

---

# 7 Desalination

---



Powering the Blue Economy: Exploring Opportunities  
for Marine Renewable Energy in Maritime Markets

April 2019

## 7. Desalination

### Key Findings

- Desalination is an energy-intensive process because of the energy required to separate salts and other dissolved solids from water. In operation, the actual pressure required is approximately two times the osmotic pressure; for seawater, this translates to about 800–1,000 pounds per square inch. The energy required to run pumps that can achieve these high pressures account for approximately 25% to 40% of the overall cost of water (Lantz, Olis, and Warren 2011).
- Wave- or tidal-powered desalination could be used to directly pressurize seawater without generating electricity for a reverse-osmosis system, eliminating one of the largest cost drivers for the production of desalinated water.
- There are two primary market segments for desalination: water utilities and isolated or small-scale distributed systems. Large-scale desalination systems require tens of megawatts to run and provide tens of million gallons of desalinated water per day. Small-scale systems vary in size from tens to hundreds of kilowatts and provide hundreds to thousands of gallons of water per day.
- Marine energy resources are inherently located near potential desalination water supplies and high population concentrations along the coast, therefore areas that have unreliable grid connections or water infrastructure may receive dual benefits from marine energy systems. In the long term, marine energy could provide low-cost, emission-free, drought-resistant drinking water to larger municipalities.
- The National Renewable Energy Laboratory's (NREL's) simulation results suggest a direct pressurization application could be more cost competitive when producing water than a wave-energy system producing electricity given current cost estimates (Yu and Jenne 2017). This finding clearly signals a near-term market opportunity for wave energy, requiring smaller cost reductions than grid-power applications.

### Opportunity Summary

Desalination is the process in which salts and other minerals are removed from a fluid, such as seawater. Reverse osmosis is a common method for seawater desalination, and the U.S. market is anticipated to reach approximately \$344 million in capital expenditures and about \$195 million in operational expenditures by 2020 (Global Water Intelligence 2016). This is a significant increase from the 2015 capital and operational expenditures, approximately \$129 million and \$124 million, respectively, with these trends expected to continue to rise as water demands and shortages increase. Globally, the seawater desalination market reached approximately \$2.6 billion in 2015 in capital expenditures, with a similar growth rate anticipated to hit over \$4.5 billion in 2020. Operational expenditures are on the same order of magnitude, approximately \$3.8 billion in 2015 and projected \$5.2 billion by 2020. For seawater desalination, energy consumption is the largest component of the operational expenditures, making up approximately 36% of the total operational expenditures. In the United States alone, this accounts for about \$45 million per year in electricity consumption using the 2015 market size and approximately \$70 million using the 2020 projections (Global Water Intelligence 2016). Currently, the desalination market is a small portion of the total U.S. water consumption, but there is an anticipated 20% increase in capacity by 2020 (Global Water Intelligence 2016).

Desalination is an energy-intensive process, and the high electricity costs have similar economic implications to fuel or other operational costs that cannot be amortized over the life of the project. The ability to bypass these energy costs could potentially be critical for development. Companies and technology developers in the marine energy space believe wave-powered desalination (Figure 7.1) may help address this issue.

NREL has researched and modeled wave-powered concepts that directly pressurize reverse-osmosis seawater desalination systems, bypassing the need for significant energy generation. In fact, NREL's simulation results

suggest a direct pressurization application could be more cost competitive when producing water than a wave-energy system producing electricity given current cost estimates (Yu and Jenne 2017). This finding signals a near-term market opportunity for wave energy requiring smaller cost reductions before the technology is commercially competitive with grid-power applications.

Other desalination technologies may include forward osmosis, ion separation, thermal processes, or several other emerging technologies, but any analysis used for this chapter leverages analysis performed for a wave-powered reverse-osmosis technology. Additionally, this chapter focuses primarily on seawater desalination for drinking water applications; however, we acknowledge that other end uses, with potentially less stringent quality requirements, are possible. Drinking water is the primary end use in this chapter because of the energy requirements for desalting seawater. Although certain markets (i.e., irrigation) may be able to accept higher salinity than drinking water applications, the amount of additional energy required to produce water that is acceptable for drinking water versus irrigation is relatively small. Therefore, this chapter focuses on drinking water as a higher value product.

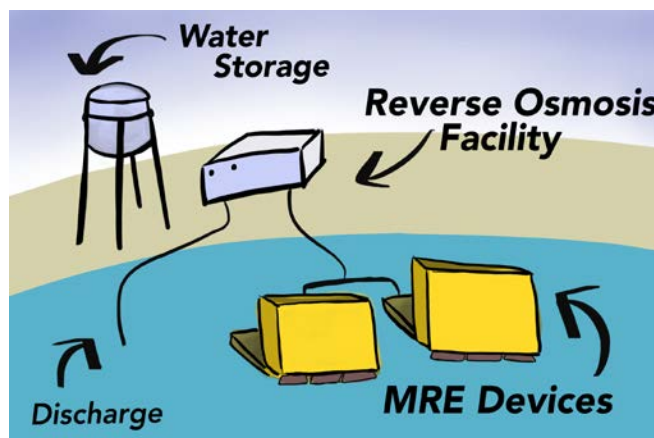


Figure 7.1. Marine renewable energy (MRE) application overview for desalination. Image courtesy of Molly Grear, Pacific Northwest National Laboratory

## Application

### Description of Application

Seawater desalination is a small but growing part of the global water industry. In the United States, the existing seawater reverse-osmosis market is at a capacity of approximately 500,000 m<sup>3</sup>/day (Global Water Intelligence 2016), translating to approximately \$45 million–\$65 million per year in electricity consumption. Currently, the desalination market is a small portion of the total U.S. water consumption, but there is an anticipated 20% increase in capacity by 2020 due to population increases and reliable drinking water demand (Global Water Intelligence 2016).

The largest customers for desalinated water are primarily water utilities with significant drinking water demands and long-term investment horizons, making the cost to produce water a primary driver for new technology and water supply adoption. However, less price-sensitive market opportunities exist in regions with few other options, such as isolated communities, disaster relief situations, and military applications. Marine energy technologies (wave and ocean current) could produce drinking water with little-to-no electricity generation. The ability to produce drinking water with minimal electricity is appealing in regions where grid-connected electricity is unreliable or costly. In addition, hybrid systems can be designed to produce both electricity and clean water if desired (e.g., Resolute Marine Energy systems).

The most likely near-term marine energy technologies for desalination are nearshore wave and tidal technologies, particularly because of the proximity to shore, enabling easier access to standard desalination



equipment. Nearshore technologies allow for more equipment to be located on land, require simpler installation techniques, and have lower maintenance costs. However, environmental and permitting challenges associated with brine discharge and inlet designs (e.g., velocity restrictions) may incentivize deepwater technologies as wave energy converter (WEC) technologies mature. Of course, the additional cost associated with getting clean water to shore, either through pumping or secondary transport, will have to be weighed against permitting cost reductions.

Because of the scalability of reverse-osmosis desalination technologies, water capacity can range from small to large. Capacity will likely be driven by the cost and performance of marine energy technologies and not the desalination technology. For remote communities that have high water costs and high renewables penetration (e.g., solar or wind), there is the potential to design hybrid systems that can be used for water production, electricity production, or load balancing. This can be achieved by diverting flow from the reverse-osmosis system to an electric generator to produce electricity. An electric motor can be installed on the reverse-osmosis pump to pull excess electricity from the grid as needed for load balancing.

Initial analysis performed by NREL suggests that a WEC that averages the electrical equivalent of 1 megawatt (MW) will produce an average of 8,100 m<sup>3</sup>/day of fresh water. The optimum ratio (8,100 m<sup>3</sup>/day per MWe-average) is dependent on the cost of both the WEC technology and the reverse-osmosis system. In an attempt to understand the most economically viable solution, NREL’s study found the optimum capacity factor for the reverse-osmosis system to be approximately 50%, but this will increase as WEC costs are reduced, resulting in an increase in the ratio of m<sup>3</sup>/day per MWe-average. A summary of the per-unit costs in both water and electricity production is shown in Table 7.1.

**Table 7.1 Per-Unit System Cost Summary.** *Source: Warner et al. (2017)*

	\$/MWE PEAK OUTPUT	\$/MWE AVERAGE OUTPUT	\$/M3 PEAK OUTPUT	\$/M3 AVERAGE OUTPUT
WEC component of capital expenditures (CapEx)	\$6,254,671	\$20,665,117	\$1,251	\$2,546
WEC component of operational expenditures (OpEx)	\$109,851	\$362,941	\$22	\$45
Reverse-osmosis component of CapEx	-	-	\$1,177	\$2,395
Reverse-osmosis component of OpEx	-	-	\$38	\$77

The deployed marine energy system could have minimal surface expression, as shown in Figure 7.2. In fact, some technologies are fixed bottom or anchor mounted below the surface, eliminating any surface expression. However, minimal surface expression implies that the device must be robust enough to withstand the marine environment. But unlike electricity production, low-cost storage in the form of water tanks can mitigate the challenges associated with resource intermittency, providing an opportunity to offset costs resulting from reliability constraints.

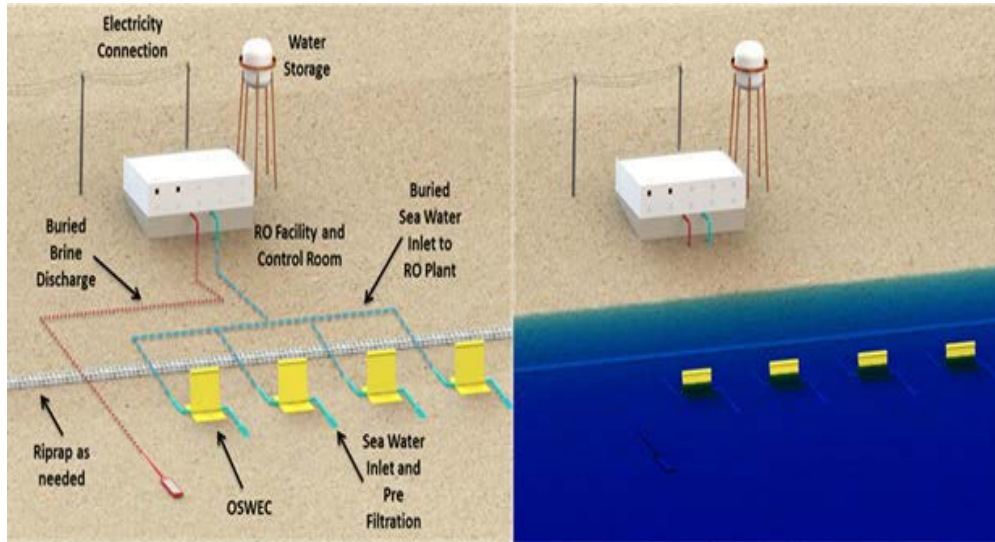


Figure 7.2. Rendering of a wave-powered desalination plant (“RO” is reverse osmosis). *Source: NREL*

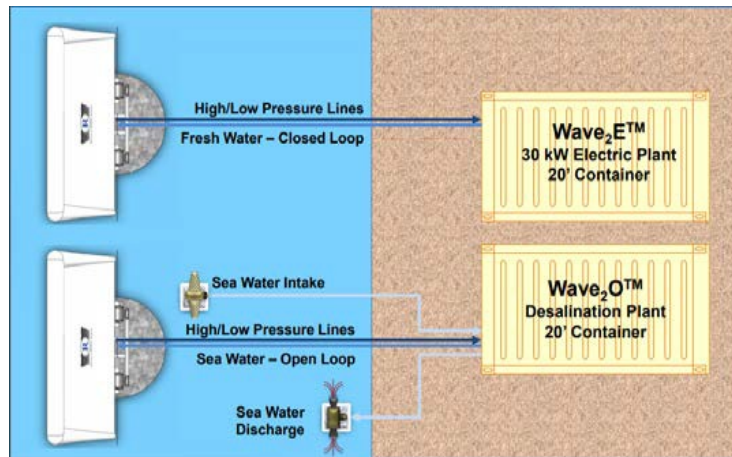


Figure 7.3. Configuration of Resolute Marine's Wave20 desalination system. *Image courtesy of Resolute Marine*

The rendering in Figure 7.2 is one of many potential application possibilities. Technology developers are designing systems that range from hybrid water and electric systems (Figure 7.3) to systems designed for easy deployment (Figure 7.4).



**Figure 7.4. SAROS wave-powered desalination demonstration unit**

Source: <https://www.digitaltrends.com/cool-tech/saros-buoy/>

## Power Requirements

Desalination is an intensive process because of the energy required to separate salts and other dissolved solids from water. The theoretical minimum amount of energy to separate the salts is a function of the osmotic pressure, or “the minimum pressure required to prevent the natural occurring transport of water from the side of the membrane with lower salinity to the side with higher salinity” (Voutchkov 2013). In operation, the actual pressure required is approximately two times the osmotic pressure; for seawater, this translates to about 800–1,000 pounds per square inch (psi) (55–69 bar). This pressure multiplied by the incoming flow rate determines the minimum amount of power required to push water through a membrane. Other processes, such as pre and postfiltration, require some energy but are orders of magnitude less energy-intensive than the primary membrane separation process. The energy required to run high-pressure pumps accounts for approximately 25%–40% of the overall cost of water. This energy is typically supplied in the form of grid-connected electricity-driving pumps, although in isolated locations, such as the U.S. Virgin Islands, diesel fuel is commonly used to create the electricity needed to drive pumps (Lantz, Olis, and Warren 2011). In addition to the filtration process, electricity is consumed for water delivery (and pumping), and some electricity is consumed for system control. In a wave-powered operation, most—and in some cases all—of the electricity can be replaced with mechanical pumping power supplied by the WEC. Table 7.2 summarizes the energy consumption for reverse-osmosis systems.

**Table 7.2. Energy Use for Traditional Reverse-Osmosis Process**

Energy Process	Existing Fuel	Use Pattern	Criticality	Average Site Energy Usage	Reference
Traditional seawater reverse osmosis	Grid/diesel	24 hour	Critical—performance	2.5–4.0 kilowatt-hours/cubic meter (m <sup>3</sup> )	Voutchkov (2013)
WEC-powered seawater reverse osmosis	-	24 hour	Critical—performance	2.8 kilowatt-hours/m <sup>3</sup> equivalent power	Yu and Jenne (2017)
Distribution	Grid/diesel	24 hour	Critical—performance	Varies with distance and elevation	

## Markets

### Description of Markets

For desalination, there are currently two primary market segments: water utilities and isolated or small-scale distributed systems. Large-scale desalination systems that feed into municipal water utilities, such as the Carlsbad Desalination Plant in San Diego, California, requires approximately 35 MW to run and provides 50 million gallons of water supply per day (Carlsbad Desalination Project 2017). Although costs for these large desalination systems are greater than typical water supply sources (i.e., surface water or groundwater), desalination becomes economically viable as other water sources become less abundant. Utilities are interested in desalination to establish control and reliability of water supply, provide drought resistance, and diversify their resources (DeOreo et al. 2011). Because of the high cost of these systems, water utilities expect long-term operation to provide maximum payout.

Operators of isolated desalination systems are likely to tolerate high technology costs if these systems provide a reliable water supply. Distributed desalination systems, such as those deployed in the U.S. Virgin Islands, where desalination is the primary source of water, are likely to be competing over the operational energy costs of diesel, waste heat, or other renewables, such as solar or wind deployed to run the specific desalination technology (Lantz, Olis, and Warren 2011). Island communities that have limited land availability may specifically provide a competitive advantage for marine energy technologies compared to solar or other renewables. Hybrid systems may also make more economic sense in these island markets, as they can produce both water and electricity. A notable example is the development project of Resolute Marine Energy in Cape Verde, Africa (Resolute Marine Energy 2017).

In the United States, the water utility market has the potential for billions of dollars in water sales per year. An initial estimate looked at the wave energy that is available in California, Oregon, Washington, Hawaii, and Alaska, with a practical limit of 15% of the total available resource (assumes 50% unavailable for access, and 30% capacity factor for the other 50%). Using these resource assumptions and water sales of \$1.60/m<sup>3</sup> (approximately the rate sold at the Carlsbad Desalination Plant), the West Coast, Alaska, and Hawaii markets could be worth approximately \$30 billion/year. This represents approximately 30% of the combined consumption in these states, with most in the state of California. The water utility desalination market could be expanded to the East Coast and the Gulf of Mexico, although these markets have less-intense wave resources and were not considered in the analysis mentioned earlier. Florida, North Carolina, and Texas have shown interest in desalination technologies and therefore the use of current energy converters, and localized applications (e.g., disaster relief, military bases, isolated water supply) may help expand the technology to the

East Coast and Gulf of Mexico. To understand the magnitude of this opportunity, further analysis is required but will likely face some of the similar challenges associated with grid-connected ocean current technologies (e.g., distance to shore).

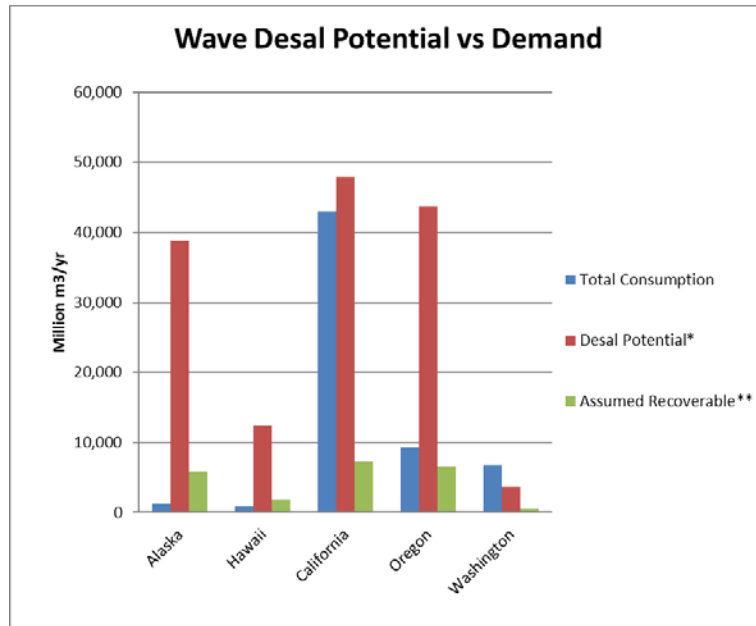
Overall, isolated markets are much smaller market opportunities, but are less sensitive to price. The total demand has not been quantified but will likely depend on many factors, such as costs, water availability, and anticipated growth. However, smaller, isolated markets can provide critical technology stepping stones to achieve cost reductions and other design evolutions important to developing competitive solutions. In fact, the wind industry followed this pattern when scaling from the 75-kilowatt machines common in the 1980s to the 3-MW machines by 2010 (Lantz, Hand, and Wiser 2012). In addition, some isolated markets are less price-sensitive to water supply options because of limited or scarce water resources and high energy costs for standard desalination installations. Additionally, in areas where diesel power dominates the electrical market and limited water resources exist, such as the U.S. Virgin Islands, the volatility of petroleum prices represents a commodities risk that renewable technologies might mitigate.

One of the most significant technical challenges, like other renewable technologies, will be matching the marine energy resource with water demand. Typically, the most significant wave energy resources occur during winter months and the lowest harvestable conditions occur during the summer months. The magnitude of the demand and resource availability will drive storage requirements (e.g., tanks, reservoirs).

Prescriptive regulations often borrowed from existing practices are likely to be refined and made less burdensome as marine energy and reverse-osmosis desalination technologies are more widely adopted. This has been shown with other technologies (e.g., wind and geothermal), wherein the regulations have evolved as the technologies become accepted. Existing permitting costs for desalination facilities can often drive total project costs higher but are dependent on many factors, including size, location, and local environmental concerns. For example, the permitting processes and consultations for the Carlsbad Desalination Plant in San Diego took 11 years to develop and permit because of challenges associated with land use, local opposition, and other environmental concerns (Water Reuse Association 2012). Nonetheless, California does have some of the most stringent and precautionary permitting processes, and as the technology becomes more widely understood by regulators and local communities, these costs will be reduced. Alternatively, small-scale systems create more manageable brine discharge, and smaller, low-flow intake systems will have reduced impacts on marine life and less difficult permitting challenges. Wave energy systems will have their own challenges because of the nascent state of the technology, but like desalination technologies, these costs are anticipated to be reduced as the technology matures and its impacts are better understood. Much of this is caused by regulators taking a conservative and precautionary approach that includes significant data collection efforts both before and after installation. However, this data collection can enable a quicker process later on.

The analysis on market size is visualized in Figure 7.5. Of the five states evaluated, Hawaii and Alaska have a recoverable resource potential that equals the total water consumption of those states. California and Oregon have resources that make up more than half of the market potential and those resources are smaller than the total water consumption. This implies that a large percentage of this resource could be exploited without producing more water than is currently needed.





**Figure 7.5. The total clean water consumption by state compared to what can be produced using local wave energy**

\*Resource knockdown factor of 0.5 (Kilcher and Thresher 2016); \*\*Assumes 30% capture width ratio and 50% of resource exploitable for desalination

In addition to the markets mentioned earlier, additional analysis needs to be performed to quantify the market potential for different end uses in which lower water quality is acceptable. Given that energy consumption is a function of both resource water quality (i.e., salt content) and desired water quality, markets that do not need to reach the same level of total dissolved solids as drinking water may provide an entry point for marine-energy-powered desalination systems.

### Power Options

The competition for marine desalination is diverse and site-specific. For large water utilities (e.g., San Diego Water Authority), other water sources will typically be considered before desalination technologies (i.e., surface water, groundwater, advanced water treatment for water reuse, water recycling, and water conservation portfolio options). Although desalination is considered a last resort, it is also considered a drought-resistant source of water, making it appealing within a water portfolio. Once desalination technologies are deemed acceptable, and in some cases necessary, to maintain water supply, energy sources that are reliable and low cost will compete with marine energy. Desalination is inherently energy-intensive, and when available, low-cost grid connections are preferred, particularly for large water utilities. In smaller, remote, or isolated locations where desalination is prominent, diesel-powered generators are typically used (Lantz, Olis, and Warren 2011). This is primarily driven by the reliability of diesel generation, and the perception that reverse-osmosis technologies must have an electricity input. Other renewables (e.g., wind, solar, geothermal) have been proposed and used in certain parts of the world for both membrane and thermal desalination technologies, although membrane technologies are the most common because they are the most energy efficient.

Marine energy has some specific advantages compared to other renewables or even diesel-powered systems. Given that marine energy technologies are inherently offshore, they will not be competing with land use as is the case with solar. In areas where social acceptance is a larger driver than water accessibility, fully or mostly submerged marine energy technologies will have less line-of-sight permitting and siting challenges than wind. Fully submerged technologies may even be designed at depths that can allow local fishing boats to travel through the water safely.

## Geographic Relevance

Coastal regions with limited freshwater resources are the potential geographic opportunities for marine-energy-powered desalination. For WEC technologies, California, Oregon, Washington, Alaska, and Hawaii have promising wave resources. Yet, the abundant water availability of the Pacific Northwest will likely prevent large-scale adoption in Washington and Oregon. The East Coast has an existing but less-intense wave resource, which may suit smaller-scale and distributed applications. On the other hand, both tidal and ocean current resources on the East Coast could satisfy the resource demands of larger-scale desalination projects.

## Marine Energy Potential Value Proposition

In the near term, marine-energy-powered systems could supply significant drinking water for communities with high water supply costs or limited electrical grid availability. Marine energy resources are, by definition, in marine environments where seawater is inherently available. Areas with high energy availability, either through wave energy or currents, will provide better opportunities for mixing of brine. Additionally, approximately 40% of the population lives near the coast in the United States (National Oceanic and Atmospheric Administration 2017). Marine energy resources are inherently located near potential desalination water supplies, therefore areas that have unreliable grid connections or water infrastructure may receive dual benefits from marine energy systems. In the long term, marine energy could provide low-cost, emission-free, drought-resistant drinking water to larger municipalities. This capability is envisioned using an array of WECs that pump water directly to shore. The water pumped to shore can either be pumped at the pressure needed for reverse osmosis (800-plus pound per square inch), or water can be pumped at high volume and low pressure and then converted to high pressure using pressure intensifiers. Both systems are technically feasible, but each has different costs and efficiencies, and therefore will require detailed technoeconomic analyses to determine which is the most appropriate. Either scenario will then use existing reverse-osmosis technology on land to enable low-cost maintenance and easy access for system repairs.

For wave-powered desalination, the most significant technical challenge is managing the energy variability from wave to wave (i.e., timescale of seconds). This can be mitigated a number of different ways, from the use of hydraulic accumulators to staggering wave devices (i.e., phase shift). A combination of these techniques can be used, but each technique adds cost, and therefore requires a detailed technoeconomic assessment to understand the most appropriate combination.

When considering economic competitiveness, marine energy technologies are currently more expensive than other renewables, although costs are expected to drop as marine energy technologies mature. However, existing estimates suggest that a reverse-osmosis component of capital expenditures (CapEx) is on the same order of magnitude as the marine energy technology component of a wave-powered desalination system, implying that as marine energy costs are reduced the desalination component will drive total system costs. Given the already-high CapEx associated with building reverse-osmosis plants, cost reductions in wave energy will have significant impacts on the unit cost of water from NREL's modeled \$1.80/m<sup>3</sup>. This is promising, given that today's costs are not far from commercially viable for a wave-powered reverse-osmosis plant. Additionally, for existing reverse-osmosis systems, energy consumption is a large portion of the overall cost, which implies that renewable technologies are well-suited for long-term cost reductions.

## Path Forward

Because of the maturity of existing reverse-osmosis technologies, the path to market will primarily require research and development (R&D) advancements on the marine energy systems and the reverse-osmosis marine energy system integration. Specific R&D challenges are listed in this section. However, once specific technical challenges have been addressed, technologies will need to be demonstrated for reliability as well as social and environmental acceptability.

The high energy requirements for desalination, whether at the large or distributed scale, require very similar, if not identical, marine energy technology advancements as we expect with utility-scale marine energy. Large-

scale water utilities will require water production that is equivalent to multimegawatt marine energy arrays. However, similar to the comparison of isolated power markets and utility-scale power markets, the early marine energy desalination opportunities will likely be able to take advantage of much smaller-scale marine energy devices. This will provide marine energy developers with the ability to develop marine energy technologies with lower financial risk and reduced installation and maintenance per unit. Although, additional analysis is still needed to quantify the size of these smaller markets.

However, one large difference is the need for high-volume, low-pressure pumps. Electricity generation, specifically where hydraulics are used, is typically designed for higher pressures (3,000–5,000 psi), reducing the size of the pumps needed. Seawater reverse-osmosis systems are typically designed to operate between 800–1,200 psi, requiring nearly five times the volumetric flow per unit of energy captured. As pumps are made larger, whether linear or rotary, the tolerances required for seals and alignment can drive up the cost of the primary pump within the power take-off. This challenge is amplified in scenarios in which low pressure (<100 psi) water is delivered to shore and boosted to the required pressure for separation, as suggested by previous wave-powered desalination companies SAROS and Aquamarine.

To reliably make clean drinking water using WECs to pressurize a standard reverse-osmosis desalination system, there are significant R&D challenges associated with technology integration. Membrane performance and reliability in oscillatory flow is poorly understood by the existing membrane industry. As stated earlier, pressure and flow can be smoothed to a certain level, but at an additional cost. To optimize a system for low-cost operation, membrane reliability must be fully understood. Another technical challenge will be energy recovery units for dynamic operation. Similar to membranes, energy recovery units commonly used in reverse-osmosis applications to recover the energy within the rejected brine are not designed to function outside of steady-state operation. Pretreatment technologies will also need to be developed for wave energy applications. Just like membrane performance, existing pretreatment technologies are not designed for the oscillatory wave inputs and therefore are likely a significant R&D challenge.

In addition, the Carlsbad Desalination Plant has demonstrated the importance that environmental and permitting changes can have on commercial viability. Permitting for large facilities can take many years and be a significant component of the total CapEx. The Carlsbad plant project cost has been estimated at approximately \$650 million (3,400 m<sup>3</sup>/day) (Global Water Intelligence 2016), with about half of that cost related to permitting and environmental mitigation.

The system supply chain consists of two major components: the desalination plant and water delivery. The desalination plant consists of the WEC and reverse-osmosis unit. There are already a number of manufacturers that produce skid-mounted, small-scale reverse-osmosis systems, both modular units and custom-designed applications. For large-scale facilities, engineering design firms usually develop and coordinate the delivery of specialized, often state-of-the-art systems. Marine energy manufacturers, however, are limited in scope and size, and often are working toward proof-of-concept technologies rather than commercial systems. There are a handful of U.S. wave energy developers, but none have achieved significant commercialization or clear demonstration of their technology. Pilot- and laboratory-scale demonstrations will likely streamline this process. Water delivery will depend on the specific region and existing infrastructure.

As mentioned earlier, there are significant regulatory challenges with both wave energy and desalination technologies. Large-scale systems will have the most challenges but developing small-scale technologies may mitigate the large-scale challenges before they arise. This is primarily caused by the volumes of water in the intake and discharge and not the technology type. The U.S. Environmental Protection Agency requires the salinity of the surrounding seawater to stay within a 4% prescribed variance (e.g., up to 4% variance) and within a prescribed location of the discharge (Southern California Coastal Water Research Project 2012). The larger the plant, the more challenging this becomes, driving up the cost and the time it takes to evaluate the discharge.

Small-scale systems could potentially enter the market in the near term, as there are already wave energy developers nearing this milestone. Resolute Marine Energy is currently planning an installation off Cape Verde, Africa, where the cost of water is higher than in the United States and electricity production is also needed. The biggest challenge with near-term success is likely to be integrating the wave energy system with the mature reverse-osmosis technology and doing so reliably for years to come. Wave energy devices have yet to demonstrate multiyear operation in the United States and until this has been demonstrated, it will be challenging for any wave energy developer to penetrate either the desalination or electricity market.

Reverse-osmosis technologies inherently have significant job creation potential because of the cleaning and replacement of membranes. A typical reverse-osmosis system has hundreds to thousands of commercial off-the-shelf membranes. During typical operation, membranes may last up to 5 years (Cooley and Ajami 2012), with cleaning occurring every couple of weeks to months, but the reliability of membranes is unknown in oscillatory flow conditions posed by wave energy resources. These maintenance cycles typically require human intervention and therefore future job creation.

Finally, WEC-powered desalination has many synergies with utility-scale generation. The first synergy is that the wave device can be built to nearly any size with the optimal size being very similar if not equivalent to utility-generation WECs. This is because of the technology needed to maximize energy capture and reduce costs. Pressurizing seawater and pushing it through a membrane has a lot of similarities to a hydraulic power take-off, with the biggest difference being pressure and flow rates. Electricity generation systems are typically designed for higher pressure (3,000–5,000 psi) and lower flow rates, whereas reverse-osmosis systems aim to produce pressures around 800–1,200 psi. Additionally, concepts, such as pressure and flow smoothing that are necessary for longer membrane life, directly benefit utility-scale generation by allowing lower-cost generators, power electronics, and power cables to shore.

### **Potential Partners**

The most likely organizations that would be interested in co-development of projects in the near term are municipalities already deploying or building desalination facilities to mitigate drought or water scarcity risks. Interested municipalities could range from small cities, such as Monterey, California, to smaller towns or small regional service areas, such as Coastal Oregon or the Outer Banks. The challenge with municipality partners is that they are inherently risk-averse organizations with little appetite for costly innovation. Significant demonstration projects will likely not be of interest to these organizations or might challenge their traditional business model. At the component level, given the level of hydraulic smoothing that will need to be performed, hydraulic equipment suppliers also provide obvious codevelopment opportunities. Membrane manufacturers such as Dow, pretreatment suppliers, and energy recovery devices could all be potential partners. In addition, smaller, flexible, and cost-effective systems could find application in rural coastal and island communities with water supply challenges and high-energy costs, such as those based in Alaska, Hawaii, the Caribbean, and across the globe nonprofit organizations, aid organizations, and emergency management organizations. In addition, other government agencies focused on disaster relief or rural development could be co-development partners. Emergency organizations, such as the Federal Emergency Management Agency, the National Guard, and the U.S. Army Corps of Engineers, could all be relevant allies. Also, disaster aid and relief institutions, such as the Red Cross, United States Agency for International Development, and World Bank would be interested organizations. Finally, many water resource agencies, institutions, and academic partners could be potential market partners, such as CalDesal, the Water Council, and the Water Environment Federation.



## References

- Carlsbad Desalination Project. 2017. “FAQs.” Accessed February 2018. <http://www.carlsbaddesal.com/faqs.html>.
- Cooley, Heather, and Newsha Ajami. 2012. *Key Issues for Desalination in California: Costs and Financing*. Oakland, CA: Pacific Institute. <http://pacinst.org/publication/costs-and-financing-of-seawater-desalination-in-california/>.
- DeOreo, W., P. Mayer, L. Martien, M. Hayden, A. Funk, M. Kramer-Duffield, R. Davis, J. Henderson, B. Raucher, P. Gleick, M. Heberger. 2011. *California Single-Family Water Use Efficiency Study* (Technical Report). Aquacraft, Inc. Water Engineering and Management, Boulder, CO (US). <http://water.cityofdavis.org/Media/PublicWorks/Documents/PDF/PW/Water/Documents/California-Single-Family-Home-Water-Use-Efficiency-Study-20110420.pdf>.
- Ghadiryantar Hoffman, Justin, Ronald C. Pate, Thomas Drennen, and Jason C. Quinn. 2017. “Techno-economic assessment of open microalgae production systems.” *Algal Research*, 23: 51–57. <https://www.sciencedirect.com/science/article/pii/S2211926416303046>.
- Kam, K. and M. Doeff. 2012. “Electrode Materials for Lithium Ion Batteries.” *Materials Matters*, Aldrich Materials Science. 7(4), 56. <https://www.sigmaaldrich.com/content/dam/sigmaaldrich/docs/Aldrich/Brochure/1/material-matters-v7n4.pdf>.
- Kilcher, Levi, and Robert Thresher. 2016. *Marine Hydrokinetic Energy Site Identification and Ranking 3909 Methodology Part I: Wave Energy* (Technical Report). NREL/TP-5000-66038. Golden, CO (US): National Renewable Energy Laboratory. <https://www.nrel.gov/docs/fy17osti/66038.pdf>.
- Lantz, Eric, Dan Olis, and Adam Warren. 2011. *U.S. Virgin Islands Energy Road Map: Analysis* (Technical Report). NREL/TP-7A20-52360. Golden, CO (US): National Renewable Energy Laboratory. <https://www.nrel.gov/docs/fy11osti/52360.pdf>.
- Lantz, Eric, Maureen Hand, and Ryan Wiser. 2012. *The Past and Future Cost of Wind Energy: Preprint*. NREL/CP-6A20-54526. Golden, CO (US): National Renewable Energy Laboratory. <https://www.nrel.gov/docs/fy12osti/54526.pdf>.
- National Oceanic and Atmospheric Administration. 2017. “What percentage of the American population lives near the coast?” Accessed April 2, 2018. <https://oceanservice.noaa.gov/facts/population.html>.
- National Research Council. 2008. *Desalination: A National Perspective*. Washington, DC: The National Academies Press. <https://doi.org/10.17226/12184>.
- Resolute Marine Energy. 2017. *Resolute Marine Launches Feasibility Studies in Cape Verde*. Accessed February 2018. <http://www.resolutemarine.com/news/resolute-marine-launches-feasibility-studies-in-cape-verde>.
- Southern California Coastal Water Research Project. 2012. *Management of Brine Discharge to Coastal Waters Recommendations of a Science Advisory Panel*. Technical Report 694, Costa Mesa, CA. [https://www.waterboards.ca.gov/water\\_issues/programs/ocean/desalination/docs/dpr051812.pdf](https://www.waterboards.ca.gov/water_issues/programs/ocean/desalination/docs/dpr051812.pdf).
- Voutchkov, Nikolay. 2013. *Desalination Engineering Planning and Design*. McGraw-Hill.
- Warner, Ethan, Kristi Moriarty, John Lewis, Anelia Milbrandt, Amy Scwab. 2017. *2015 Bioenergy Market Report*. Prepared by the National Renewable Energy Laboratory for the U.S. Department of Energy. <https://www.nrel.gov/docs/fy17osti/66995.pdf>.

Water Reuse Association. 2012. *Seawater Desalination Costs*. [https://watereuse.org/wp-content/uploads/2015/10/WateReuse\\_Desal\\_Cost\\_White\\_Paper.pdf](https://watereuse.org/wp-content/uploads/2015/10/WateReuse_Desal_Cost_White_Paper.pdf).

Yu, Yi-Hsiang, and Dale Jenne. 2017. “Analysis of a Wave-Powered, Reverse-Osmosis System and Its Economic Availability in the United States.” *36th Annual International Conference on Ocean, Offshore and Artic Engineering*. Trondheim, Norway. June 25–30. <https://www.nrel.gov/docs/fy17osti/67973.pdf>.