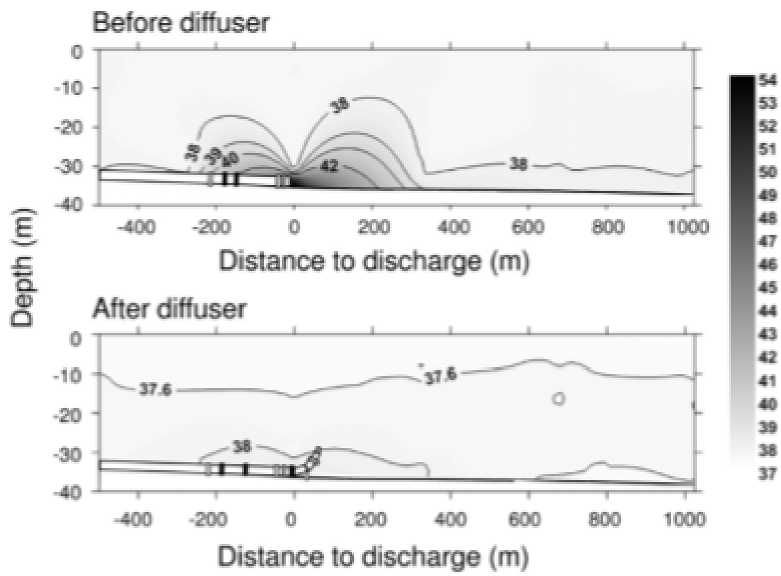


Figure 10: Salinity levels at varying distances from outfall before and after diffuser installation. Salinity is measured on colored scale in g/L (ppt).

In addition to increased salinity, brine from thermal desalination can carry latent heat as a byproduct. In SWRCB’s Water Quality Control Plan for Control of Temperature in the Coastal and Interstate Waters and Enclosed Bays of California of 1975, new plants discharging to open ocean are required to discharge at a temperature no more than 20°F above receive water’s temperature, away from areas of biological significance, and in a way that achieves heat dispersion and an overall increase of no more than 4°F . Discharges to estuaries and enclosed bays have stricter standards, prohibiting discharges in excess of 4°F above the receiving water’s temperature. Should a plant not adhere to these thermal waste standards, brine discharge containing excess heat could fail to mix appropriately with the natural environment due to water density differences. Increased temperature in brine discharge is less of a concern for membrane desalination processes, since the resulting discharge is typically within limits for ambient ocean temperatures (Elsaid et al., 2020). In the same way as brine, slight temperature elevations in localized pockets have the potential to provide an advantage for hardier or invasive species. These small changes could affect the ecosystem as a whole over longer periods of time; more research is recommended to determine the long-term effects of opportunistic species in desalination outfall locations.

Other ways in which brine discharge could potentially affect the marine environment is through pH and dissolved oxygen (DO) changes. The use of anti-scalants will often result in slightly acidic brine; however, seawater's alkaline state of approximately 8.1 is expected to neutralize acidity relatively quickly. A 2021 study by Fallatah et al. found that pH was not correlated with either of the two desalination plants studied for environmental impacts. However, the local conditions should be assessed prior to assumption, as relatively few studies have focused on pH and DO concentrations post-desalination.

Less is known on the effects of the remaining mineral and metal constituents in desalination discharge for several reasons; fewer studies have been conducted, and it's often challenging to ascertain whether an observed effect is due to increased salinity or heat versus the effect of chemicals only. This is a gap in research that warrants future in situ studies. It's important to note that the heavy metal, mineral content other than salts, and man-made chemical levels contained in brine are typically low (Rezaei et al., 2022) and are removed via post-treatment processes (Zhou et al., 2013). While thermal desalination discharge is likely to contain higher levels of metals, a case study found discharges to have metal concentrations still within US EPA's limits (Fallatah et al., 2021). Discharges from membrane desalination typically contain very low levels due to low heat, stainless steel materials, and non-metal components (Elsaid et al., 2020).

Brine outfalls impact the environment in more ways than just the discharge of brine itself - the construction of artificial structures also has an effect on species composition. Fish assemblages increased in species richness after the construction of brine outfall structures at the Sydney Desalination Plant independent of whether the plant was in operation (Kelaher et al., 2022). This could be because of fish attraction to moving water columns or more likely due to increased habitat opportunity on the 4-foot outfall risers. Conversely, while not typically addressed as an environmental impact of desalination, the construction phase of brine discharge systems via subsurface diffusers does come with a cost (Missimer & Maliva, 2018). A study by Kelaher & Coleman in 2022 found that outlet construction contributed to reef damage and grout sedimentation for years following the project. Initial installation disturbance should not be neglected in a review of environmental impacts. Additionally, a separate paper by Kelaher & Coleman from the same study found that initial construction of discharge outlets dislodged kelp species; the empty sea floor was then re-colonized by algal turf after the construction phase ended, and the kelp was unable to compete (Kelaher & Coleman, 2022). This was the only case study to include ecosystem recovery in post-construction sites, and results will likely vary widely based on location.

While this study is primarily focused on coastal desalination, it does merit acknowledgement that inland groundwater desalination plants do not have options for ocean discharge. Instead, common methods of non-coastal brine disposal typically involve evaporation ponds or deep well injection. While evaporation ponds add value to the plant by producing economically viable fertilizers and salts from the waste brine, using this method dramatically increases the land use footprint (Einav et al., 2002). Injection wells use less area, but have the potential to contaminate soils and groundwater should the injected saline migrate to a freshwater aquifer (Foster et al., 2012).

Recent developments in circular economy trends propose use of the valuable, mineral-laden brine waste in industrial processes like concrete production (Fattah et al., 2017), agricultural irrigation of salt-tolerant crops (Czuba et al., 2022), and recovery of solid salt and fertilizer materials (Giwa et al., 2017). One of the most promising methods of converting brine from waste to valorized resource is zero liquid discharge, or ZLD (Elginoz et al., 2022, Chen et al., 2021). ZLD uses subsequent processing after desalination to remove all water content from the brine. MVC or MED, both of which use pressurized water vapor for hypersaline solutions, can recover up to 98% of the water content (Pinnu & Bigham, 2021); although the addition of this step requires almost 40 kWh/m^3. Membrane crystallization is also a practiced method of extracting solid resources from brine, but could also be energy intensive and cost-prohibitive (Shokri & Fard, 2022; Kyriakarakos et al., 2022). A last example of brine valorization is Bipolar Membrane Electrodialysis (EDBM), which converts salty water into diluted salts, acids, and bases (Herrero-Gonzalez et al., 2018). Improvements in the field of brine reuse and ZLD are expected to revolutionize desalination waste discharge practices (Giwa et al., 2017) and include desalination processes in circular economy trends.

In addition to salts, desalination brine contains trace amounts of lithium, copper, and rubidium, both valuable heavy metals used widely in the technology sector (Khan et al., 2021). While land extraction can be a challenge for heavy metal recovery, seawater mining from brine has the potential to offset demand for land-based mining. Employing a brine processing step also eliminates discharge into natural waterways; however, the environmental cost is converted from an environmental impact to an energy consumption impact. The energy required to process complete removal of liquid from desalination waste as well as the transportation costs should be considered in a lifecycle analysis (LCA).

5.3 Greenhouse Gas (GHG) Emissions

Due to reliance on supplied power to hydraulically pump water against a gradient, desalination's carbon footprint is positively correlated to consumption of fossil fuels-based electricity and the use of embedded GHG-emitting processes for operation. If desalination plants were to be powered solely by renewable sources without reliance on other fossil fuel-linked industrial processes, GHG emissions would primarily be attributed to the use of chemicals like coagulants, flocculants, and anti-scalants. Using a tool developed by University of California Berkeley (WESTWeb), the actualized burden of SWRO or BWRO attributable to GHG emissions can be determined based on plant materials and transportation, see Figure 11 (Cornejo et al., 2014). While these costs may be necessary to mitigate other environmental concerns like ecosystem damage, the burden still remains to be addressed. More study may be

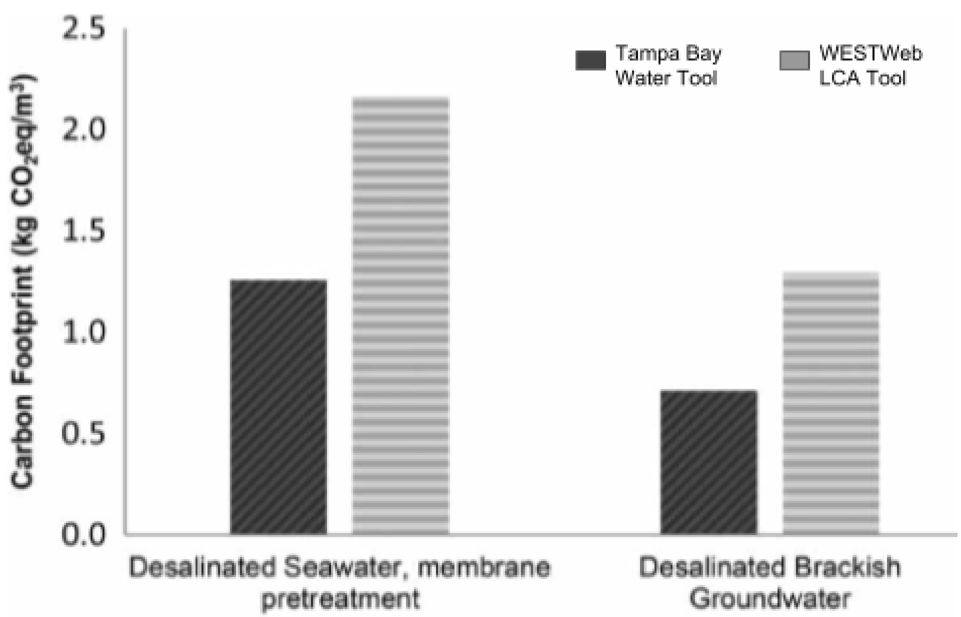


Figure 11: Carbon footprint estimates based on two LCA tools. Cornejo et al, 2014.

necessary to reduce the carbon footprint for the auxiliary processes.

One example of embedded GHG emissions comes from a case study in the Greek islands. Researchers noted that freshwater is sometimes transported from the mainland to islands via water tankers under diesel power. This process is financially costly, increases GHG emissions, and embeds a carbon footprint. The authors recommended that water hauling should not be intended as a permanent solution for water scarcity, encouraging water production alternatives like desalination for the islands (Kyriakarakos et al., 2022). If uncontrolled, GHG emissions will negatively affect marine environments through ocean acidification, warming seawater temperatures, and extreme or unusual weather events. Combined with desalination-linked environmental concerns like IM&E, brine outfall, and ocean floor disturbance, this cumulative impact places stress on coastal ecosystems (Sharifinia et al., 2019). Research is currently not available in regards to the outcomes of cumulative desalination stress on coastal environments, and future study is recommended.

5.4 Water Displacement & Land Use

One of the more difficult challenges for California water managers is freshwater distribution. Water located in Northern California is transported long distances to the Central Valley and Southern California for agricultural and urban use. The resulting water displacement has negatively affected water conditions in the Delta, Sacramento River, and San Joaquin River (Grimaldo et al., 2021); diversion from critical habitats has affected anadromous fish, endangering some of California's economically viable resources (Grimaldo et al., 2021). In terms of water displacement effects, freshwater produced by desalination would not incur a comparable level of impact; sea levels would remain unchanged and intake of desalination feedwater does not fundamentally change the water availability (Williams, 2018). In this regard, desalination could be seen as a way to alleviate environmental pressure when compared with other fresh water production methods.

Land use conflicts arise when available space for development is scarce. While the footprint for desalination processes would be comparable with other industrial plants (Einav et al., 2002), the energy needed to sustainably power the desalination plant must likely come from either wind or solar. One example of environmental land use tensions exacerbated by desalination is a case study by Roth and Tal in 2022. Limited space for habitat conservation and prime solar PV generation came into conflict in Israel. This Mediterranean country has a sustainability goal of 70% renewable energy by 2030, but also needs to expand their desalination operations for fresh water production (Roth & Tal, 2022). Assuming that 1000 megawatts of solar PV generation requires an approximately 10 km^2 footprint, the study researchers found that a space only slightly less than the largest city of Tehran (approximately 40 km^2) would be required to meet Israel's 2030 desalination needs. This conflict can also arise when desalination needs come into conflict with prime beachfront property or high tourism areas. The social and environmental impact of converting open space to industrial purposes must be considered as an additional sustainability factor.

6. Discussion: Management Recommendations

When considering only energy consumption impacts, major indicators of sustainability are centered primarily on qualitative consumption, energy recovery, and efficiency of the desalination plant itself. However, when considering environmental impacts, there is less reason to focus on the design and efficiency of the desalination technology; sustainability factors center on the intake design, outfall design, waste management, and associated GHG emissions. These considerations interact with the natural, coastal environment and the larger regional ecology. When considered holistically, major indicators of desalination sustainability in regards to both energy and environmental impacts are energy consumption, GHG emissions, intake design & siting, outfall design & siting, construction/mitigation, land use, and waste management.

The relative scale index presented in this research combines available sustainability considerations from the literature using Noam Lior's definition of sustainable activities (see Figure 12 below). The selected considerations are then presented in an accessible and visible metric for assessing desalination sustainability. Desalination indicators are based only on major, commercial methods of desalination and the associated design and siting characteristics; not included in the relative scale index are water production methods outside of desalination. Also not included is fiscal conditions; while acknowledging that monetary cost is a major consideration in any municipal or regional project, this research does not include cost as a sustainability indicator based on the interpreted definition of sustainable activities (see Figure 12 below). In cases where qualitative information is used, relative rankings are based on available literature and are interpretation-based. Major sustainability indicators are discussed in detail below and visual depictions of each are presented in Figure 13.

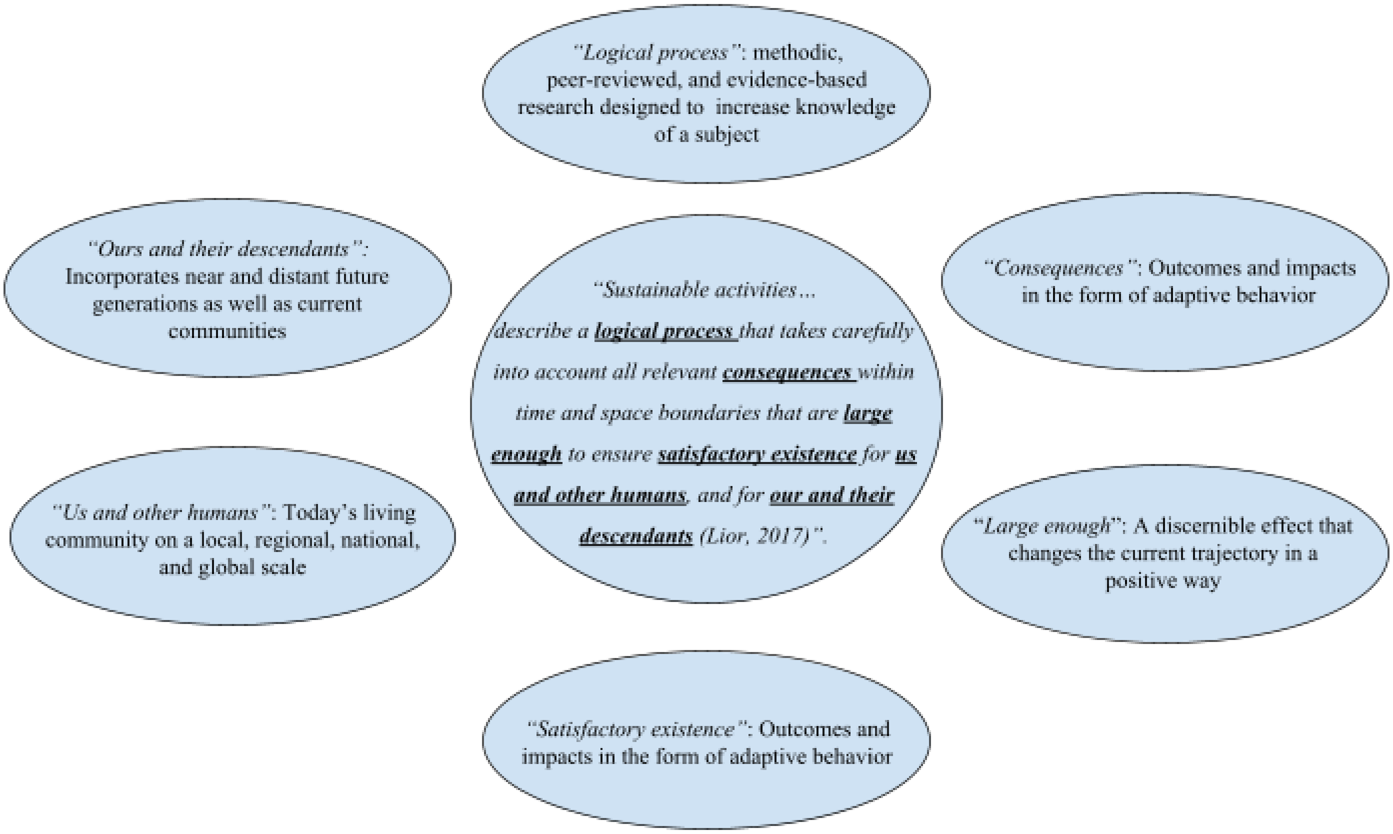


Figure 12: Illustration of expanded sustainable activity definitions applied to desalination activities for the coastal communities. General definition of sustainable activities taken from Noam Lior's 2017 article, expanded definitions for desalination activities adapted from reviewed literature.

6.1 Major Sustainability Indicators

Energy consumption is determined primarily by associated processes within the desalination step. Location is less of an influential factor, as many desalination plants are located in relative proximity to intakes and outfalls. In general, membrane-based technology is the most energy efficient method of desalination, and thermal processes are the least energy efficient. The use of ERDs (presented as a separate indicator), can decrease overall energy consumption. The addition of a brine processing auxiliary process, due to its need for thermal energy for crystallization and high salinity evaporation, is by far the most energy-consumptive process included in this indicator review. A consideration to note is that while BWRO may be the least consumptive form of desalination and MSF is the most consumptive, the feedwater quality is the determining factor as to which desalination methods are available for plant design. Hypersaline feedwater, for example, may be most efficiently processed through a thermal desalting technology method.

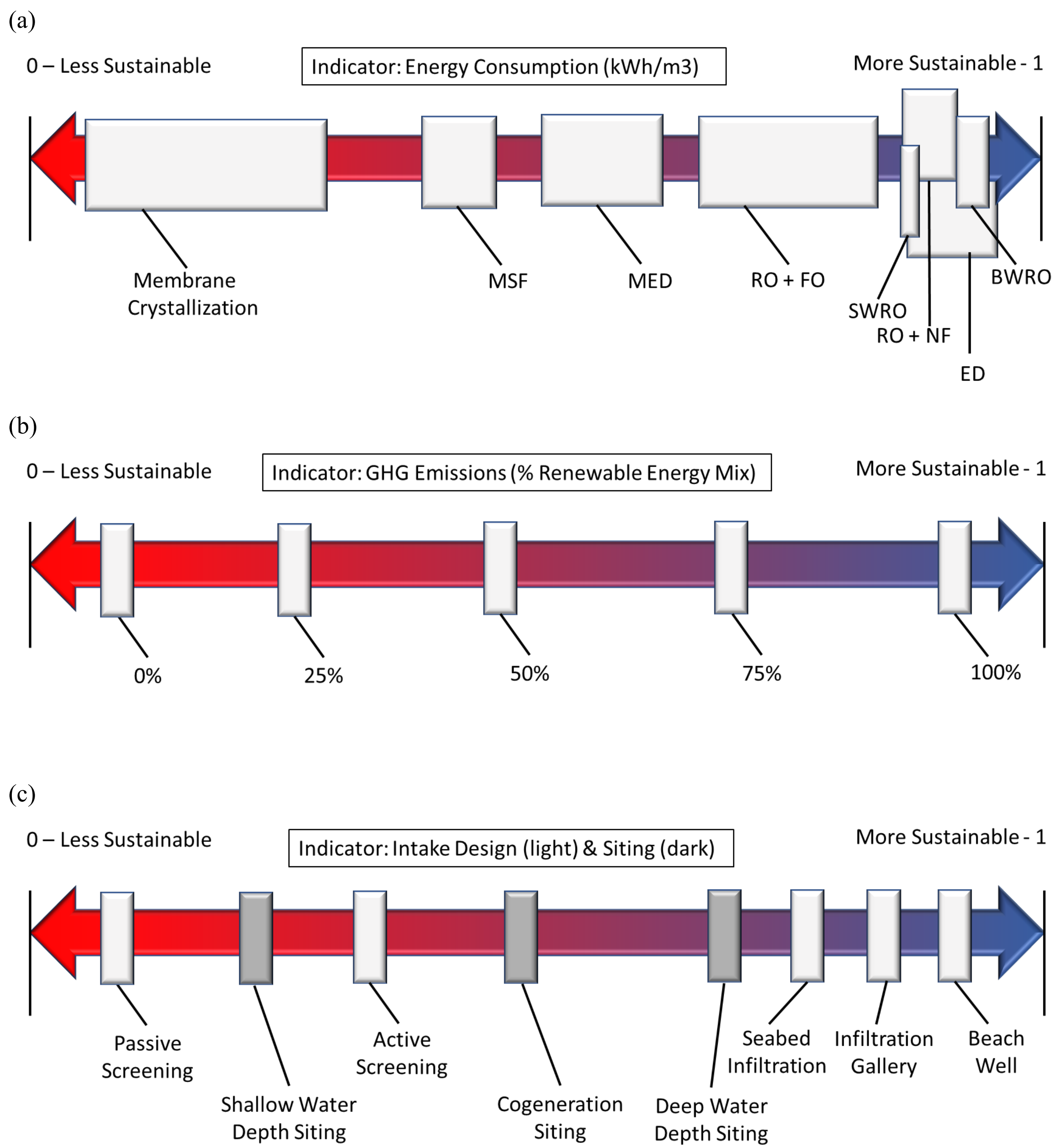
GHG emissions are more a function of the energy source than the plant design itself and should be compared separately from total energy consumption. Because of this, local conditions and renewable energy availability are highly influential in total GHG emissions. This indicator ranks GHG emissions not in total pounds (kg CO_2eq/m^3), but in relative percentage of the energy mix. For plants utilizing 100% renewable energy sources for desalination, the relative sustainability is much higher than plants receiving energy from 50% renewable energy grid. In this way, energy consumption and its associated carbon footprint can be decoupled and compared separately. This also could take into account community commitment to sustainability, as the local municipal grid must have the ability to provide renewable energy in the first place. It's important to consider that even if the energy mix is 100% renewable energy, there will still be some embedded GHG emissions to account for in the form of chemical use. An LCA can be used to determine specific carbon footprints.

Intake Design & Siting measures the relative impact to marine organisms in the benthic environment around desalination intake systems. In general, deeper water will have less biological productivity, and thus less of an IM&E impact versus shallow water siting where more bioproductivity is expected. The designs of the intakes are relatively ranked based on mitigation of IM&E mostly and somewhat on the construction disturbance expected from installation. For example, infiltration galleries have an almost zero percent IM&E risk, but will incur a disturbance of some level on the marine ecosystem (level of disturbance is presented as a separate indicator).

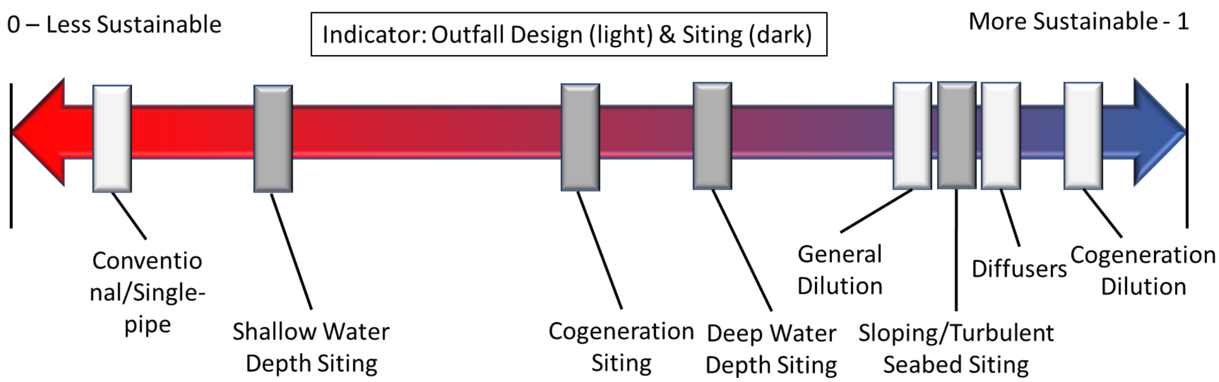
Outfall Design & Siting also measures the relative impact to marine organisms in benthic environments; the siting impact is somewhat similar to intake indicator, with some exceptions. Distance from land is the primary measure for siting location, but slope of seabed is also important - the ability to mix the outfall brine with the receiving water is critical for preventing salinity pools from forming. Turbulence will also increase mixing zone effectiveness, reducing the chance that salinity will have a negative effect on the local ecosystem. The design of the outfall piping itself is also important. conventional piping systems make no attempt to encourage mixing, while diffusers have been shown to be effective in dispersing discharge clouds and reducing salinity concentrations. Other options include dilution prior to discharge, thus decreasing salinity to ambient levels in seawater, or diluting with power plant cooling water, if available. This last option could be considered the most sustainable option since besides resulting in reduced salinity levels, construction of a new outfall would not be necessary.

Construction Disturbance & Restoration/Mitigation Effectiveness refers to the relative effectiveness of restoring benthic environments to their prior state of productivity; however, there is very little research conducted on recovery of desalination-affected ecosystems, so this indicator is not current able to reflect best management practices (BMP) or best available technology (BAT). Until more information is available, it includes broad, descriptive categories of high, moderate, and minimal ecosystem disturbance based on best professional judgment (BPJ). Post-construction restoration and mitigation to sites adjacent to affected areas has also not been studied thoroughly. BPJ will be required to determine the relative sustainability of this indicator beyond ternary categories of no restoration/mitigation, mitigation at location other than damage site, or restoration at damage site.

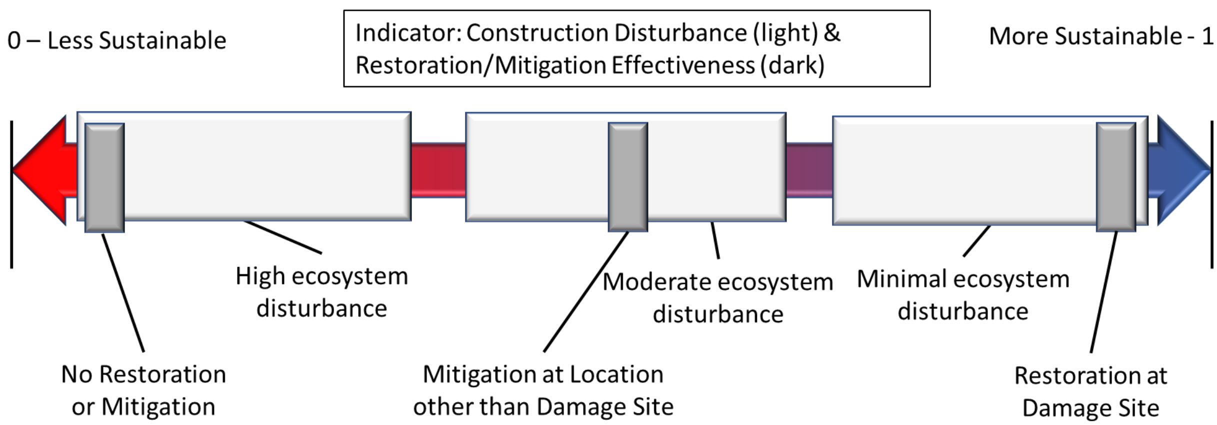
Lastly, the Waste Management indicator includes management practices for both use of brine and re-capture of energy in the form of ERDs. This scale gives a prediction of alignment with a circular economy, encouraging reuse, repurposing, and conservation of existing resources. There are numerous ways ERDs are employed, but for simplicity, this relative index combines all energy recovery techniques into one broad category with the understanding that any recovery of embedded energy will be more sustainable that failure to re-capture spent energy. Similarly, there are numerous emerging technologies which can be categorized as ZLD-related processes. For the sake of simplicity, all solid brine processing methods were included as more sustainable waste practices than environmental discharge of raw materials.


(a)
0 – Less Sustainable
Indicator: Energy Consumption (kWh/m3)
More Sustainable - 1
Membrane Crystallization
MSF
MED
RO + FO
SWRO
RO + NF
ED
BWRO
(b)
0 – Less Sustainable
Indicator: GHG Emissions (% Renewable Energy Mix)
More Sustainable - 1
0%
25%
50%
75%
100%
(c)
0 – Less Sustainable
Indicator: Intake Design (light) & Siting (dark)
More Sustainable - 1
Passive Screening
Shallow Water Depth Siting
Active Screening
Cogeneration Siting
Deep Water Depth Siting
Seabed Infiltration
Infiltration Gallery
Beach Well

(d)



(e)



(f)

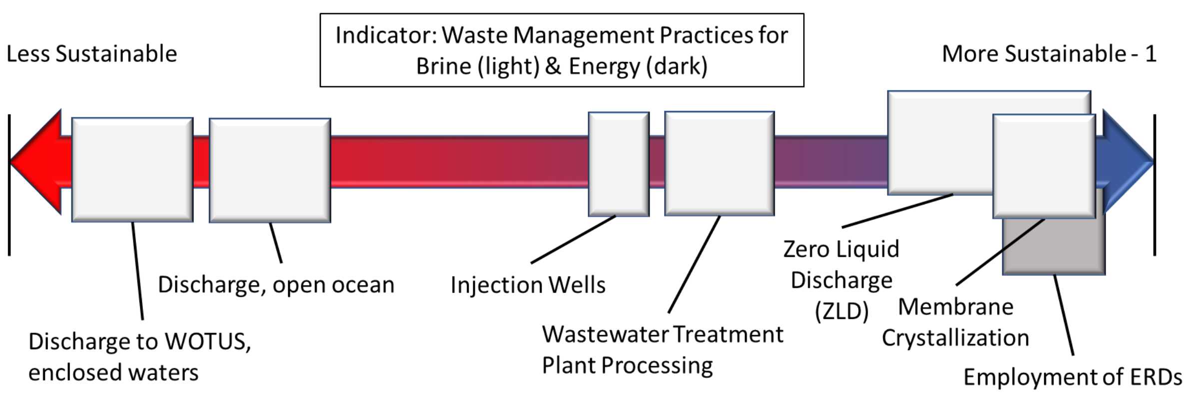


Figure 13. Major desalination sustainability indicators, relative sustainability based on information gathered from reviewed literature. (a) Energy consumption in terms of power consumption per kilowatt hour per cubic meter of produced water (b) Greenhouse gas (GHG) emissions scale in terms of renewable energy percentage from electrical grid (c) Relative sustainability of intake design and siting (d) Relative sustainability of outfall design and siting (e) Burden of construction disturbance to ecosystem and relative effectiveness of restoration or mitigation measures (f) Relative sustainability of waste management practices employed for brine disposal and waste energy.

6.2 Additional Sustainability Considerations

Although not included in this research's index as stand-alone indicators, there are other factors to consider when evaluating sustainability. These include resilience to climate change, opportunities for cogeneration with similar industrial sites, chemical use reduction or replacement with low-impact alternatives, space availability, regularity of use, and community commitment to sustainability. These additional indicators are less likely to have quantitative measurements and may be subjective, such as community commitment to sustainable desalination. Similarly, some indicators may not be applicable to every coastal locality, such as co-generation opportunities. In lieu of an indicator scale, Table 6 provides a list of questions for consideration when designing and siting large-scale desalination in coastal settings.

Table 6: Additional sustainability considerations for desalination siting and design.

Factor	**Consideration**
Resilience to Climate Change	● What climate change impacts are predicted for the local area? ● What climate mitigations are in place? ● Is the addition of desalination expected to mitigate or exacerbate climate change impacts for the local area?
Cogeneration Opportunities	● Are cogeneration opportunities available? ● Will cogeneration increase or decrease energy consumption? ● Will cogeneration increase or decrease waste production?
Chemical Use	● What are the chemical requirements for the designed operation? ● What replacements can be made to lessen the carbon footprint?
Land Availability	● Is space available for both the designed plant and a sustainable energy source? ● Will the designated site, intakes, or outfalls conflict with land conservation efforts?
Use Regularity	● Will the plant be needed continuously or intermittently? ● Is the plant designed for urgent needs only (for example, peak tourism season or seasonal drought conditions)?
Community Commitment to Sustainability	● Does the community understand the implications of a desalination plant? ● Do the community have the knowledge to make informed decisions? ● Is the community committed to conserving existing water resources?

7. Limitations & Future Research

This research focused solely on established and developing technologies applied in large-scale desalination plants for water production. As such, there were significant and innovative technologies still in nascent development that were omitted from the scope of this project, as well as small-scale or microgrid options. Additionally, the case study research was geographically focused on coastal community freshwater use specifically, albeit including examples from around the globe; however, the scope of this project did not include inland, agricultural, or industrial applications for desalting, and only lightly touched on brackish water desalination. All of these applications and technologies warrant further study and consideration to determine the overall sustainability of all desalination operations. Abundant information is available on technical design of desalination plants, but less research has been conducted on how implemented designs will impact the natural environment long-term.

During the research process, there were very few studies that mentioned ocean floor restoration after outfall construction, and none that studied the efficacy of benthic restoration post-installation at intake and outfall sites. Understanding that alterations to the natural environment can have long-term consequences, it would be interesting for future research to focus on restoration efficacy specifically at intake and outfall for desalination sites. The knowledge currently unavailable could provide insight to reverse initial construction damage and lead to healthy steady-state conditions for desalination-affected environments.

Similarly, there were several areas of insufficient information. Very little conclusive evidence was available for true IM&E impacts of juvenile takings. Currently available literature was conflicting, and more data is needed specifically for open ocean intakes in order to determine the population level impacts. The effects of heavy metal and chemical levels in brine discharge were also difficult to ascertain from the available literature; as salinity is the predominant constituent in brine, the impact of other constituents appears masked. While the assumption can be drawn that chemical levels are too low to be significant, an analysis must be conducted on the discharge stream under in situ mixing conditions.

Since the demand for freshwater contributes to the demand for intensive technology, it is imperative that increased freshwater production be accompanied with a corresponding increase in social responsibility and conservation of currently available resources (Le Quesne et al., 2021). Access to increased water must not result in increased water waste, and desalination must not be intended to replace water conservation or reuse efforts. In practice, the addition of a freshwater supply should be in complement with reducing current water demand and preserving available water supplies (Roth & Tal, 2022).

This research acknowledges the role that climate change plays in ocean health; the studies used to develop the desalination sustainability index today may not be applicable tomorrow in the face of a rapidly changing ocean environment (Tubi & Williams, 2021)Remove. For example, case studies found that some sentinel taxa are currently unaffected by slight salinity changes in their environment; however, the cumulative effects may be negative when these species come under pressure to adapt to rising sea water temperatures, sea level depth changes, and ocean acidification. It is important to incorporate the influence of climate change (physically, economically, socially) in sustainably-focused designs, and future research is recommended to study how climate change will affect desalination viability and impact.

8. Conclusions

This research found that energy consumption is more often a function of the plant's design. All components ranging from technologies used to auxiliary processes to waste disposal methods all play a role in either reducing or compounding energy consumption. Energy consumption can be used as a proxy for GHG emissions, depending on the grid's renewable energy mix. Additionally, energy consumption can also be used as a proxy for the relative cost per unit of water produced by desalination, since the cost of energy is a major determining factor in desalination production. Environmental impacts, however, are more closely related to external factors in the coastal environment, as well as siting design, construction and restoration, and the brine disposal method. Since desalination has not been found to be a single-size-fits-all solution, it's important to consider that desalination designs should be tailored to each unique situation for a sustainable water portfolio.

This research demonstrates that focusing solely on the design of the plant or on local site characteristics will not capture a holistic view of large-scale desalination impacts. This research presents this relative scale index as a concept – this model brings together all the sustainability factors and visually indicates sustainable options. Desalination is a variable form of freshwater production; there are a multitude of factors playing a role in energy consumption and environmental impacts. With this variability in mind, desalination should be designed centered around the local coastal conditions to minimize environmental damage and lower energy consumption as well.

Appendix A: Definitions & Acronyms

Best available technology: A common, general term for accepted, preferred, or standard technology or techniques.

Brine: Waste product of concentrated salty water resulting from desalination processes. Can contain other minerals, chemicals, inorganic material, or heat.

Benthic: Referring to the bottom of a water body.

Bioproductivity: A measure of an ecosystem's biological production over a set period of time, usually measured in biomass (carbon or energy content).

Best management practice: Methods or actions that have been found to be the most effective and practical.

Best professional judgment: Expert opinion that sheds light on a specific subject and is peer accepted.

Circular economy: Concept in which the economy is centered on waste reduction by reusing or repurposing materials. Extends the lifespan of a resource.

Cogeneration: Also referred to as co-location, constructing similar industrial plants together in order to share resources or reduce waste.

Embedded/embodied energy: The energy used to make or to use a product (spent energy). Used in this project to refer to energy still available for recovery after desalting.

Emerging technologies: Theoretical or pilot-tested methods not commercially available, currently in research & design phase.

Fouling: Accumulation of undesirable solids on the membrane's surface. Can be permanent or temporary.

Large-scale: As used in this project, refers to desalination plants producing water at the million gal/day range and capable of supporting large populations.

Mixing zones: Areas of turbulence or seabed elevation that promote uniform mixing of hot/cold or lighter/denser water.

Nexus thinking: Using an holistic approach to a problem that considers impacts not only to a single sector, but to all connected sectors as well.

Osmoconformers: Organisms unable to regulate cellular osmosis, sensitive to changes in salinity (such as jellyfish).

Salinity: The level of salts dissolved in water, usually expressed as a unitless number in ppt. Referred to in this project using g/l or ppt for clarity.

Sentinel taxa: Species or groups that could be representative of an exposure, typically used for contaminant study.

Valorization: Organized process of encouraging use of or increasing price or status for a product or resource.

AEC	Actual Energy Consumption		EU	European Union		MVC	Mechanical Vapor Compression
BAT	Best Available Technology		FO	Forward Osmosis		NF	Nanofiltration
BMP	Best Management Practices		GHG	Greenhouse Gases		PRO	Pressurized Retarded Osmosis
BPJ	Best Professional Judgment		IM&E	Impingement, Entrainment, & Entrapment		PV	Photovoltaic
BWRO	Brackish Water Reverse Osmosis		KSA	Kingdom of Saudi Arabia		RR	Recovery Ratio
CDI	Capacitive Deionization		kWh/m^3	kilowatt hours per cubic meter		SEC	Specific Energy Consumption
CBT	Charge-based Technologies		kWh/ML	kilowatt hours per mega liter		SGE	Salinity Gradient Energy
CSP	Concentrated Solar Power		LCA	Life Cycle Assessment		SWRCB	State Water Resources Control Board
DO	Dissolved Oxygen		MED	Multi-Effect Distillation		SWRO	Seawater Reverse Osmosis
ED	Electrodialysis		MENA	Middle East North Africa		TBT	Top Brine Temperature
EDBM	Bipolar Membrane Electrodialysis		MGD	Million Gallons per Day		WOTUS	Waters of the United States
ERD	Energy Recovery Devices		MSF	Multi-Stage Flash		ZLD	Zero Liquid Discharge

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